Development of a Novel Open Architecture Rapid Prototyping System

By

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,

and that any and all revisions required by the final

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To my parents

and brother

ABSTRACT

Rapid Prototyping (RP) is a crucial technology in order to reduce the product development time. Today this technology is not only used for prototyping in product development but also manufacturing of small volume products and rapid tooling for some special cases. Moreover, beside the production industry, it is used in a wide range of areas from art to medicine. RP technology enables 3D model designed by using a computer aided design (CAD) program to be manufactured layer-by-layer. This advanced technology allows users to save significant amount of time over the conventional manufacturing methods. Many different RP methods have been developed in the last two decades and well known ones are stereolithography (SL), selective laser sintering (SLS), laminated object manufacturing (LOM) and fused deposition modeling (FDM). A wide range of materials including ceramics, polymers and metals can be used for production with these methods. In addition, living cells can also be used to create tissues with RP technology.

In this thesis, a novel open architecture rapid prototyping system is developed including all its hardware as well as its software. The hardware includes a 3-axis machine that is precisely controlled by a PC via a servo system. Since the system is open architecture, various tool path generation algorithms developed in-house can be implemented. Three different slicing and path generation software are created. In the developed software, the operator can generate tool paths manually as well as using stereolithography files (STL file) or cutter location source files (CLS file) as inputs. The STL or CLS files for any part can be obtained from any commercially available solid model based CAD/CAM programs. The developed software processes 3D CAD data and generates electronic signals to drive the servo system. Moreover, a new rapid prototyping robot dispensing (RPBOD) unit is developed and integrated to the system. Various 3D parts produced by this new open architecture RP system are also presented.

ÖZETÇE

Hızlı Prototipleme (HP), ürün geliştirme döngülerinin hızlandırılması ihtiyacından dolayı ortaya çıkmış önemli bir teknolojidir. Bugün bu teknoloji sadece ürün geliştirme sırasında prototipleme için değil, ayni zamanda az hacimli ürünlerin direk üretilmesinde ve bazı özel durumlarda kullanılmak üzere hızlı alet ve takım üretiminde de kullanılmaktadır. Bununla beraber, üretim endüstrisinin yanında, HP teknolojisi sanattan tıp'a birçok alanda daha kullanılmaktadır. HP teknolojisi, CAD programında tasarlanmış 3 boyutlu bir modelin katman-katman üretiminin yapılmasına olanak sağlamaktadır. Bu gelişmiş teknoloji geleneksel üretim yöntemleri ile karşılaştırıldığında önemli bir zaman tasarrufu sağlamaktadır. Son yirmi senelik zaman diliminde pek çok farklı HP yöntemi geliştirilmiştir ve bunlardan en çok bilinenleri stereolithografi (SL), selective laser sintering (SLS), laminated object manufacturing (LOM) ve fused deposition modeling (FDM) dır. Seramik, polimer ve metal gibi birçok değişik malzemeler bu HP yöntemlerinde kullanılabilmektedir. Buna ek olarak, HP teknolojisi yaşayan hücreleri kullanarak dokular üretmeye de olanak sağlamaktadır.

Bu tez kapsamında, açık mimariye sahip yeni bir HP sistemi, tüm yazılım ve donanımı dâhil olmak üzere geliştirilmiştir. Donanım, bilgisayar kontrollü bir servo sistem tarafından kontrol edilen 3 eksenli bir makineyi kapsamaktadır. Tasarlanan sistem açık mimariye sahip olduğu için, çok çeşitli takım yolu üretme algoritmaları tasarlanıp uygulanabilinir. Proje kapsamın 3 farklı katmanlara ayırma ve yol üretme algoritması geliştirilmiştir. Geliştirilen yazılımı kullanarak operatör kendisi manüel olarak bir yol üretebileceği gibi stereolithography (STL) yada kesici uç konumu kaynak (KUKK) dosyalarını da girdi olarak kullanarak yol üretebilir. 3 boyutlu bir parçanın STL yada KUKK dosyaları piyasada bulunan herhangi bir katı model tabanlı CAD/CAM programından elde edilebilir. Tasarlanan yazılım 3D CAD verisini işleyerek servo sistemi sürecek elektrik sinyallerin

üretir. Ek olarak, yeni bir RPBOD (Rapid prototyping robot dispensing) ünitesi geliştirilmiş ve sisteme bütünleştirilmiştir. Ayrıca bu tezde, geliştirilen açık mimariye sahip HP makinesi kullanılarak üretilmiş parçaların bazıları da sunulmaktadır.

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I dedicate this thesis to my family because it would not be possible without their morale support. I would like to thank my beloved mother for her prayers and guidance of life. I would like to thank my father who has been spirit for me and has always believed in me even I have given up. I would like to thank my wise younger brother who has been able to make me laugh.

Finally, Thank God for my good destiny and success in life…

Erdem Cerit

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NOMENCLATURE

3DP	3 Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
BPM	Ballistic Particle Modeling
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CLFDM	Curved Layer Fused Deposition Modeling
CLSF	Cutter Location Source File
CNC	Computer Numerical Controlled
FDM	Fused Deposition Modeling
LOM	Laminated Object Manufacturing
PDT	Product Development Time
PVC	Polyvinyl Chloride
RM	Rapid Manufacturing
RP	Rapid Prototyping
RPBOD	Rapid Prototyping Robot Dispensing
RPM	Rapid Prototyping Machine
RT	Rapid Tooling
RTV	Room Temperature Vulcanization
SL	Stereolithography (RP method)
SLA	Stereolithography Apparatus
SLS	Selective Laser Sintering
STL	Standard Triangulation Language or Stereolithography (File format)
TtM	Time-to-Market
UV	Ultraviolet

Chapter 1

INTRODUCTION

New technologies and innovations are urged by necessities. For the last two decades, reduction of the product development time (PDT) has been crucial and the greatest source of gaining advantage in competitive global market for companies, since the key objectives and important factors of product development cycle like quality, reliability, and product cost and performance have been satisfied by most of the leading companies [1]. Time spent from designing the product until putting it on the shelf is called time-to-market (TtM). If a company is able to decrease TtM for its new product, it gains advantages in market like increased market share and profit. It can be said that the rapid prototyping (RP) that is a layer-by-layer manufacturing technology was urged by this necessity of decreasing PDT. Researches show that the RP technology can cut the TtM by 90% [2]. However, today, this technology is not only used for prototyping to decrease the production time, but also used in a wide range of applications such as creating work of art, modeling in architecture, planning surgery and producing custom biomedical devices and implants in medicine, and manufacturing small volume of custom products in production industry which is, in this case, called rapid manufacturing (RM). Even some researchers claim that in the future, rapid prototyping machines (RPMs) will be used at homes like today's desktop printers to produce custom designs and products [3]. This prevision sounds possible when the fast development of this technology is considered.

Rapid prototyping is a new and recently developing technology. Since 1987, after the first commercial rapid prototyping machine was used [4], this technology has developed rapidly. The reason why this new technology has became so popular is its working principles. RP allows an object to be built directly from a computer-aided design (CAD) data by adding materials layer-by-layer in a relatively shorter time than traditional manufacturing techniques. With the help of this technology, very complex parts which can not be produced with conventional manufacturing methods, is now able to be produced in one go. Recently, a wide range of materials including ceramics [7], polymers [6] and metals [8] can be used in RP technology. Although the RP is a twenty years old technology, lots of different methods have been developed [4, 5] and today, a wide range of RP methods are commercially available such as stereolithography (SL), fused-deposition modeling (FDM), ballistic-particle manufacturing (BPM), three-dimensional printing (3DP), selective laser sintering (SLS), laminated-object manufacturing (LOM) and several newly developing methods.

In this study, an open architecture rapid prototyping system is developed in which, initially, a similar method to FDM is used as material deposition method. In this method, while the deposition head is following a path, a filament of polymer is heated just below its melting point and then this almost melted filament is pushed through a small nozzle. From this nozzle polymer is deposited on to the manufacturing ground. The material immediately solidifies and by repeating this process for each layer, the prototype is produced [6]. A wide range of materials are used in FDM method. But in industry, the most preferred material is Acrylonitrile butadiene styrene (ABS) [6]. In the first version of the system, ABS and some other polymers were examined. However, because of the encountered problems which are discussed in Section 3.1.2.1, different methods and materials have been tried. In the recent system, silicone (polysiloxane) is used as production material. The deposition system and method is also changed. Currently used method is being used in rapid prototyping systems in last decade [9, 10] and is quite different than the FDM method. This method is called rapid prototyping robot dispensing (RPBOD) in the literature. In the current deposition system, no heating sub-system is needed to melt the material because the current production material, silicone, is in liquid form at room temperature, and viscous enough to be deposited on a surface without any heating process. It solidifies in minutes after it gets in contact with air. The material is deposited by using a dispensing system that basically consists of a syringe and a stepper motor. As mentioned before, the current production material is chosen as silicone since it is cheap, non-toxic, and easy to use and obtain. As hardware, a RPM is manufactured that consists of a moving X-Y table carrying the prototype and a deposition sub-system attached to a ball-screw mechanism driven by a servo motor which provides the motion in Z direction.

As software, three different programs which create the path followed by deposition system while creating the prototype are written. Two of these programs are STL file and cutter location source file (CLSF) based, respectively. STL file format is the most common format that is used in RP industry. It defines surface of a solid model with small triangles adjacent to each other. First algorithm accept STL file as an input and then creates virtual planes that intersect with triangles define the surface of the model. From intersection points, borders of each layer are found. Finally a zig-zag path is generated for each layer. Second algorithm accepts CLSFs as input. These files are used in computer numerical controlled (CNC) machines to define paths for milling operations. They contain data about type of motion and coordinates of the nodes on path. The written algorithm processes these data to generate path for RP operation. Third program allows operator to define the path by manually entering the coordinates of the nodes that are on the path. In this thesis, this newly developed RP system and its recent outputs are introduced.

Chapter 2

LITERATURE REVIEW

2.1 Prototyping and Product Development Process

The roots of the manufacturing and production can be traced back to about 5000-4000 B.C. [11]. Man kind has to design and manufacture objects and products for their needs. Therefore, the steps of this old action – product development– are well defined during the history and, today, for the production of almost all of the products, the same steps are followed (Figure-2.1).

Older approaches of product development process contain serial steps, but in the new approach all disciplines are involved in the early design stages. Communication between departments and different disciplines are increased. So the time spent for iterations is decreased. This new approach is called concurrent engineering or in a more clear way, it can be called as time compression engineering.

Technological advances and solutions in computer and manufacturing technologies can now provide opportunity to perform tasks simultaneously in product development processes [12]. The use of CAD, computer-aided engineering (CAE) and computer-aided manufacturing (CAM) techniques have simplified the design, the analysis and the prototyping steps of the product development process. The influence of these technologies can be best observed in “the computer-aided design” block of the diagram given in Figure-2.1.

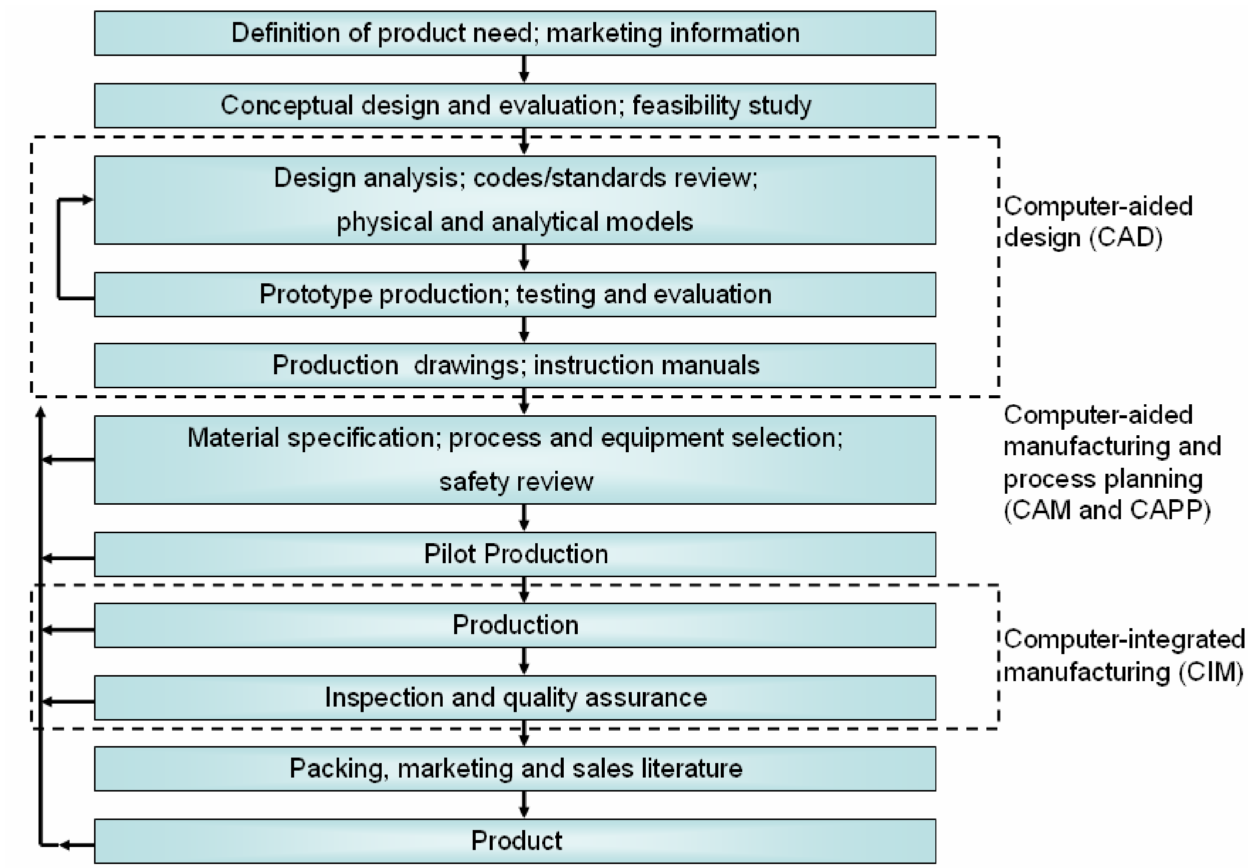


Figure 2. 1: Steps of product development process [11]

The concern of this study is the prototyping section of this block**.** Before the rapid prototyping concept, it is important to know well what a prototype is. Prototype can be defined as the original working model of a newly designed product [11]. At least one prototype is produced for almost every industrial product before the mass production of this product begins. The product can be a Boeing 737 passenger airplane (Figure-2.2) or a toy (Figure-2.3). In fact, the prototype does not have to be a working model of the product. It can be used just for visualization of the design, for marketing, for testing the functionality of some parts of the product or can be used as proof of concept.

Figure 2. 2: The prototype 737-100 lifts off from Boeing Field on its first flight on April 9, 1967. [http://www.boeing.com/news/frontiers/archive/2007/december/i_ca03.pdf]

According to the results of the investigations and the tests done on the prototype, if it is necessary, the preliminary design is changed and then another prototype is produced. This iterative process goes on until the desired end-design is reached. If this iteration process can be speed up, the time spent for the whole product development process is decreased. Here is where the RP technology steps in. With the conventional methods, prototyping process can be very costly and time consuming. Technical drawings of the parts must be prepared. The necessary molds and tools must be produced to make the parts of the prototypes. Sometimes, skilled artists are necessary to make some parts of the prototype or the whole prototype from the clay (Figure-2.3-a). However, the RP technology makes the things easier for both designers and engineers.

Figure 2. 3: a) A sculptured prototype of a toy b) Produced toy
[http://rappelz.gpotato.com/?m=community&a=commcenter&id=97]
[http://www.hk-gensen.com/index.htm]

2.2 Rapid Prototyping

The technique of layer-by-layer manufacturing of an object by using CAD data is called rapid prototyping (RP). This technique is also referred to as solid free-form fabrication, layered manufacturing, material addition manufacturing or desktop manufacturing [13, 14, 15, 16]. At first, the aim of RP technology was to reduce the prototyping time in product development process. However, today, it is used in a wide range of applications such as creating work of art, modeling in architecture, planning surgery, producing custom biomedical devices and implants in medicine, and manufacturing small volume of custom products in production industry [12, 17]. When RP technology is used for tooling, it is referred to as rapid tooling (RT) [21-24], and it is referred to as rapid manufacturing when this technology is used to produce end-products [25].

The term “Rapid” indicates the speed of the manufacturing process, because RP methods permit objects to be manufactured relatively faster than the conventional manufacturing methods.

The working principles and the followed steps are same for all of the RP methods. First, the model that will be produced is designed by using a solid based modeling program. Then, this 3D CAD model should be sliced into series of layers. There are two methods of slicing: STereoLithography (STL)-based slicing and direct slicing (Figure-2.4). In this study, both slicing methods are used. In Figure-2.5, steps of an RP method in which STL-based slicing is used, are shown.

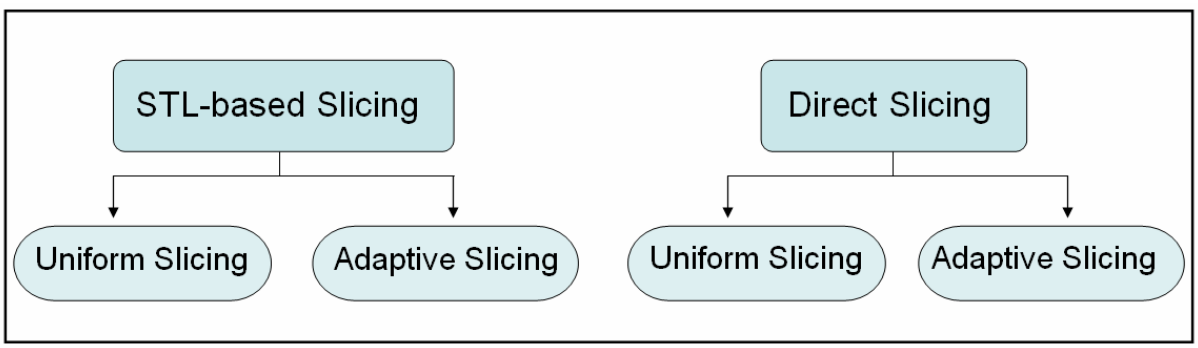


Figure 2. 4: Slicing methods used in RP technology

Before the STL-based slicing operation, the CAD model should be converted to STL file format, also known as Standard Triangulation Language file. It can be said that, recently, STL file format is a de facto standard file format for RP industry [18, 19]. This file format was first developed and published by 3D systems company to use in their rapid prototyping system StereoLithography Apparatus (SLA) [19].

After the generation of the STL file, it is imported to the slicing and the path generation program of the RP system. All of the commercial RP systems have their own slicing and path generation software. Also, for some of the CAD programs rapid prototyping modules have been newly developed that can be used for slicing and path generation operations. The slicing program divides the model into a series of thin layers. Since the thickness of these layers is very small compared to the height of the 3D model, it can be said that a complex 3D problem is divided into a series of simpler 2D problems (Figure-2.5-c). After the layering operation, the software of the RP system generates paths that will be followed while producing each layer. Last, the RP machine produces the model layer-by-layer. This production process is fully automated and requires no human intervention. Therefore, RP processes speed up product development times. Moreover, RP technology makes it possible to deal with more complex geometries that can not be produced with conventional methods.

a) b) c) d) e)

Figure 2. 5: a) Model is designed in a CAD program b) Model is exported in STL file format c) & d) Model is divided into a series of thin layers e) Layer-by-layer RP machine produces the model

2.3 Steps of RP Process in More Detail

2.3.1 Designing the Model

This is not a special step. Any commercially available CAD program can be used to design the model which will be produced. In this study, Unigraphics NX CAD program is used. However, while designing, some properties of the RP machine must be considered. For example, every RP machine has a resolution, that is, the minimum layer thickness which can be provided by the machine. This property depends on the deposition system of the RP machine. The details that are smaller than the resolution value of the machine can not be produced. So, the design engineer should be careful about this property.

2.3.2 Slicing the Model

The designed model should be sliced into layers before the production process. Previously, it is mentioned that there are two main methods of slicing in RP operations: STL-based (tessellated model based) slicing and direct slicing (Figure-2.4). The STL is de facto standard file format for RP applications and STL files are used in the slicing and path generation processes widely because of its two major strengths, namely, simplicity and independence from specific CAD modeling methods[19]. On the other hand, there are some disadvantages of STL file format. The size of STL files can be very big because of the redundancy caused by the duplication of vertices and edges as shown in Figure-2.6 [19]. Nevertheless, the STL file format approximates the surface of the CAD model with triangles and this first order approximation causes the geometric inaccuracies. Moreover, the list of triangles without topological information may cause defects in STL files such as gaps and overlaps which require repair software [31-34].

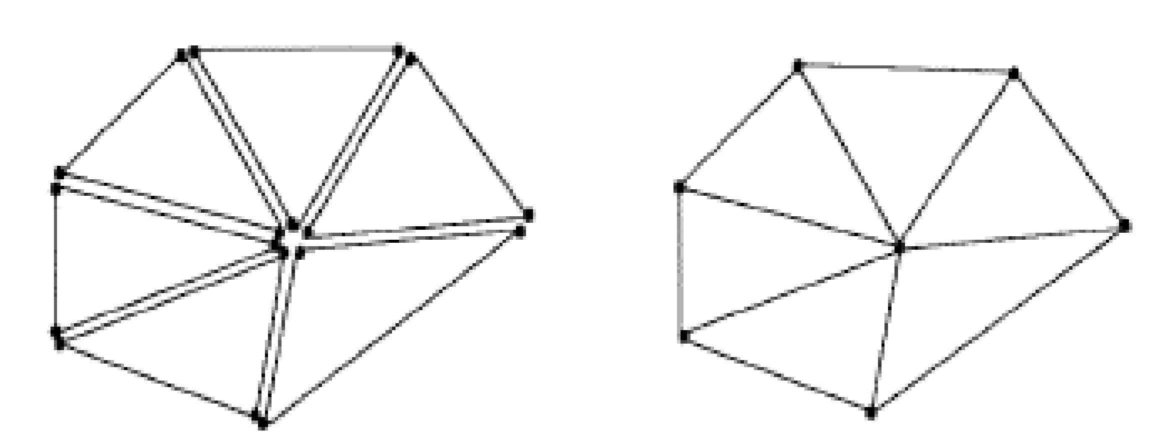


Figure 2. 6: Redundancy in STL file. [19]

The other method, direct slicing, has some advantages over STL-based slicing. The main advantage is that the original part is directly used in slicing operation and since there is no approximation, the resultant model is more accurate. Reduced file size, decrease RP machine pre-processing time, and elimination of repair routines are the other advantages of direct slicing [27]. Unfortunately, every direct slicing algorithm can only be used for a specific set of CAD software and machine, and is not applicable to any other CAD combinations. For example, Chang [28] proposed a direct slicing method for PowerSHAPE models and Ma et al. [29] presented a direct-adaptive slicing algorithm for NURBS based surface models in their paper. Although there are some attempts to make a universal direct slicing algorithm, these kind of new solutions have not been truly accepted by the RP industry yet. For example, Zhou [30] proposed a direct slicing approach which is not rely on a specific CAD system. In this approach, the CAD model is transferred to slicing system by neutral STEP files and then the model is sliced.

As a matter of fact, STL-based slicing is still the most popular slicing approach in RP industry and STL files are accepted as standard format for transferring CAD model data to

RP systems [20]. It reduces the problem to finding plan-plane intersections; it is simple and independent from specific CAD modeling methods.

As can be seen in Figure-2.4, both STL-based and direct slicing methods have sub classes: Uniform slicing and adaptive slicing. In uniform slicing, thickness of each layer is equal. The user defines a thickness layer and slicing operation occurs based on this value. If the layer thickness is small, more accurate and smoother surface obtained. But in this situation, the file size can be extremely big and the production time can be very long. On the other hand, if the chosen layer thickness is too big, the smoothness of the surface can be lost if the geometry is complex (See Figure-2.7).

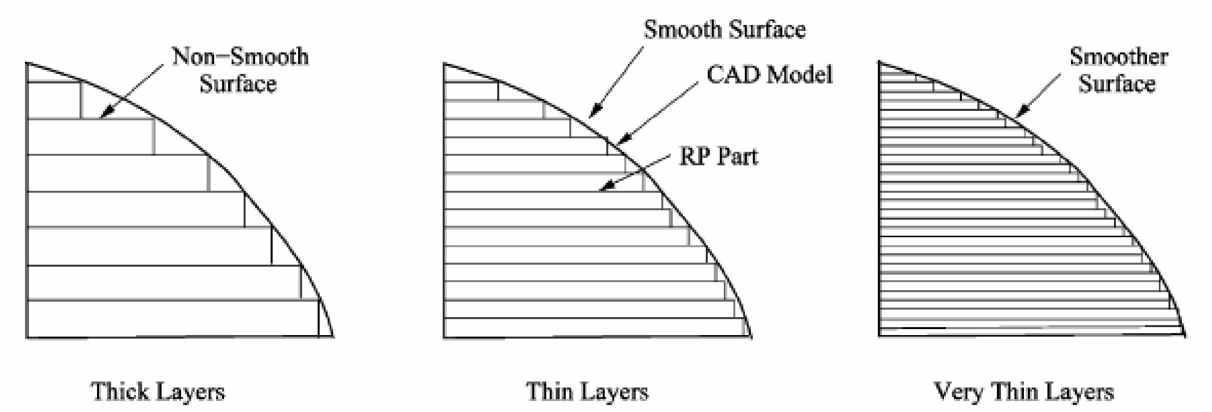


Figure 2. 7: Effect of layer thickness on surface finish [27]

However, in adaptive slicing, the layer thicknesses are variable and the thickness of layers determined based on two concepts: limiting cusp height and limited deviation of cross-sectional area (plane normal to Z axis) of the part [27, 35]. Limiting cusp height method is an important and widely used method first defined by Dolenc and Makela [36] (See Figure-2.8). The cusp height can be defined as the distance between the intended and the approximated surface at each facet. The user specifies a maximum allowable cusp height, and then based on this allowable cusp height; the thickness of the current layer is calculated by using the normals around the boundary of the preceding horizontal plane [35].

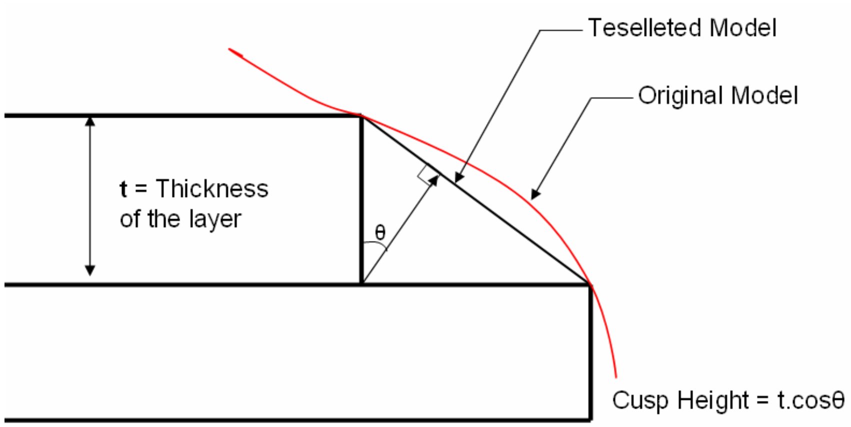


Figure 2. 8: Definition of the cusp height [35]

The uniform slicing algorithms are simpler than the adaptive slicing algorithms. Nevermore, the peak features of the model can be lost when uniform slicing methods are used and this is the most important advantage of adaptive slicing. This situation is shown in Figure-2.9. A peak feature may occur on areas where sudden changes exist such as a corner, a boundary curve or an interior area of a surface [29].

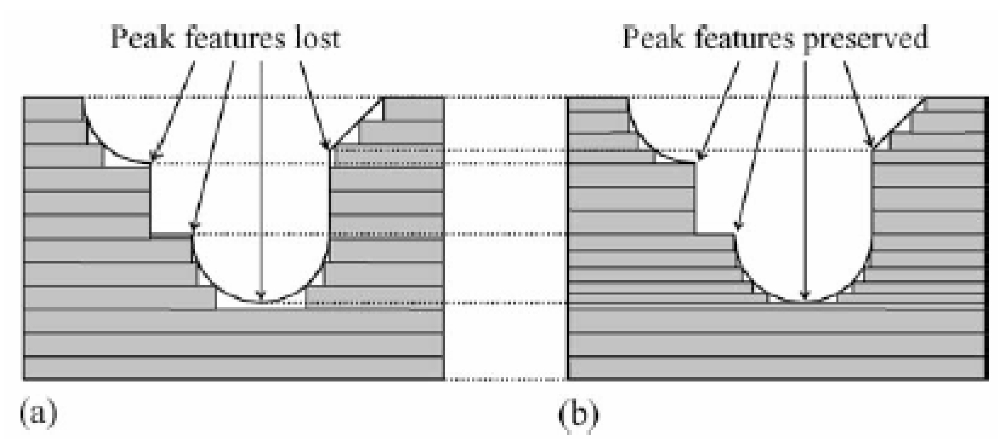
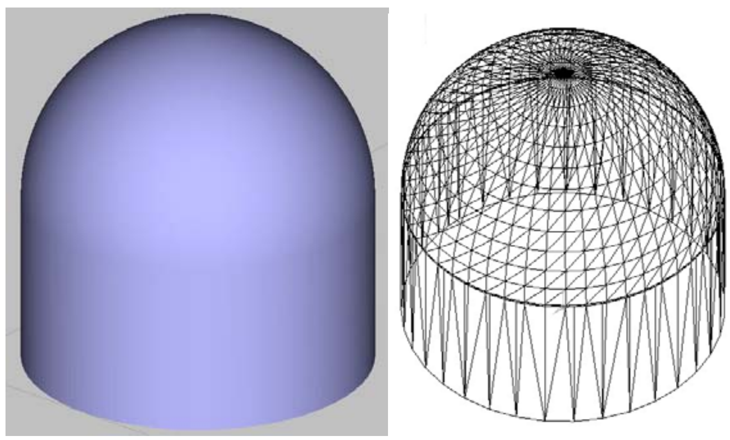


Figure 2. 9: a) with uniform slicing, peak features might be lost; b) with adaptive slicing peak features can be preserved [29]

2.3.2.1 STL file format

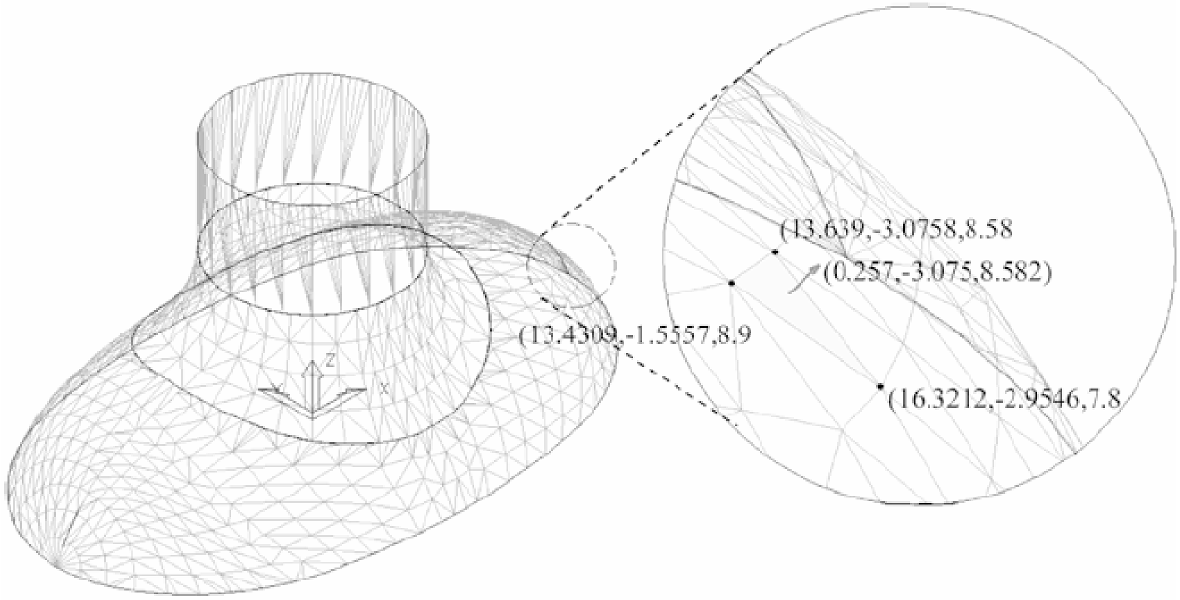
Since, in RP industry, STL file format is the most common interface between CAD data and RP systems, this file format should be understood well. In an STL file format, the surface of the 3D model is meshed with triangles which share common sides and vertices. This process is called tessellation [19, 20] (See Figure-2.10).



a) b)

Figure 2. 10: a) CAD model, b) tessellated version of this CAD model

The 3D model is not defined as a solid object but a closed surface like a shell without thickness. None of the features like texture and color are specified in this file format. Each triangle in the file is defined by a facet normal and three vertex coordinates as shown in Figure-2.11. The vertices are arranged in a particular order such that if right hand rule is applied, the resultant vector is the facet normal which is pointing outwards. Almost all of the CAD programs are capable of producing an STL file. For this study, Unigraphics NX-4 CAD program has been being used. But other well known CAD programs such as ProEngineer, SolidWorks, AutoCad (Versions R14-2000i), Mechanical Desktop can also be used to design a 3D model and to produce the STL file of a CAD model.




```
triangular
   facet normal 2.571755e-001 -1.844326e-001 9.486018e-001
      outer loop
         vertex     1.363903e+001 -3.075754e+000 8.582368e+000
         vertex     1.632122e+001 -2.954581e+000 7.878757e+000
         vertex     1.343088e+001 -1.555650e+000 8.934345e+000
      endloop
   endfacet
endtriagular
```

Figure 2. 11: The triangular format for STL files

In STL format, the geometry of the model is approximated with a shell consists of triangles wrapping the model. The error caused by approximating the model geometry is called chordal error [26] (Figure-2.12). As mentioned in previous section, in direct slicing, since the slicing operation is done directly by using the real model geometry, this kind of approximation error is prevented.

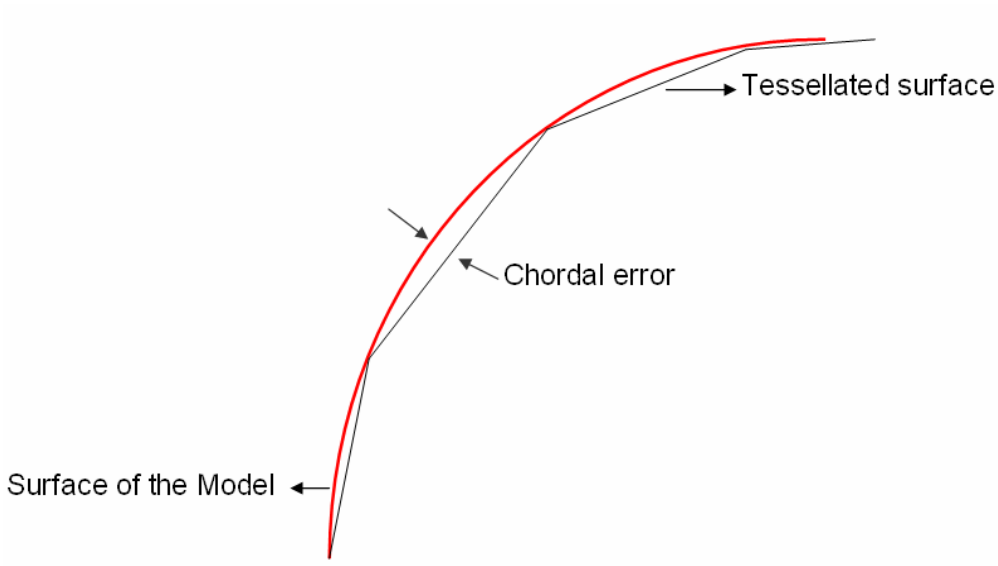


Figure 2. 12: Chordal error caused by the tessellation of the surface

2.3.3 Production of the prototype

After the slicing operation, the software of the RP system generates the path for each slice of layer to be followed by the deposition subsystem of the RP machine. The most commonly used path type is zig-zag path with 45° cut angle (Figure2.13). However, the path type can vary according to the RP system like periphery path or zig-zag path.

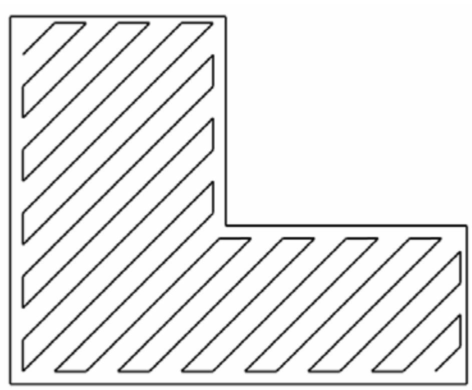


Figure 2. 13: Zig-zag path with 45° cut angle

Layer-by-layer, according to working principle of the RP machine, the production material is deposited, or is cured by a laser or UV light source by following the generated path. After a layer is completed, either the platform on which the deposition has taken place lowered vertically down by an amount of the next horizontal intersection plane, or the deposition head is elevated. Then the second layer is deposited directly on to the previous one. The layers are horizontal and flat. This layered manufacturing process causes a surface problem known as staircase effect [27] which shown in Figure-2.14.

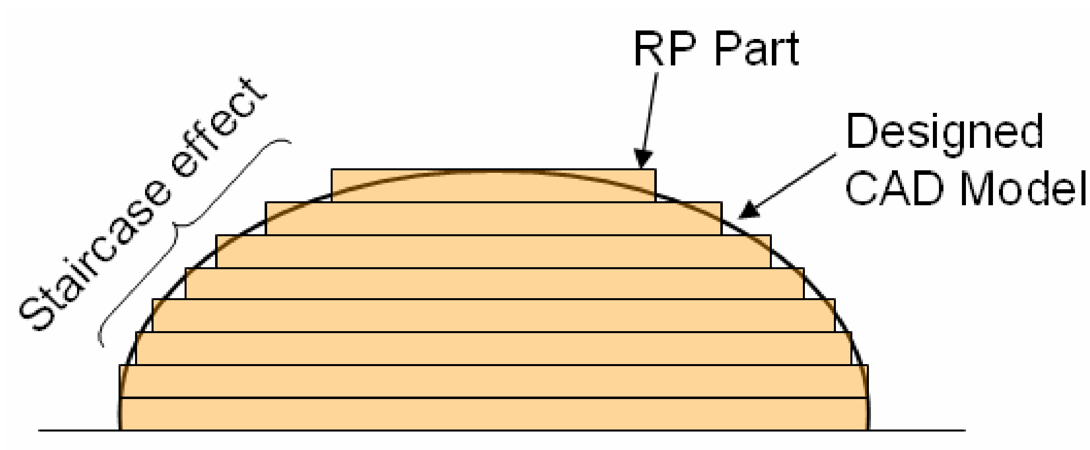


Figure 2. 14: Staircase effect

Staircase effect can not be eliminated on the RP part. However, recently there are some attempts to create curved layers to reduce the stair-step effect of the RP procedure. Chakraborty et al. [37] developed a technique named "Curved Layer Fused Deposition Modeling" (CLFDM). In this technique, the material is deposited in curved layers instead of flat layers (Figure-2.15). This technique does not only eliminate the staircase effect but also improve the surface quality, increase the build speed and reduce the waste.

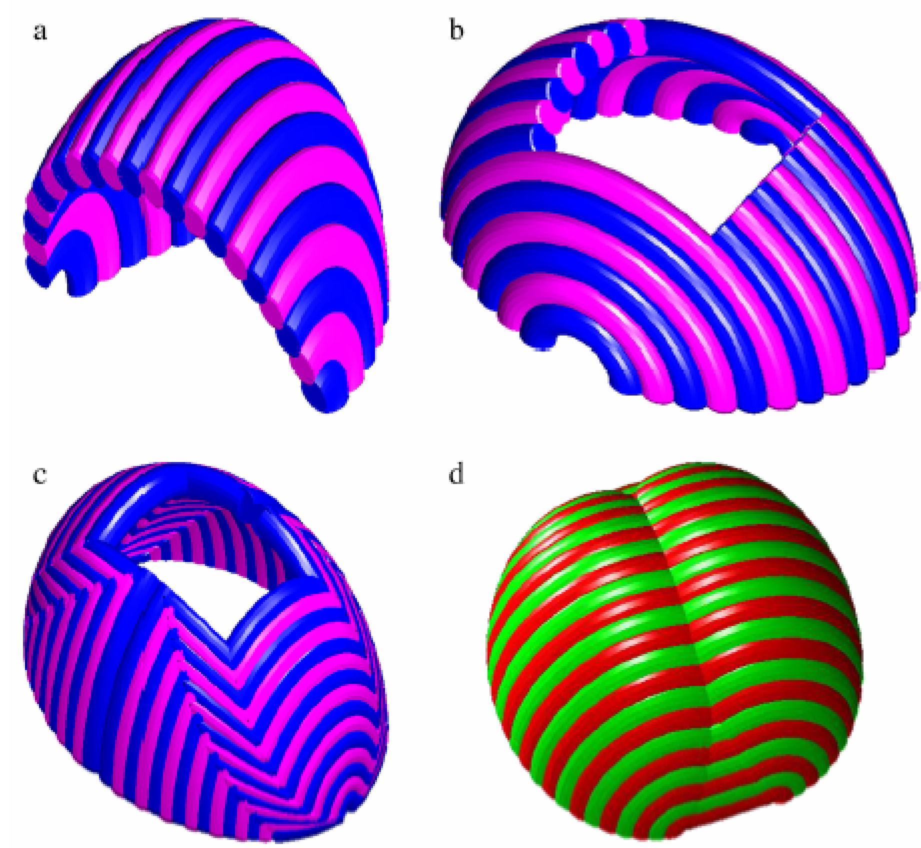


Figure 2. 15: Model development of different complex geometries using CLFDM — (a) A hemispherical surface with a straight trim on one side (b) Trimmed surface of a part in the interior, discontinuous filament deposition method (c) Trimmed surface of a part in the interior, continuous filament deposition method (d) Surface made of two patches, continuous filament method. [37]

2.3.4. Production materials

A wide range of materials, from thermoplastics to metals, are available in RP industry [4, 5]. The production material depends on the RP system used and the end-user chooses the RP system according to aim of the application.

Mainly, there are five material classes in RP industry: photopolymers, thermoplastics, metals, ceramics, and biocompatible materials.

2.3.4.1 Photopolymers

Photopolymers or in other words photosensitive monomer resins are cured by exposing ultraviolet (UV) light -laser. First, the material is in liquid phase and filled in a container. Then, by following a path, UV light is exposed from a source onto the resin and the irradiated areas of photopolymer react chemically and become solid. In this kind of processes, there is no need for support material since the uncured liquid resin supports the product in the container. RP companies have their own formulations for photopolymers. However, most of the time, they are a mixture of acrylic monomers, oligomers (polymer intermediates), and a photo initiator (a compound which undergoes a reaction upon the absorption of light) [11].

2.3.4.2 Thermoplastics

Thermoplastics are one of the most widely used material types in RP industry because of the strength of the produced product. In the systems in which the thermoplastics are used, the used material is in a form of filament. The material is locally heated to a semi-liquid state or just above its melting point (0.5 °C above) and this molten material solidifies about 0.1 seconds after the deposition and cold welds to the previous layer [5]. ABS and polycarbonate are the most preferred thermoplastics in RP industry because of their properties. The produced prototypes are durable enough to be used in end-use.

The support material is needed in the systems where thermoplastics are used if the next slice should be placed in a location where no material exists beneath to support it. The support material is produced with a less dense filament. Therefore it is weaker than the production material and after the production process is completed, the support material can be broken off easily [11]. In Figure-2.16, it is shown that how support material is used in an RP process and how it is detached from the part after the production. In addition, the support material can be a soluble material and the production of part is completed, the part is placed in a liquid tank the support material dissolves.

Figure 2. 16: The use of support material in a Fused Deposition Modeling RP process [38]

2.3.4.3 Metals

Metals are used in RP processes in three ways. In first method, the metals which have low melting points are melted and are spread on to the production surface by using an ink-jet type mechanism and in second method; the metal powder is sintered by using a laser. In third method, an inorganic-binder material is deposited from a print head on a surface of metal powders. However, a post-process may be needed after the third method in an oven.

Common metals used in RP systems are stainless steels (infiltrated with bronze), aluminum, titanium and silicon dioxide.

2.3.4.4 Ceramics

The ceramics have been newly begun to be used in RP systems. The aim is to produce high strength structural ceramics parts. Tsang [39] made a detailed literature survey about the use of ceramics in RP technology and showed in his paper that all commercially available RP methods have been used to produce ceramics parts –Stereolithography (SL), Selective Laser Sintering (SLS), 3D Printing (3DP), Fused Deposition Modeling (FDM) and Laminated Object Manufacturing (LOM). In most of the methods, raw ceramics material can not be used directly in the production process. The ceramics powder is mixed with a binder material and then it is used. For example, Ashley [40] mentioned about a formulation consists of ceramics powder and binder mixture which contains of polymer, elastomer, tackifier and wax. This mixture is used to produce filaments by Materials engineers at Rutgers University Center for Ceramics Research and Allied Signal Inc. (There are two types of processes for filament fabrication; screw extrusion process and piston extrusion process [8]. The same methods are also used for metal filament production). These filaments are used in an FDM machine to produce part. After the completion of the part, it is subjected to binder removal and sintering steps to produce fully dense structural ceramics. SLS can be a good example to explain the purpose of the binding material. In SLS, again the ceramics powder is mixed with a binder and then is subjected to a laser beam which is following a path. Binder is melted locally and when it solidifies the ceramics powder is bind together.

After all methods, a thermal post-processing must be done on the part such as sintering in the furnace.

In research, materials like alumina (Al_2O_3) based ceramic pastes, silicon oxide granules and silicon nitride (SiN) is used to produce ceramic parts.

2.3.4.5 Biocompatible Materials

RP has potential to be used to produce custom implants and patient-specific scaffolds. There are a few materials classified as safe transport into the theatre in medical applications but none are currently capable of being placed inside the body [12]. However, there are many researches about producing artificial organs and tissue scaffolding by using RP machines and different materials have been experimented in these studies. For example, Wang et al. [41] made a study to show the potential of the RP technology to produce bioartificial livers. In the paper they mentioned about biomaterial challenges. The example of hepatocyte cell (liver cell) constructs which were built by RP machines, are presented (Figure-2.17).

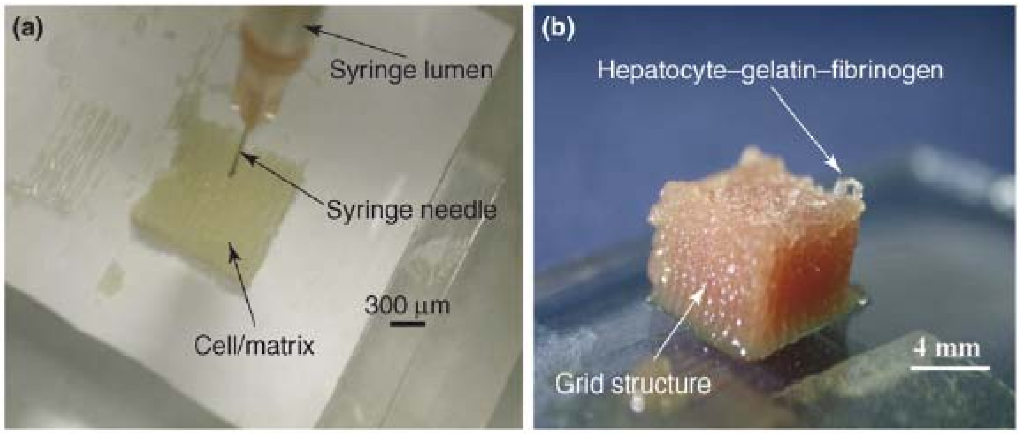


Figure 2. 17: 3D hepatocyte–hydrogel constructs with open channels fabricated by the cell-assembly machine developed at Qinghua University. Photographs of (a) the assembly process of hepatocyte with gelatin–chitosan matrix and (b) a grid-square 3D structure of a hepatocyte–gelatin–fibrinogen. [41]

Yeong et al. [42] investigated the place of RP technology in tissue engineering and compared the available RP methods that are used in tissue engineering. While comparing the methods, the used materials are mentioned in detail. Lopez-Heredia et al. [43] proposed a new method to produce porous titanium coated with calcium phosphate as a scaffold for bone tissue. Both coated and uncoated titanium scaffolds were produced and successfully implanted into dorsal subcutaneous pouches of rats. At the end of 4 weeks, cell spreading on the Ti scaffolds were observed. Zein et al. [44] used bioresorbable polymer poly(e-caprolactone) to produce scaffolds. Cohen et al. [45] were successfully able to print the pre-cell-seeded alginate hydrogels composed of a solution of alginate a calcium cross-linker solution. Moreover, Ang et al. [10] and Geng et al. [46] used chitosan while producing scaffolds. In Figure-2.18, the produced chitosan scaffolds can be seen.

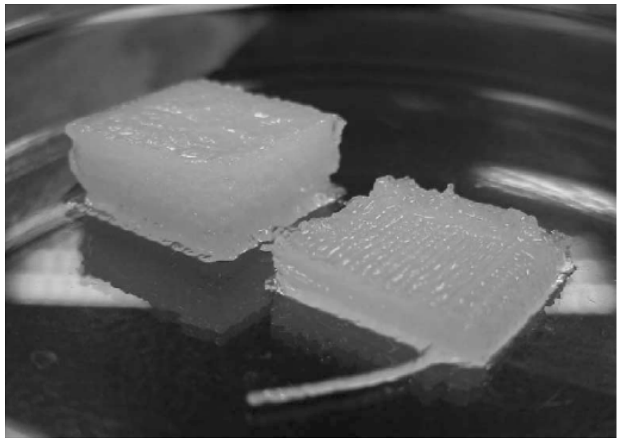


Figure 2. 18: The chitosan scaffolds on the left (21 layers) and right (10 layers) were fabricated with line pitches of 0.8 and 0.9 mm, respectively. [10]

Ang et al. also proved that the printed chitosan–hydroxyapatite scaffolds were biocompatible (Figure-2.19). Foregoing research examples were given to show that RP technology has begun to be used widely in medical researches and lots of different materials have been tested researches. However, none of the produce scaffolds of implants were tested in human body.

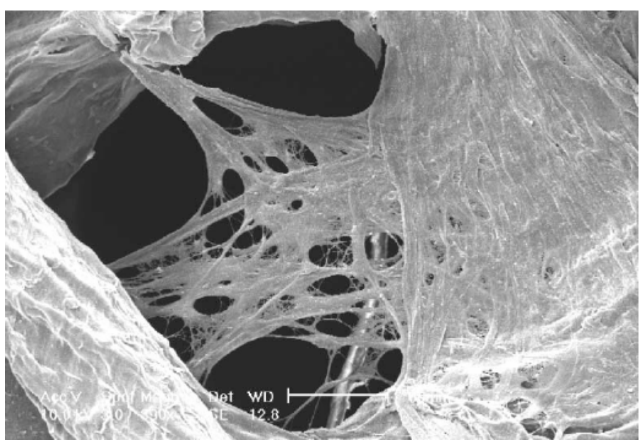


Figure 2. 19: SEM image shows good cell attachment and proliferation in the third week of the in vitro culture. [10]

2.4 History of Rapid Prototyping

3D systems introduced the first commercial RP machine, SLA-1, and shipped it to three customers in 1988 [46]. This date is a mile stone in the history of RP and has been mentioned as the beginning of the RP technology in most of the resources and papers [4, 15, 47-52]. However, the origins of RP technology can be traced back to the last quarter of 19th century. Beaman [46] specified two technical areas as the ancestors of the RP technology: Topography and Photosculpture.

In 1892, Blanther [53] proposed a technique for manufacturing of contour relief maps. This was a layered method for making a mold for topographical relief maps. In this method, wax plates on which topographical contour lines was impressed, was used, and by stowing these plates after cutting them from contour lines, both positive and negative 3D surfaces of a terrain was obtained (Figure-2.20). At last, the printed relief-map was obtained by pressing a printed map of paper into relief between positive and negative forms.

Blanther's method had been improved by B.V. Perera (1940), E.E Zang (1940), T.A. Gaskin (1973), K. Matsubara (1974), P.L. DiMatteo (1976) and T. Nakagawa (1979 & 1985) respectively [46].

Photosculpture was emerged in 19th century as an attempt to create the exact 3D replicas of objects. In 1860, François Willéme successfully performed this technology. His method involved photographing the object simultaneously by using 24 cameras which was placed equally spaced around a circular room (Figure-2.21). Then, by an artisan, 1/24th of a cylindrical portion of the figure was carved out by using each of the silhouettes of 24 photographs [46].

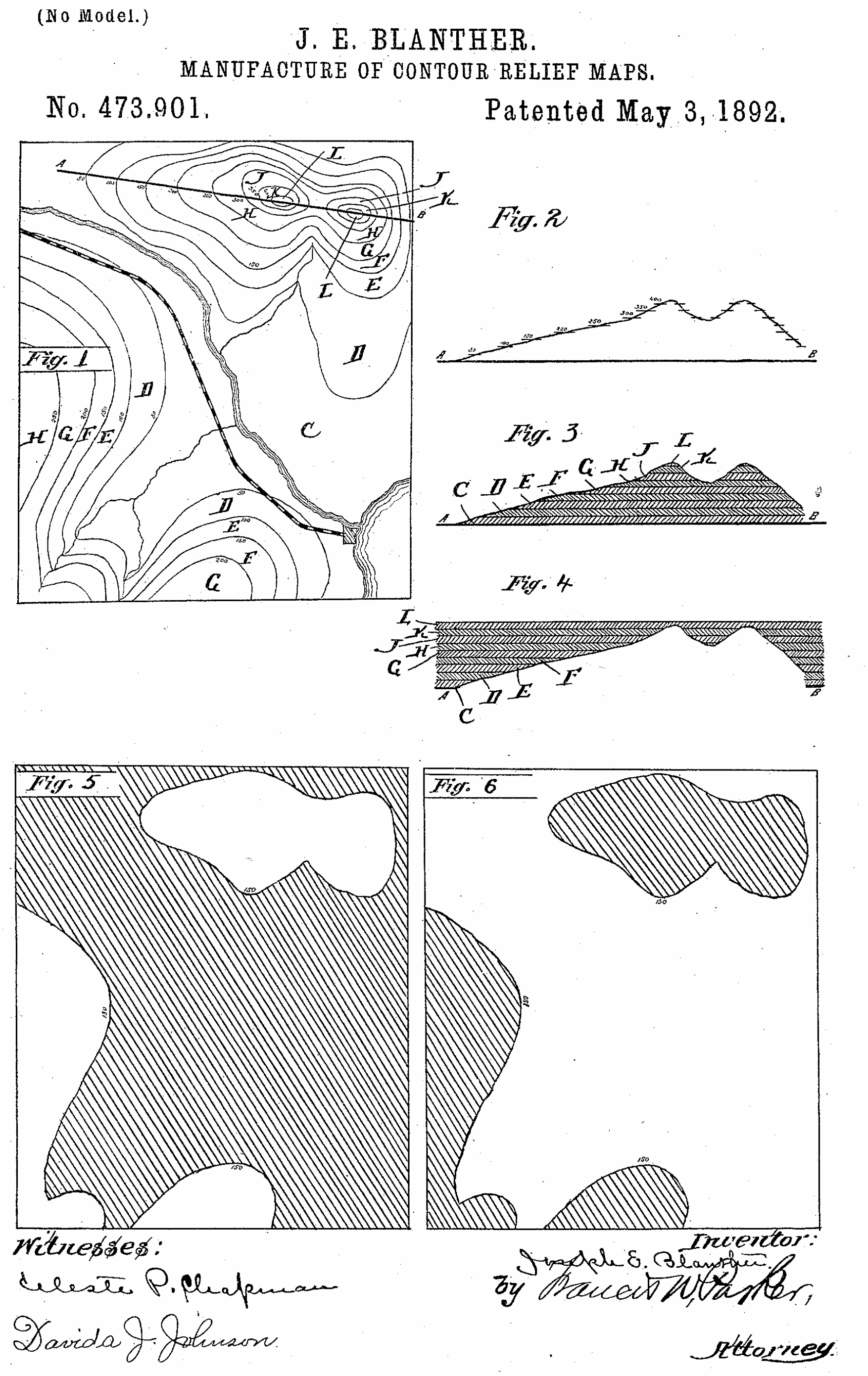


Figure 2. 20: The illustration page from Blanther's patent [53]

Some attempts were made by other developers to improve the photosculpture [46]: C. Baese (1904), F. H. Monteah (1924), I. Morioka (1935 & 1944) and O. J. Munz.

Figure 2. 21: Admiral Farragut sits, late 1860s, for photosculpture [46]

The system proposed by Munz [54] is important because this system has almost the same features with current stereolithography techniques. His proposed system is shown in Figure-2.22. In Munz's method, photo-glyph recording, the scanned object is manufactured layer-by-layer by selectively exposing a transparent photo emulsion. After each layer is completed, the platform (number 10 in Figure-2.22) which carries the manufactured object is lowered by a rack and pinion mechanism (number 6 in Figure-2.22). During this process, a photo emulsion is fed from a photo-chemical supply tank (number 2 in Figure-2.22) into the recording space which is defined by a cylinder (number 3 in Figure-2.22) to keep the liquid at the same level represented by the letter “D” in the figure.

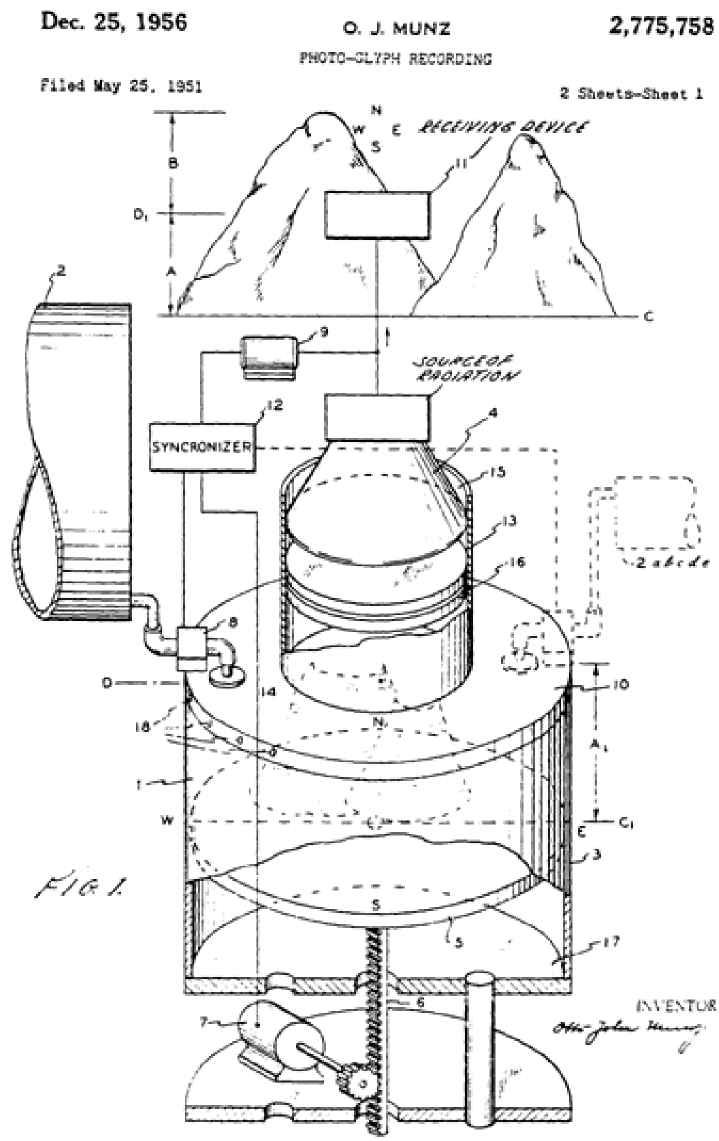


Figure 2. 22: The system proposed by Munz to reproduce a three-dimensional image of an object [54]

Beaman [46] created a chronological map for RP (Figure-2.23) by using the most important inventions and the miles stones in the RP history. In this map, when it comes to 1970s, he combined the roots coming from the origins of RP technology-topography and photosculpture. There are several important methods which were mentioned in the map of Beaman such as W. K. Swainson's method (1968) in which plastic patterns can be produced by selectively polymerizing a photosensitive polymer at the intersection of two laser beams (Figure-2.24). After Swainson, P. A. Ciraud (1972) proposed a method for fabricating objects from powdered materials by heating particles locally and fusing them together employing a laser, electron beam, or plasma. As can be understood easily, Ciraud's method is very similar to SLS method. In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute introduced a photopolymer RP system in which a mask is used to control the exposure of the UV source to produce the layers of the model. At 3M Corporation, A. J. Herbert conducted a parallel study to Kodama's study in 1982. In his system, a UV laser beam was directed to a polymer to cure it. The direction of the laser is controlled by a mirror system on an x-y plotter. After the completion of one layer, the polymer vessel is lower and new liquid photopolymer is added (See Figure-2.25). The stereolithography method which is currently being used is very similar to Herbert's experimental technique. The pictures of the parts produced by using Herbert's and Kodama's methods can be seen in Figure-2.26. It is obvious that these first RP parts are very primitive compared to today's intricate parts.

Besides the foregoing works, there are a numerous patents covering existing commercial RP processes. Beaman [46] listed most prominent patents but since his work was done in 1997, this list did not cover the new patents. Because of this reason a patent research is done in the context of this study. The updated list is given in Table-2.1.

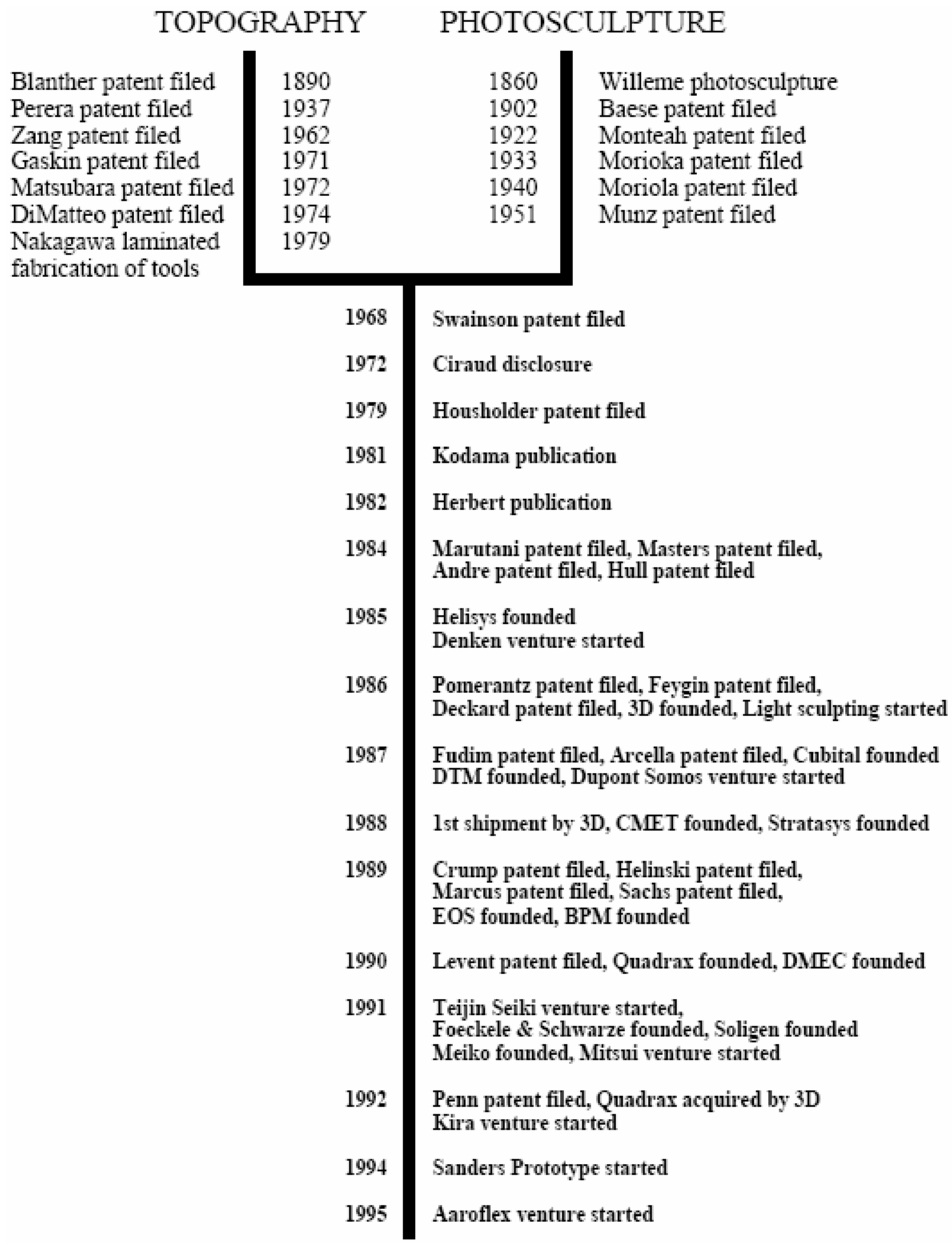


Figure 2. 23: Chronology of RP based on some of the major time events [46]

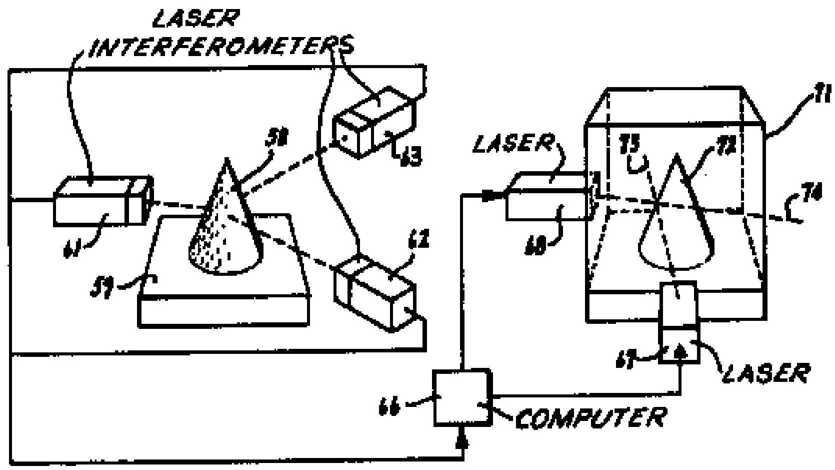


Figure 2. 24: Swainson's photosculpture process using intersecting laser beams [46]

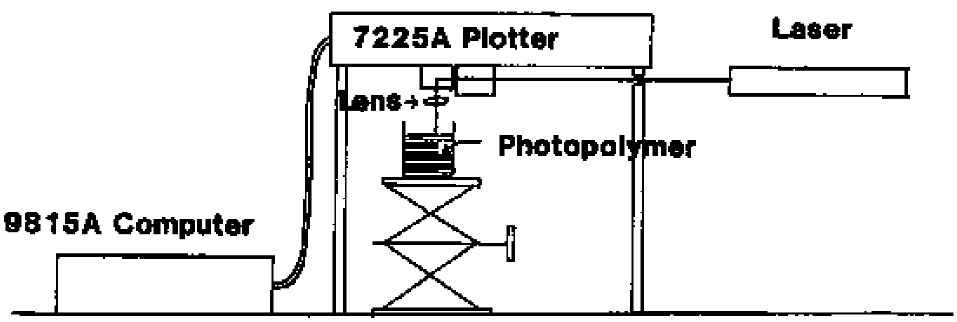


Figure 2. 25: Herbert's photopolymer process [46]

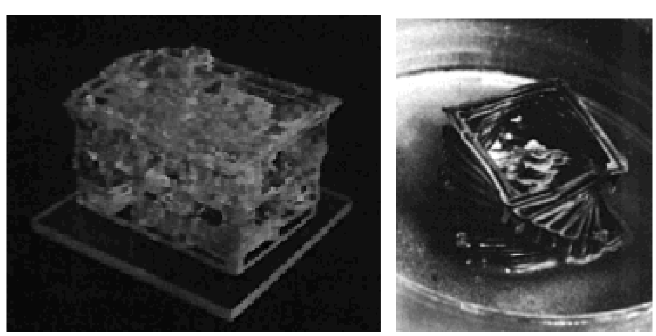


Figure 2. 26: Early RP parts; from left to right by Kodama and Herbert [46]

Table 2. 1: Active Rapid Prototyping Patents

Inventor Name	Title	Filed	Country
Housholder	Molding process	Dec-79	U.S.
Murutani	Optical molding method	May-84	Japan
Masters	Computer automated manufacturing process and system	Jul-84	U.S.
André et al.	Apparatus for making a model of an industrial part	Jul-84	France
Hull	Apparatus for making three-dimensional objects by stereolithography	Aug-84	U.S.
Pomerantz et al.	Three-dimensional mapping and modeling apparatus	Jun-86	Israel
Feygin	Apparatus and method for forming an integral object from laminations	Jun-86	U.S.
Deckard	Method and apparatus for producing parts by selective sintering	Oct-86	U.S.
Fudim	Method and apparatus for producing three-dimensional objects by photo solidification; radiating an uncured photopolymer	Feb-87	U.S.
Arcella et al.	Casting shapes	Mar-87	U.S.
Crump	Apparatus and method for creating three-dimensional objects	Oct-89	U.S.
Helinski	Method and means for constructing three-dimensional articles by particle deposition	Nov-89	U.S.
Marcus	Gas phase selective beam deposition: three-dimensional, computer-controlled	Dec-89	U.S.
Sachs et al.	Three-dimensional printing	Dec-89	U.S.
Levent et al.	Method and apparatus for fabricating three-dimensional articles by thermal spray deposition	Dec-90	U.S.
Penn	System, method, and process for making three-dimensional objects	Jun-92	U.S.
Bredt et al. [55]	Method of three dimensional printing	Sep-96	U.S.
Russell et al. [56]	Method and apparatus for prototyping a three-dimensional object	Dec-96	U.S
Graf et al. [57]	Apparatus and method for producing a three-dimensional object and for applying a layer of a powder material to a surface	Mar-98	Germany
Henningsen [58]	Rapid prototyping apparatus and method of rapid prototyping	Oct-98	Denmark
Manners et al. [59]	Stereolithographic method and apparatus for production of three dimensional objects using multiple beams of	Feb-99	U.S.

	different diameters		
Ederer et al. [60]	Rapid-prototyping method and apparatus	Oct-99	Germany
Pfeifer et al. [61]	Process and device for producing solid bodies by sequential layer buildup	Feb-03	Germany
Jandeska, Jr. et al. [62]	Aluminum/magnesium 3D-Printing rapid prototyping	Aug-04	U.S.
Huang et al. [63]	Method for rapid prototyping by using plane light as sources	Oct-04	Taiwan

Further to this list there are hundreds of patents covering existing commercial RP processes. In 1990s, with the advances in 3D CAD modeling, CAM and CNC, development in RP technology added momentum. The same rapid growth has not continued after 2000s however, the demand for RP systems is increasing every year consistently. According to Wohlers Report 2005 [64], estimated sales of 3D printers by the leading manufacturers jumped from $37.4 million in 2003 to $74.6 million in 2004, an increase of 99.5 percent. Product development organizations are not only acquiring the technology at a faster clip, but are also putting it to greater use. The number of models and prototype parts produced last year grew to an estimated 6.05 million, up from 4.83 million in 2003. That is, RP market is getting bigger.

Beaman's [46] commercial development tables containing the RP companies and the systems provided by them, and Wohlers reports [65,66] show that the U.S. is leading the RP market and U.S. companies providing a diverse range of RP technologies where as in Japan and Europe most of the companies are providing SL based systems. No machines from Asia are available for sale in the U.S. at the present time [66]. In the context of this study, Beaman's tables were updated based on the Wohlers's reports and updated version of the table can be seen in Table-2.2.

Table 2. 2: Development of RP systems

Company	**Process**	**Venture Start**	**Shipment**	**Notes**
Speed Mark	SLS	2006,Sweden	2006	Now Sintermask
Voxeljet Technology GmbH	3D Printing	2005,Germany	2005	
Solidimension	LOM	2001, Israel	2004	
Aspect Inc.	SLS	Japan	2006	
Chubunippon	SL	Japan	2003	
EOS	SLS	U.S.	2003	
Menix Co. Ltd	LOM	Korea	2002	
EnvisionTEC GmbH	Bioplotter	U.S	2002	
POM	Direct Metal Deposition	U.S.	2002	Operates as a service bureau
Genesis GmbH	Ink jet	Germany	2001	
Object Geometries	3D Printer	Israel	2000	
ProMetal	3D Printer	U.S.	1999	
Z Corp	3D Printer	U.S.	1996	
Ushio	SL	Japan	1995	Now called Unirapid Inc.
Sprax	LOM	Sweden	1994	Foam machine
Aaroflex	Stereolithography	1995 U.S.	n/a	License from DuPont (Closed in 2001)
Sanders Prototyping (now Solidscape)	Ink jet	1994,U.S.	1994	Partially developed at E-systems
Kira	LOM	1992,Japan	1994	Japan's first non-lithography system
Soligen	3D Printing	1991,U.S.	1993	Ceased operations in Jan-2006
Meiko	SL	1991,Japan	1994	Ended its SL business in 2006
Fockele&Schwarze	SL	1991,Germany	1994	Service bureau since 1992
Teijin Seiki	SL	1991,Japan	1992	License from DuPont
Mitsui	SL	1991,Japan	1991	
Quadrax	SL	1990,U.S,	1990	Technology acquired by 3D in 1992
Dmec	SL	1990,Japan	1990	Now a part of Teijin Seiki
BPM	Ink Jet	1989 U.S.	1995	Ceased operations in 1997

EOS	SL, SLS	1989,Germany	1990	
Stratasys	FDM	1988,U.S.	1991	
CMET	SL	1988,Japan	1990	
DTM	SLS	1987,U.S.	1992	Operated a service bureau from 1990-93
DuPont Somos	SL	1987,U.S.	n/a	Licensed to Teijin Seiki 1991, Aaroflex 1995
Cubital	Photomasking	1987,Israel	1991	
Light Sculpting	Photomasking	1986,U.S.	n/a	Operates as a service bureau
3D Systems	SL	1986,U.S.	1988	First commercial shipment of equipment
Helisys	LOM	1985,U.S.	1991	Fonded as Hydronetics (closed in 2000)
Denken	SL	1985,Japan	1993	Introduced first to fit on a bench top machine

2.5 Rapid Prototyping Methods

In the short history of RP technology, lots of different methods have been invented by the companies and the universities [4, 5, 15, 17, 47, 65, 66]. Some of them were disappeared in a few years because of drawback of the methods, some of them could not be popular, just a few of them could be commercialized successfully and today widely used and dominant in the market. There are many different ways of classifying RP systems. One of the best classifications was done by Chua et al. [4]. They prepared a wheel in which RP is classified based on the four primary development areas: Method, input, material, applications (Figure-2.27). However, in this section, just the most popular methods whose successes have been accepted by everyone are explained. These are: Fused deposition modeling, Stereolithography, Selective laser Sintering, Ballistic Particle Manufacturing, 3-dimensional printing, Laminated object manufacturing and Rapid prototyping robotic dispensing system.

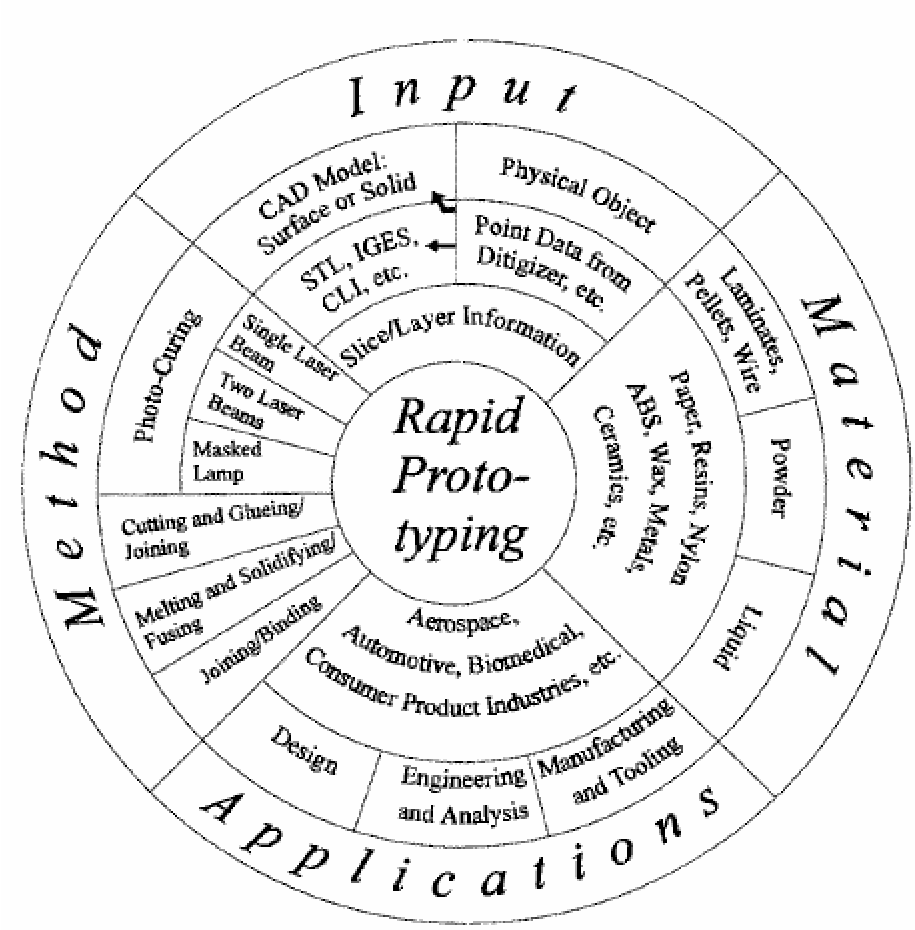


Figure 2. 27: Rapid Prototyping wheel depicting the four major aspects of RP. [4]

2.5.1 Fused Deposition Modeling [FDM]

The FDM process was developed by Scott Crump in 1989. In FDM, a thermoplastic or wax filament is extruded through a small orifice of a heated die while the deposition head is moving on a platform by following a predetermined path (Figure-2.28). The filament is heated locally just above its melting point (~+0.5 C°) at the tip of the extruder and when the extruded material contacts with the ground or the previously deposited layer, it immediately solidifies. After the completion of a layer, either the platform is lowered or the deposition head is raised as the amount of the next layer's thickness. The layer thicknesses of the FDM systems are constant and depend on the extruder-die diameter.

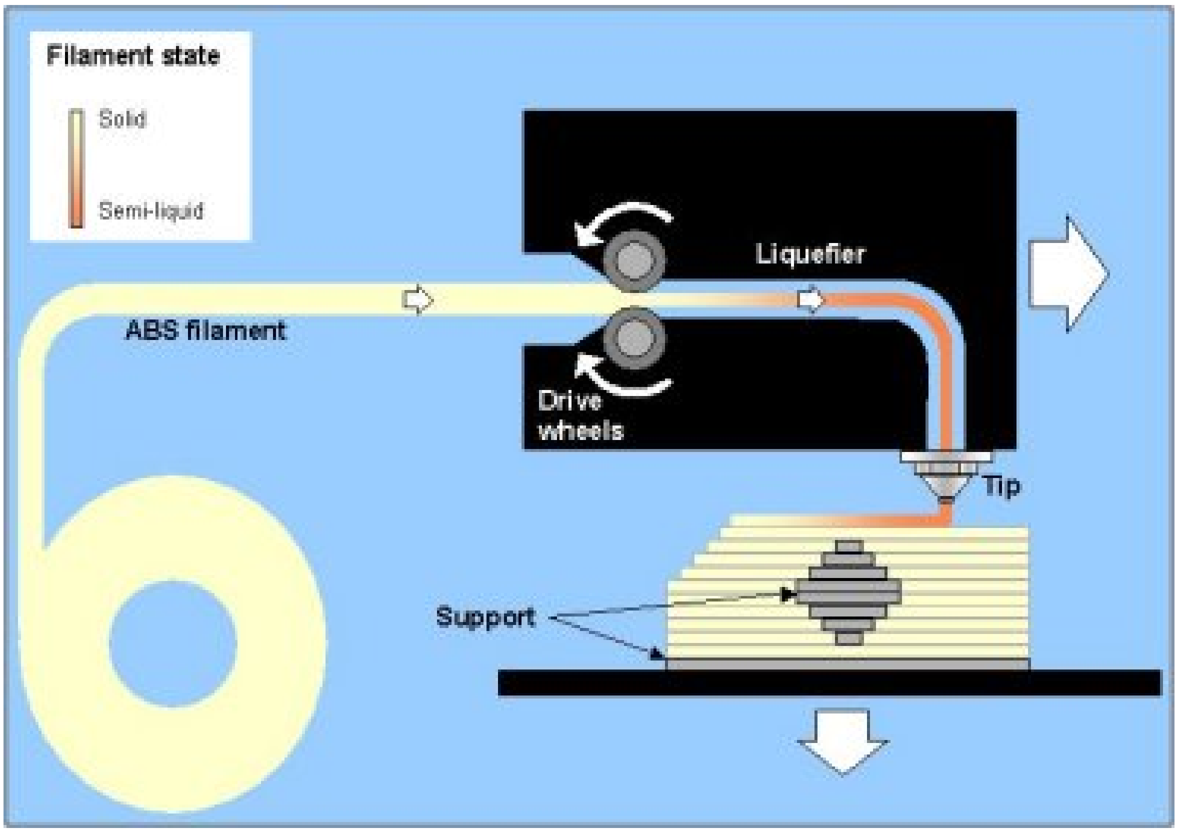


Figure 2. 28: Working principle of the FDM
[http://www.cs.cmu.edu/~rapidproto/students.03/rarevalo/project2/Process.html]

The production material is usually in filament form but some setups utilize plastic pellets fed from a hopper instead as shown in Figure-2.29. The pellets are smashed and melted with the help of a screw mechanism [6, 67].

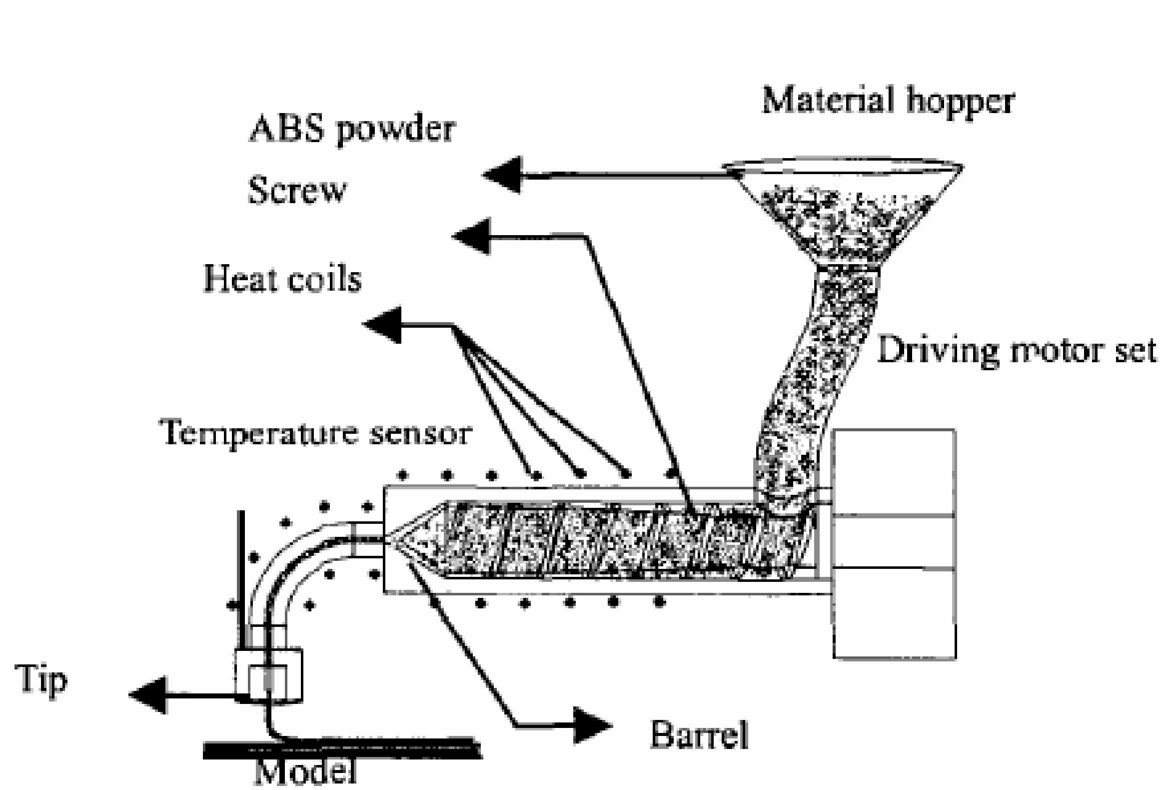


Figure 2. 29: An FDM mechanism which utilizes pellets instead of filament [67]

A second material is needed in the production in some cases, such as shown in Figure-2.30a. This kind of parts is difficult to part, because there is nothing to support the next slice when the level A is reached. In this situation, the second material called support material is used as shown in Figure-2.30b and Figure-2.16. The support material is weaker than the production material and after the production of part is completed the support material is removed from the prototype. There are two kinds of support materials. First type is removed from the part by applying some force and consequently breaking it. The second type is soluble. Therefore, the part is placed in a liquid suggested by the RP company and support material dissolves.

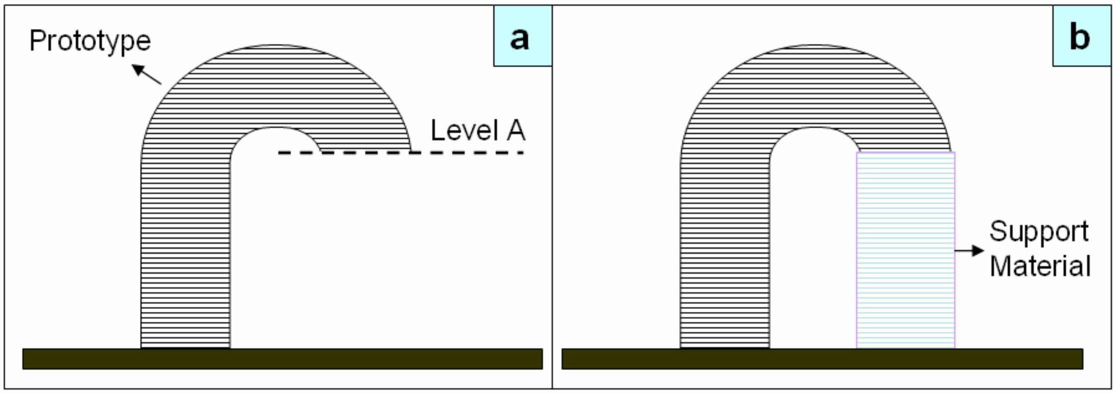


Figure 2. 30: a) A part with a protruding section which requires support material; b) Part with support structure

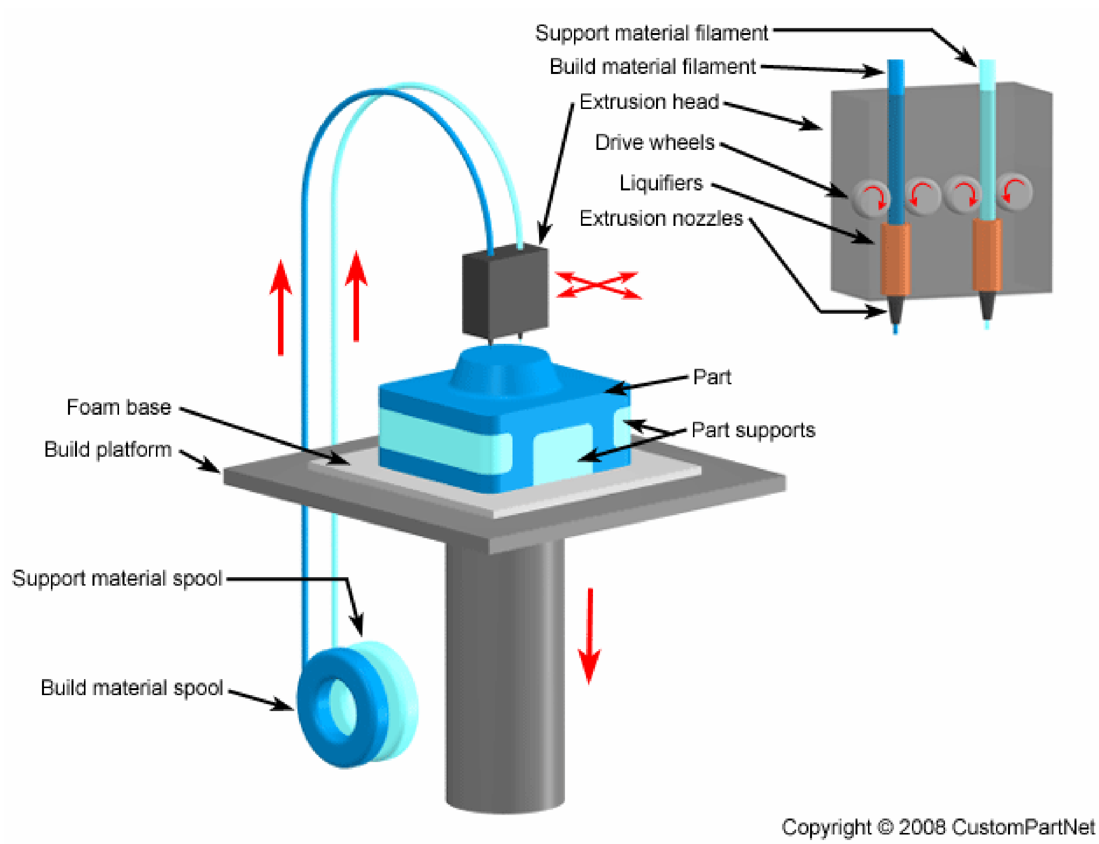


Figure 2. 31: FDM machines have a second extrusion head for support material

The support material is extruded from a second extruder head in the same manner with the build material as shown in Figure-2.31. For each layer, the slicing program of the RP system creates two different paths; one for build material and the other one for support material.

2.5.2 Stereolithography [SL]

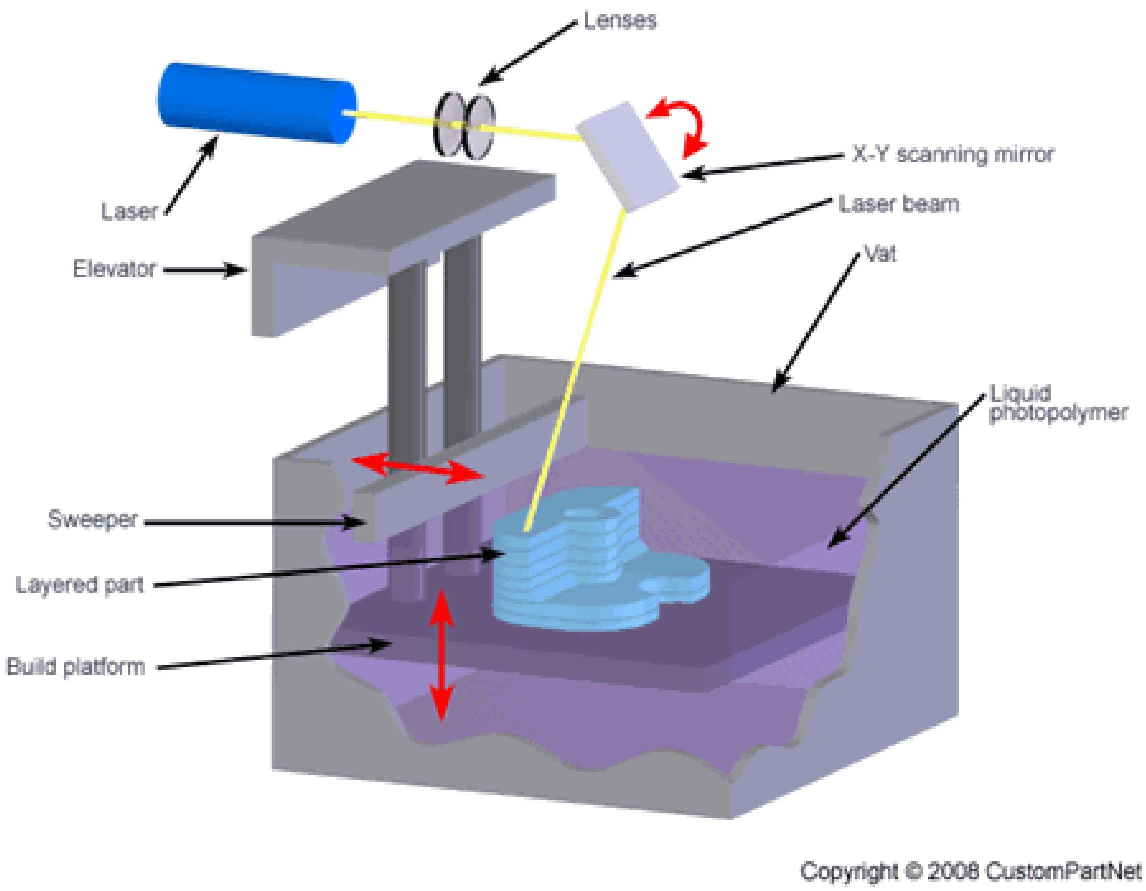


Figure 2. 32: A typical SL system

Stereolithography is one of the most commonly used RP methods and was invented by Charles Hull in 1984. In some resources, acronym of the Stereolithography is used as SLA. However, SLA stands for Stereolithography Apparatus which is the name of the 3D

Systems Inc.'s RP machine. Therefore, it is more proper to use SL instead of SLA. SLA-1 is the first commercially available machine in the world. Stereolithography file format (STL) is created to be used in the 3D Systems Inc.'s first SL system and now accepted as a file conversion standard in RP industry.

In SL, a liquid photopolymer contained in a vat is cured (solidified) by using an ultraviolet light source. A laser is used to generate the UV light. When exposed to UV light, a chemical reaction occurs on the surface of the photopolymer and the exposed area is solidifies producing parabolically cylindrical voxels [5]. A voxel is a three dimensional equivalent of a pixel and can be defined as the minimum volume that an RP system can fabricate. Diagram of photopolymerisation is given in Figure-2.33. After a layer is completed, the vat is lowered and more liquid polymer is filled in to the vat to cover the cured polymer with another layer of resin. Because of the high resin viscosity, a blade is used as a sweeper after the new resin is added in to the vat (Figure-2.34). The unused portion of the resin can be used in another process. Nevermore, the photopolymer must be shielded to avoid the premature polymerization. The system is shown in Figure-2.32.

As in FDM process, SL system can utilize weaker support sections and after the completion of the part, the support sections are removed. The completed part is post-cured in a post-processing oven to ensure that no liquid or partially cured resin remains. To produce parts with micrometer-sized features, optics are used, such as the lenses shown in Figure-2.31, and with the help of these optics highly focused laser beams are able to be obtained.

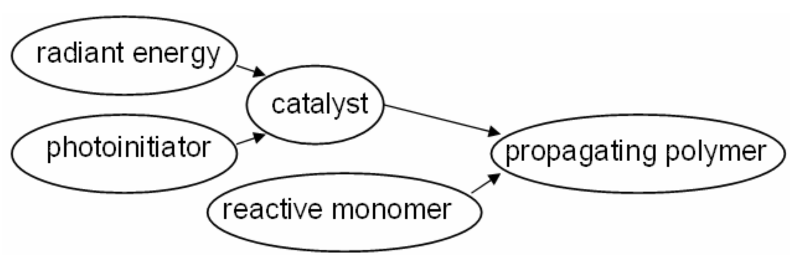


Figure 2. 33: Schematic diagram of photopolymerisation [4]

The steps of a typical SL process to create a single layer are shown in Figure-2.34.

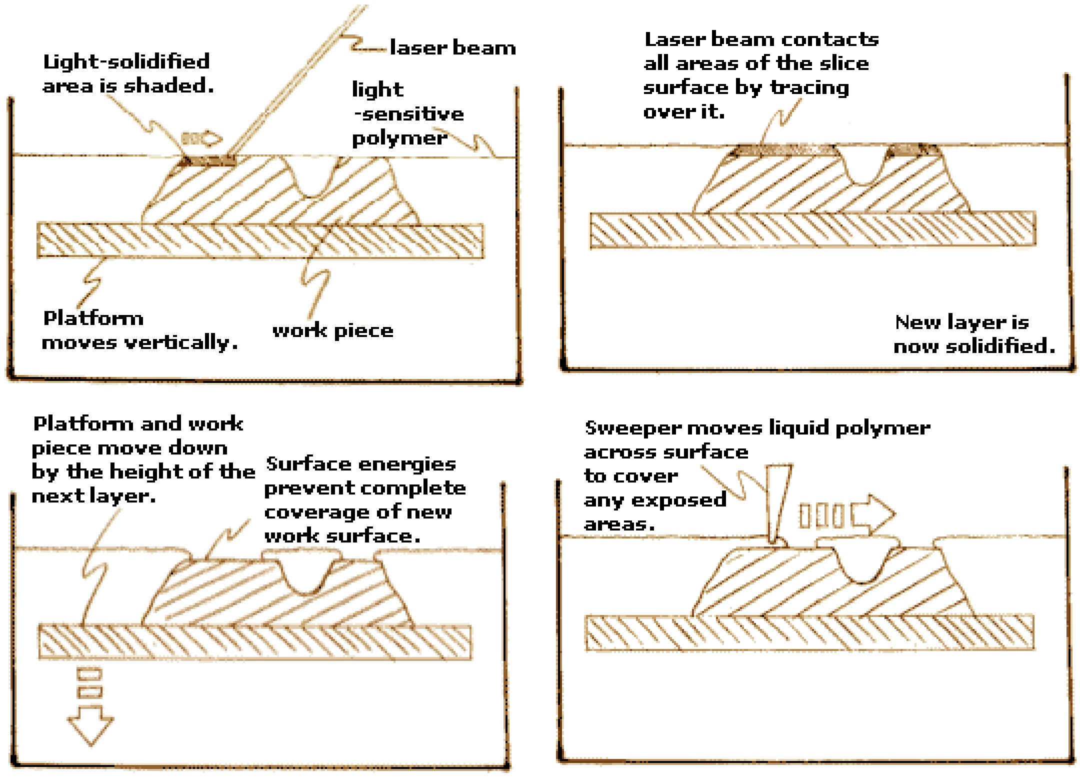


Figure 2. 34: Steps of an SL process to create single layer

2.5.3 Selective Laser Sintering [SLS]

Selected laser sintering was patented in 1989 by Carl Deckard from University of Texas at Austin. The main idea of SLS is very similar to SL technology. As the name of SLS implies, it is based on fusing or sintering (weld without melting) fine powder selectively to form an object. A CO_2 laser of power in the range 25-50 W is used [5]. The laser beam traces a predetermined path. The grains which are in direct contact with the laser beam are affected and surface tension of particles is overcome. Consequently, they fused each other. The system is shown in Figure-2.35. Before powder is sintered, the entire bed is heated just below the melting point of the used material.

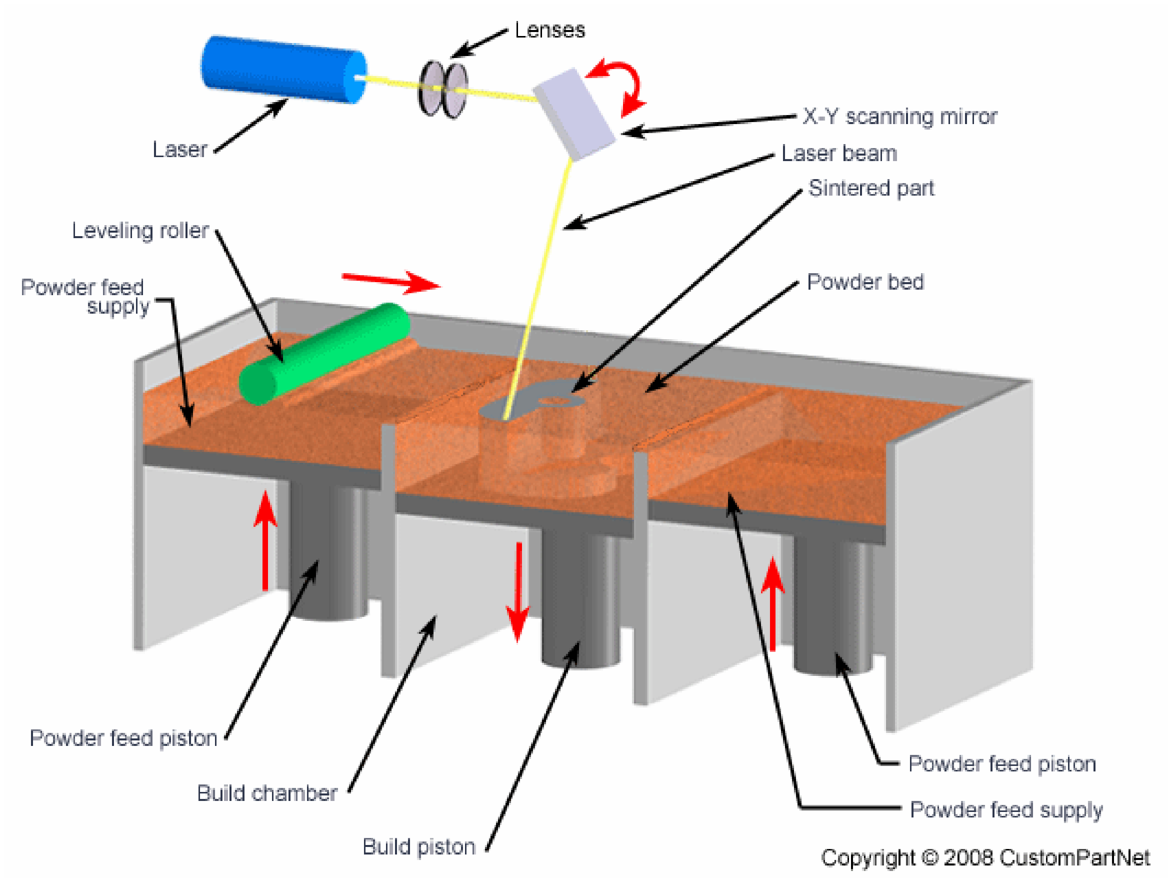


Figure 2. 35: A typical SLS system

Unlike the SL process, special support structures are not needed because unused powder in each layer acts like a support material. After the completion of each layer, powder feed cylinder is raised and the cylinder containing the part (build chamber) is lowered. Then supply powder is transferred to the build chamber by a roller mechanism (Figure-2.35). The steps are repeated until the part is completed. The completed part does not require further curing. Just ceramics parts have to be fired to develop strength [11].

Polymers such as ABS, polyvinyl chloride (PVC), nylon, polyester, polycarbonate, polystyrene and epoxy, and wax, metals and ceramics are the available materials [11, 15] which can be used in SLS systems. However, metals and ceramics require special polymer binders which are blended with the ceramics or metals powders. In the system, this binder is sintered.

2.5.4 Ballistic Particle Manufacturing [BPM]

BPM is also known as ink-jet printing. Using ink-jet type mechanisms, molten material is ejected through a small nozzle which is excited by a piezoelectric transducer. When the droplets of molten material reach the surface they immediately cold weld (Figure-2.36). This technique is inspired from 2D printers which spread tiny drops of ink onto the paper. However, instead of ink, in these systems thermoplastics, metals or wax are used which are held in melted state.

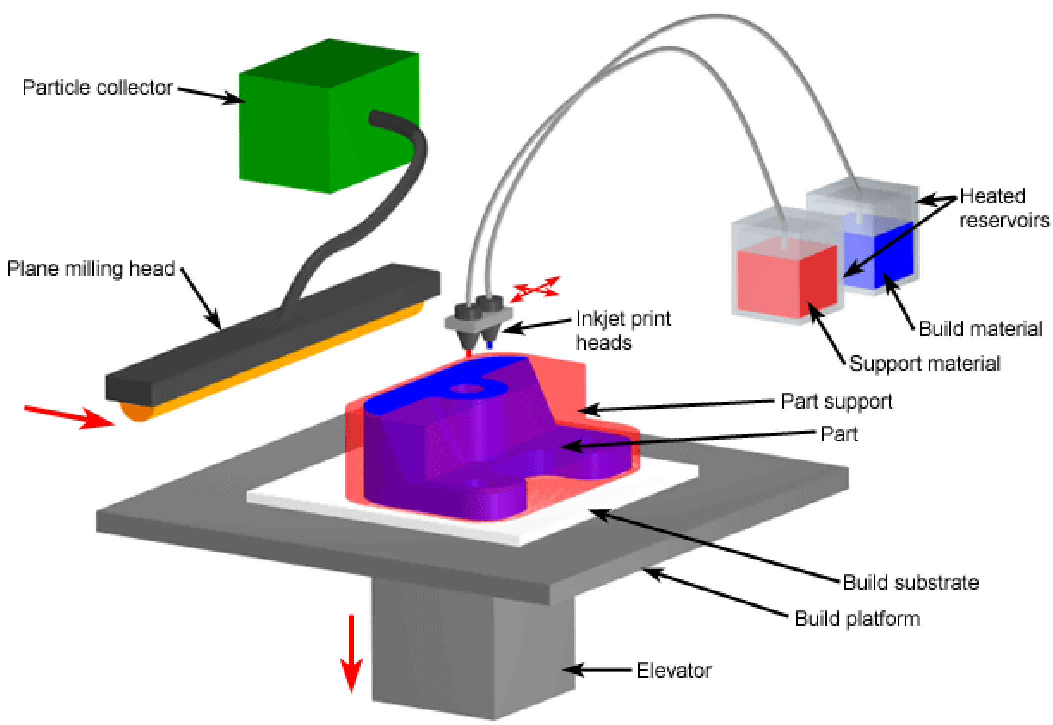


Figure 2. 36: A BPM system

After each deposited layer, a plane milling mechanism is used to smooth the surface as shown in Figure-2.36. In some cases, support material is needed to be used and when thermoplastics are used as production material, usually wax is chosen as support material.

Because of the exceptional accuracy, the BPM systems are widely preferred in jewelry industry.

2.5.5 3D-Printing [3DP]

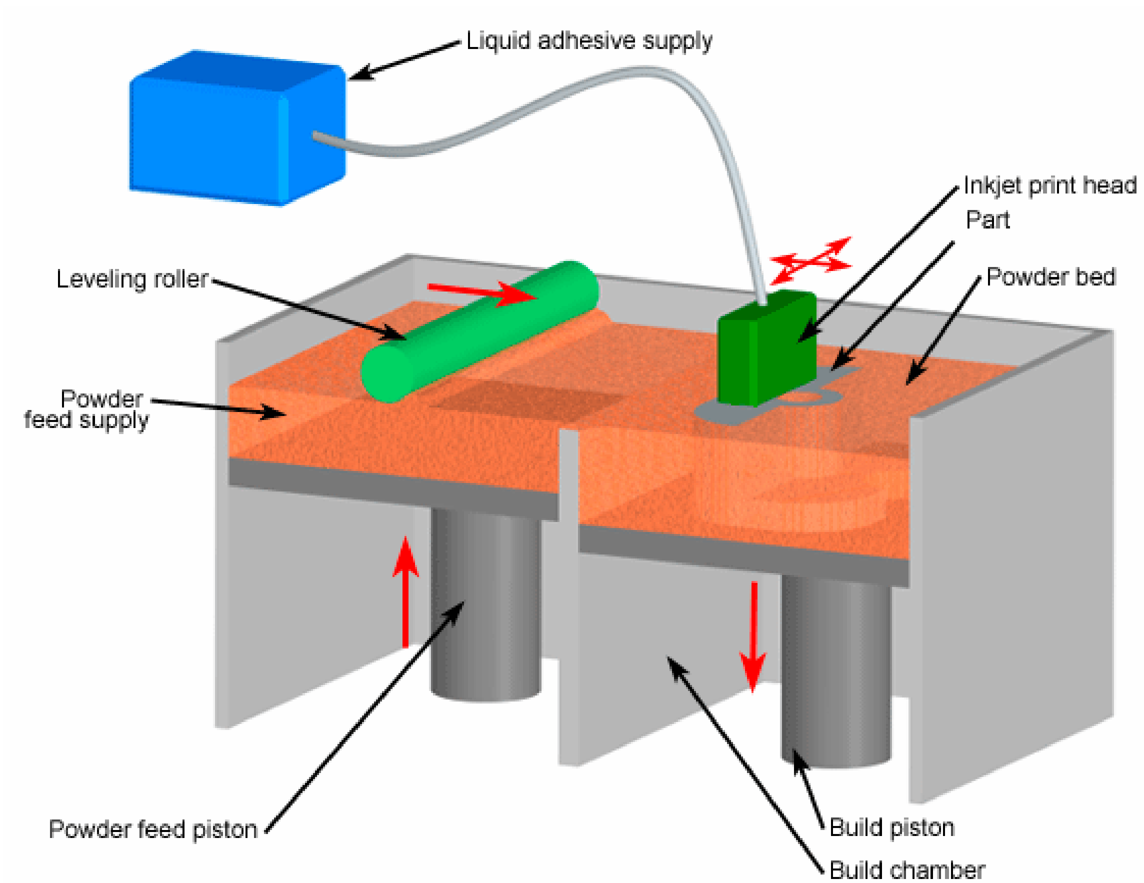


Figure 2. 37: A 3D-P system

In some of the textbooks and resources, the term “three-dimensional printing” is used for all RP techniques [38] and it is believed that in the future, instead of the terms like “rapid prototyping” or “solid freeform fabrication”, the term 3D Printer will be used to describe the systems that fabricate parts additively [68]. However, in this text, three dimensional printing is referred to an inkjet-based system like BPM. The 3DP technology was developed by Massachusetts Institute of Technology (MIT).

A binder solution is printed onto a layer of powder. It can be said that this technology is a combination of SLS and BPM. As in the SLS technology, there is a cylinder (powder bed) contains production powder and whenever a layer is completed a roller mechanism feed powder into the powder bed from a powder supply tank. Moreover, as in the BPM technology, an inkjet mechanism is used to deposit a binder solution (mostly a polymer) onto the surface. Working principles of a 3D-P system are shown in Figure-2.37.

Figure 2. 38: 3D Printers let colored parts to be produced

Commonly used materials as production powder are ceramics and metals, in more specific; aluminum oxide, silicon carbide, silica, zirconia, stainless steel, titanium, and silicon oxide powders [11]. Also some systems utilize starch and plasters as powder. Since ordinary inject mechanisms are used in 3D-P system, by adding color into the binder solution, the parts can be produced in desired colors [38] (Figure-2.38).

However, there is a disadvantage of 3D-P systems. The produced parts have porous structures. Therefore, they are lack of strength and a post-process such as sintering or infiltration of a second material might be needed. For metallic parts, a low-melting-point metal such as copper and bronze is infiltrated into the part.

2.5.6 Laminated Object Manufacturing [LOM]

The sheets of paper or plastics are used in LOM to manufacture the desired part. One side of the sheets is coated with heat-activated glue, such as polyethylene coating. A heated roller is passed on a sheet and this process causes the glue to be melted and consequently the upper and lower sheets are adhered to each other. A laser cuts out the cross section of the desired part which corresponds to the current slice. Then laser create hatches (cubes) at the non-part areas of the current layer to make it easy to detach the part from the excessive material after completion of the whole process.

After each cut is completed, the platform carrying the part is lowered by a depth equal to the thickness of the sheet. Then the new layer of sheet is unwound from the feed roll and the previous steps are repeated (Figure-2.39). The accuracy of LOM is not as high as SLS or SL methods. However, material costs are very low and very big parts can be produced with this method compared to other RP methods. LOM is not as prevalent as other methods. This can be due to the labor intensive-work to “de-cube” the trapped part after the process is completed (See Figure-2.40)

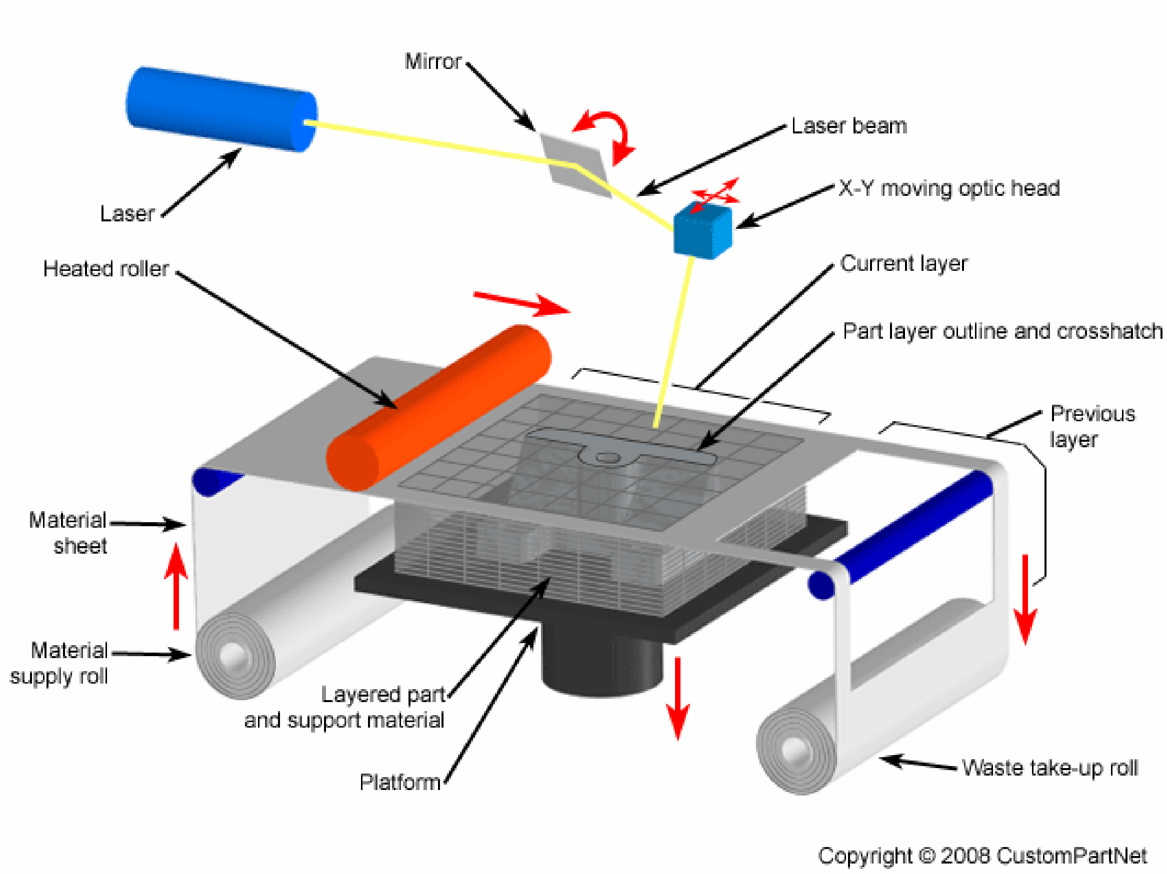


Figure 2. 39: LOM process
[http://www.custompartnet.com/wu/images/rapid-prototyping/lom.png]

Figure 2. 40: The waste material is detached from the part by the help of the hatched areas
[http://home.att.net/~castleisland/faq/faq220.htm]

Another disadvantage of this method is that it is very hard to produce hollow parts due to the difficulty in removing the waste material in the core.

Recently, metal parts can be produced by using metal sheets which were produced by bounding powder metal with adhesives. But heat treatment should be applied to the produced part of the LOM process.

2.5.7 Rapid Prototyping Robotic Dispensing [RPBOD]

The RPBOD is a very new technique and in fact it is not a commercialized RP method yet. A resembling system was built and used in this thesis study and that is why the RPBOD method is explained in this section. The RPBOD system was developed by Ang et al. [10] and was used and mentioned in several researches [42, 69, 70]. This system was developed to produce scaffolds and consist of a dispensing system and a robotic system which can move in X-, Y- and Z- directions and additionally it can rotate about Z-axis (Figure-2.41).

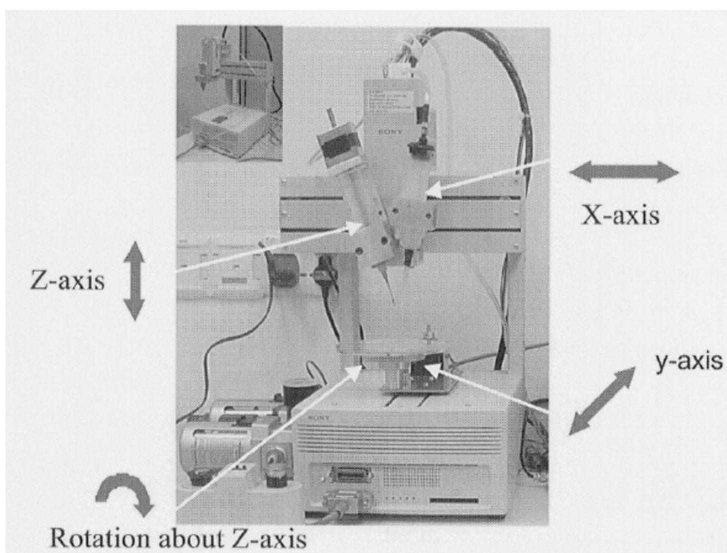


Figure 2. 41: The RPBOD system [69]

The dispensing system contains a pneumatically driven and a mechanically driven syringe dispenser which are shown in Figure-2.42.

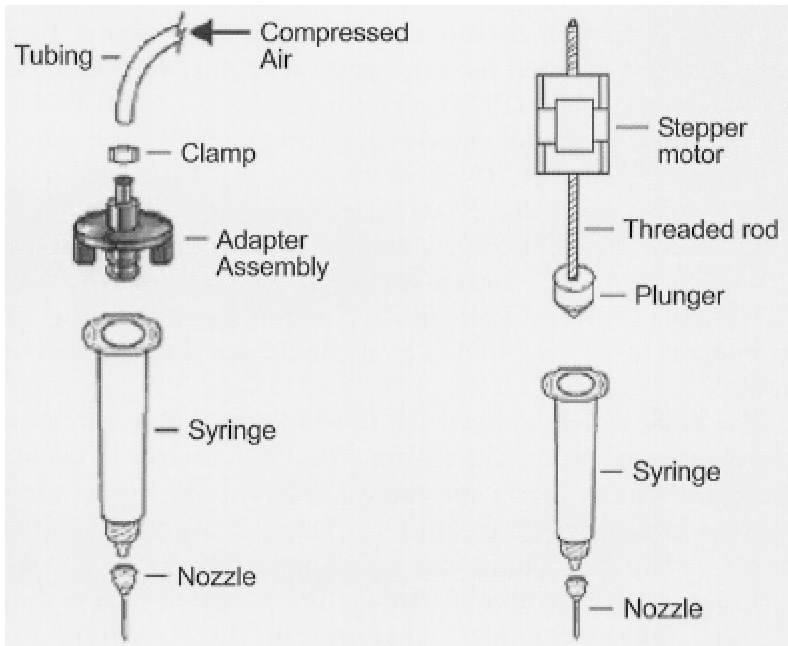


Figure 2. 42: Graphical illustration shows the pneumatic (left), and mechanical dispenser (right) assemblies [69]

The mechanical dispensing system built and used in the open architecture rapid prototyping system which has been developed in this study is similar to the one shown in Figure-2.42.

The same deposition (dispensing) system (see Figure-2.43) is also used in Fab@Home system which is an open source RP system [9, 14, 71, 72]. The project is coordinated by Even Malone from Computational Synthesis Laboratory at Cornell University. As mentioned before, this kind of dispensing system is new in RP history but the usable material range for this deposition system is very wide. Also, the use of syringe makes this deposition system very suitable for biological applications such as scaffold building by using living cells. For example, Cohen et al. [73] used Fab@Home system to fabricate cell-seeded implants. An alginate hydrogel containing living cells was deposited by using the syringe tool shown in Figure-2.43 and sample living implants was printed.

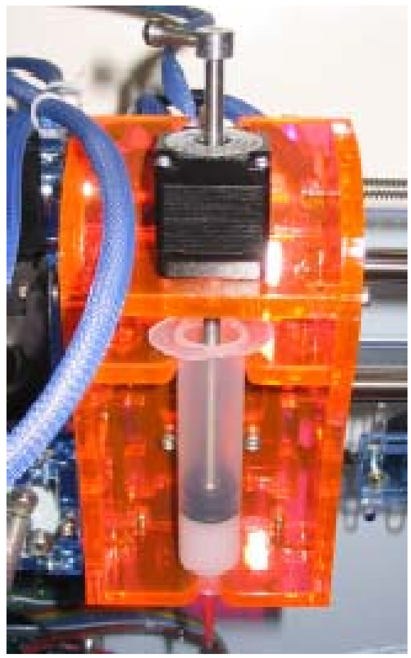


Figure 2. 43: Single syringe tool driven by a linear stepper motor [9]

2.6 Advantages and Applications of RP Technology

Primary advantages or RP technology are obvious. It shortens the production time, prevents dimensional errors in manufacturing, decreases manufacturing costs and allows producing very complex parts which can not be produced with conventional methods. Also, since the process is very simple, there is no need for a detailed process planning and trained personal. There are different ways of classifying the applications of RP technology. For example, Kochan et al. classified the applications of RP under four major titles, as shown in Figure-2.44: industry, architecture, recuperation, and other applications such as jewelry and archaeology.

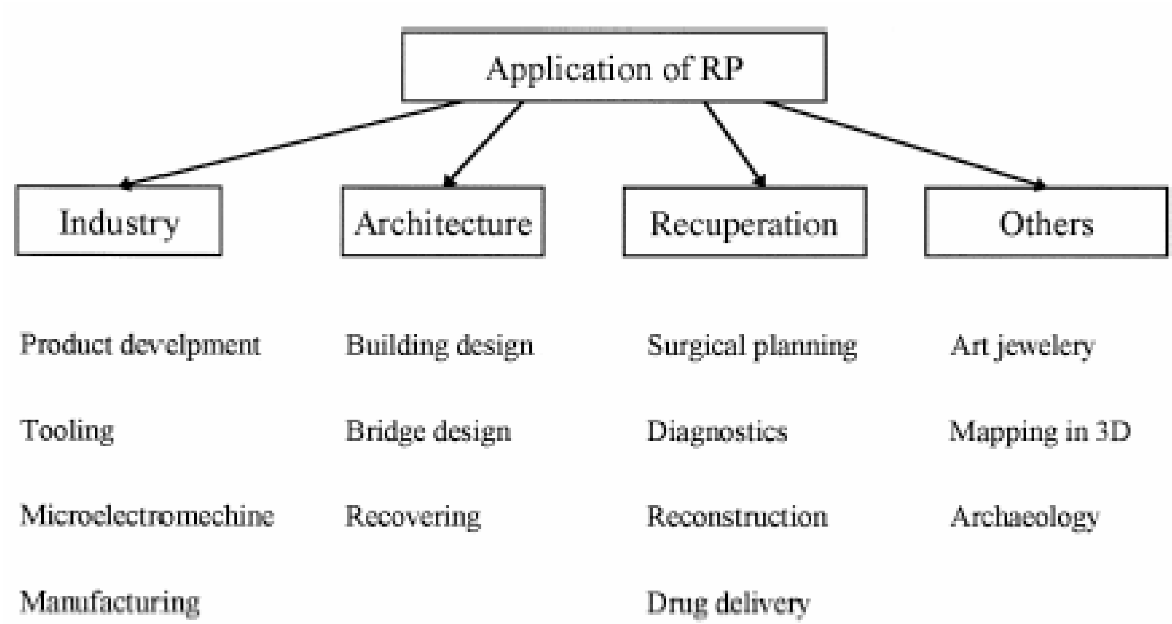


Figure 2. 44: Applications of RP according to Kochan et al. [47]

Raja and Fernandes [38] made a more detailed list of applications of RP technology by giving the usage percentage of the produced RP models. Their classifications with the corresponding percentage values can be seen in Figure-2.45. The result of their research shows that the 33.9% of all RP models is used for fit and function applications. Also, more than one-forth of all RP models are being used as patterns for prototype tooling and metal casting, as well as for tooling inserts. Only 6.6% of the models are used in direct manufacturing category. However, the quality of RP models (durability, accuracy, reproducibility) has being improved very fast and recently more durable materials such as metals have been available for this technology. These improvements make RP models more suitable for end-use and as a result, the percentage of used models for rapid manufacturing applications is going to increase drastically in the following years. In the light of the results presented by Raja and Fernandes, it can also be said that the RP technology is still mainly used in product development.

Quoting	1.3%
Ergonomic studies	3.0%
Proposals	3.9%
Other	4.6%
Visual aids for tool makers	5.0%
Direct manufacturing	6.6%
Tooling components	7.2%
Patterns for cast metal	8.3%
Patterns for prototype tooling	10.6%
Fit/assembly	12.5%
Visual aids for engineering	15.6%
Functional models	21.4%

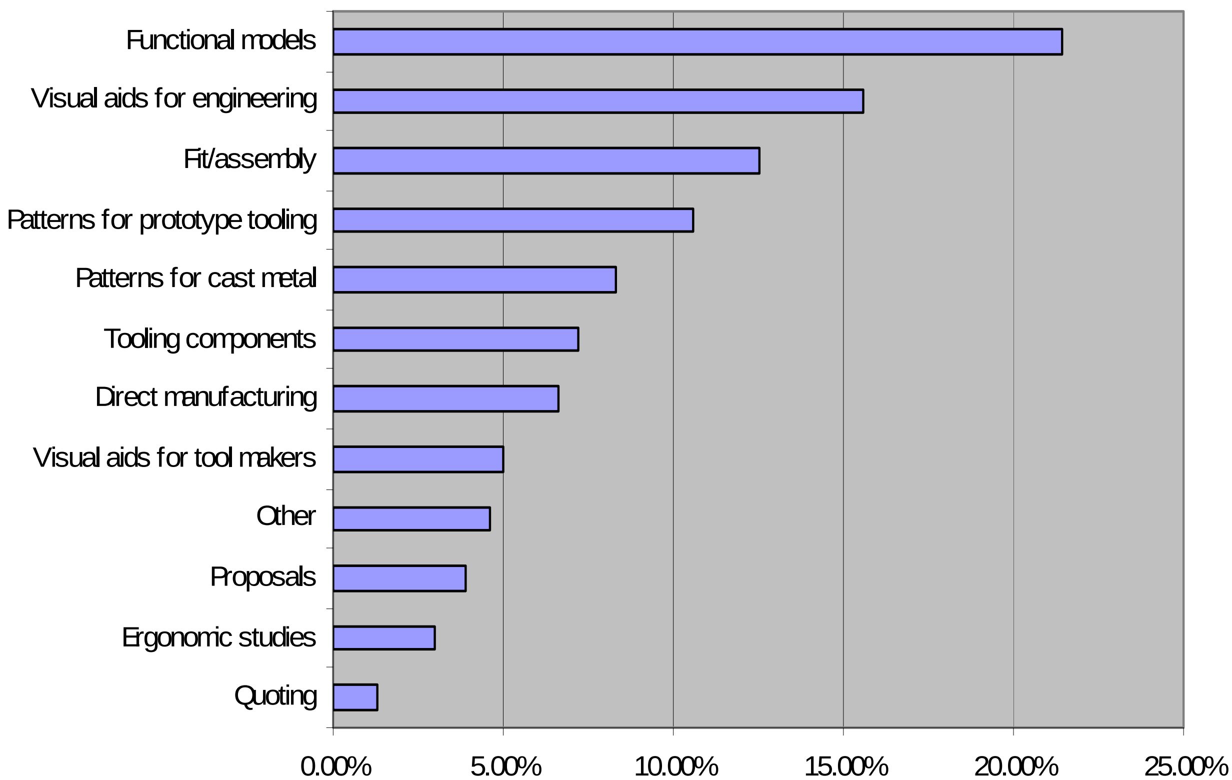


Figure 2. 45: Use of RP models [38]

As seen in the Figure-2.45, most of the RP models are used as functional models. If the mechanical behavior of the model suits the designer's wishes for its application, the model is called functional model [38]. Some tests can be done on the functional models. For example, a functional model can be used for tests in wind tunnels and by using the results of the tests, current design can be improved, or the design is approved and sent for the mass production.

Second types of models are shape (or concept) models. These are used to evaluate the shape and dimensions of a product [38]. In addition, shape models are used to make decisions and to demonstrate feasibility. That is, these models can be used as proof of concept. Since the RP technology allows inexpensive and quick production of parts, the designers can produce multiple concepts of a design i.e., if there is more than one candidate designs for a product, the shape models of each design is used as proof of concept and one of them is chosen easily because making elimination is easier when you have a physical model in hand. After the elimination, the chosen model can be improved. Sega Dreamcast game console's controller can be a good example for the foregoing explanation. In Figure-2.46a, there are seven prototypes of the Sega Dreamcast game console's controller, and the best one was chosen among them (Figure-2.46b).

Figure 2. 46: a) Shape models of Sega game console's controller; b) one of them was chosen and produced [http://www.gwn.com/articles/article.php/id/745/p/title/title/Wiimote_a_Copy_of_Dreamcast_Prototype.html]

Figure-2.45 shows that the second application where RP models are commonly used is visual aids for engineering. The RP models are very helpful while understanding working principles of a design. It is more practical and easier to investigate a new design on a physical model of it (See Figure-2.47). Engineers and designers are able to have opportunity to improve the project on a functional and working physical model.

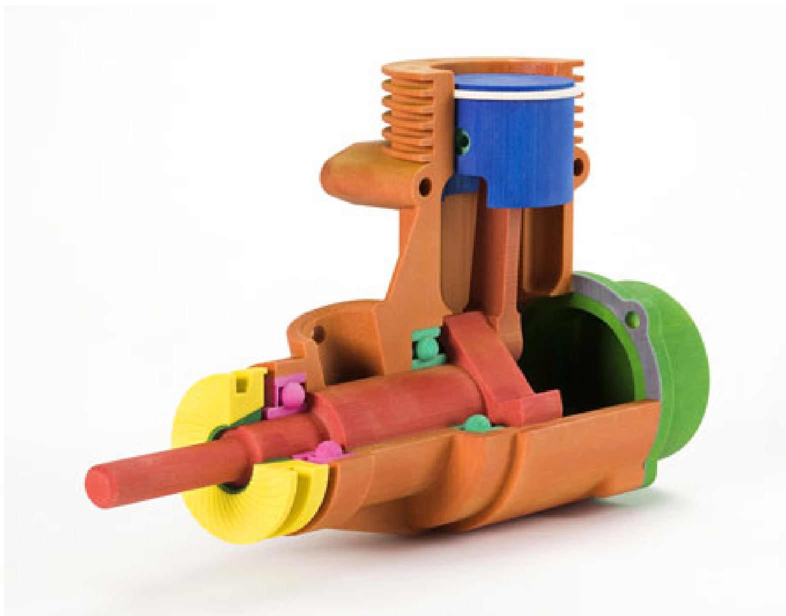


Figure 2. 47: A working RP model which shows the inside of a piston mechanism [http://www.zcorp.com/imagesets/53/show.aspx]

In addition, RP technology can be very useful in applications where product confidentiality is important. For example, RP technology may allow a project team of an engineering company, which is responsible from a military project, to produce the designed part and to work on it without a need of a service provider. By this way no person except the members of project team does see the details of the project until it is finished and it is ensured that the considered design remain inside the company.

Another advantage of RP technology is that it gives encouragement or chance to designers to present their ideas. Designers sometimes may afraid to represent their new ideas and projects. First of all, they have to be sure whether the idea is working and feasible, or not. And second, it is a more effective way to explain a new idea to a manager or audience by using a prototype. Before RP technology, production of a prototype could be very costly and time consuming. Because of this reason, designers could not come up with every idea of them. However, today, it takes just a few hours to produce a prototype and it only costs a few dollars.

Another application area of RP technology is marketing. By using an RP model, marketing of the product can be done before it is produced. As shown in Figure-2.48, even the packaging of the product can be prepared by using the RP model and it can be presented as in an end product appearance.

Figure 2. 48: Rapid prototype of a product can be used as a marketing tool

Moreover, RP technology is capable of producing very complex parts which are either impossible or very hard to produce with conventional production methods. In Figure-2.49, there are two parts which were produced by using RP technology. These parts were produced in one go and both have moving parts.

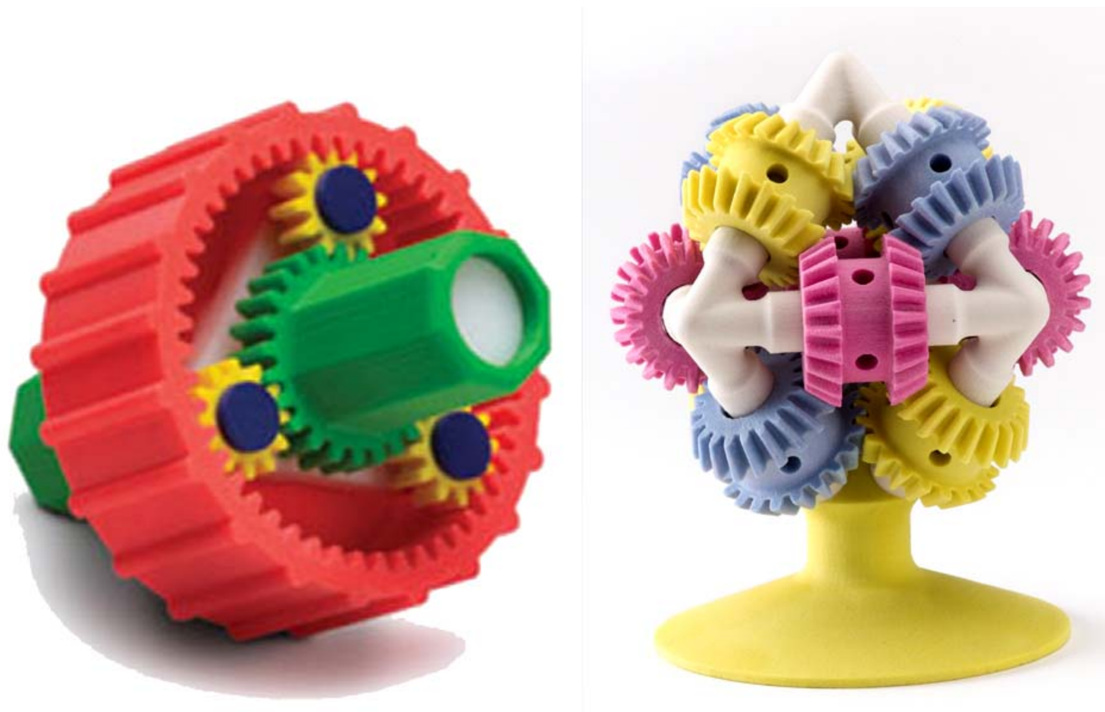


Figure 2. 49: a) A planetary gear system [www.alpha-3d.com/English/seminar.htm]**;** b) A toy with moving parts [http://www.zcorp.com/imagesets/136/show.aspx]

A new application area of RP is 3D mapping. The RP machines that can build colored parts, such as the Z corp.'s machines [74], are used to produce 3D maps from geographic information systems (GIS) data. As result, inexpensive production of high-quality terrain, urban and subsurface maps is possible in a few hours. Two of these 3D maps can be seen in Figure-2.50.

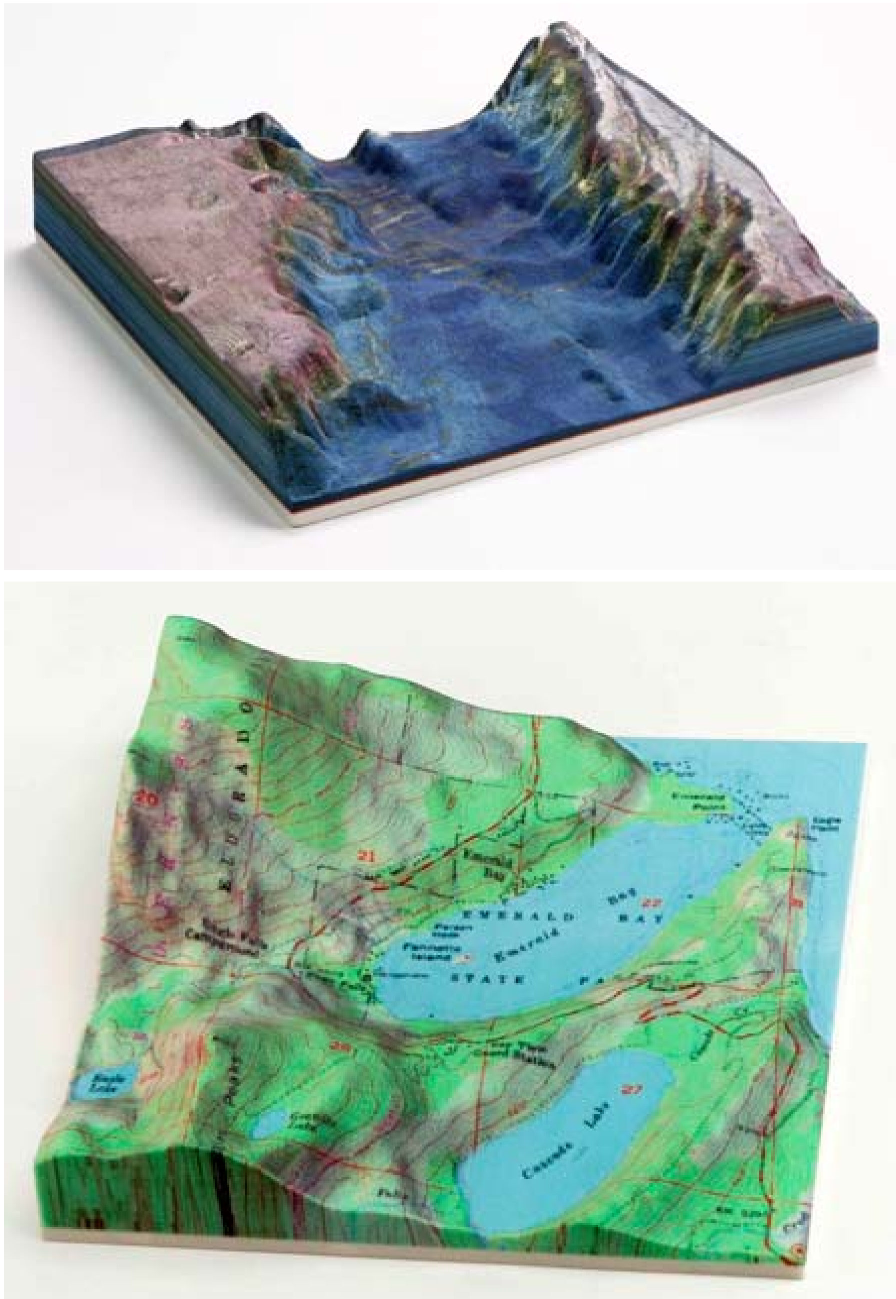


Figure 2. 50: Two 3D terrain maps built by using Z Corp.'s RP machines
[http://www.zcorp.com/Solutions/Geospatial/spage.aspx#imagesets]

The most interesting application area of RP is art. It is sometimes referred to as digital sculpturing [12]. Artists benefit from RP's capability of creating parts which are difficult or even impossible to fabricate in any other method, such as objects trapped in other objects and complex models based on mathematical equations. In addition, this technology provides different artistic media (like metals) compared to others such as clay and marble. For example, Bathsheba Grossman and Gil Bruvel use ProMetal company's RP machines while creating their work of art [75] (See Figure-2.51).

Figure 2. 51: A work of Bathsheba Grossman: Quintrino (left), an art of work from Gil Bruvel: Mask of whispers (right). [75]

Architecture is another application area of RP technology. As it is well known, models are used in architecture commonly. The building process of these models are usually time consuming and require skilled artists. However, RP machines are capable of building these models (See Figure-2.52). While speeding up the model making processes, RP technology allows building flawless models in the most cost effective way. Recently, the RP machines of 3D systems and Z corp. are affectively used by companies and architectures for building architectural models [74, 76].

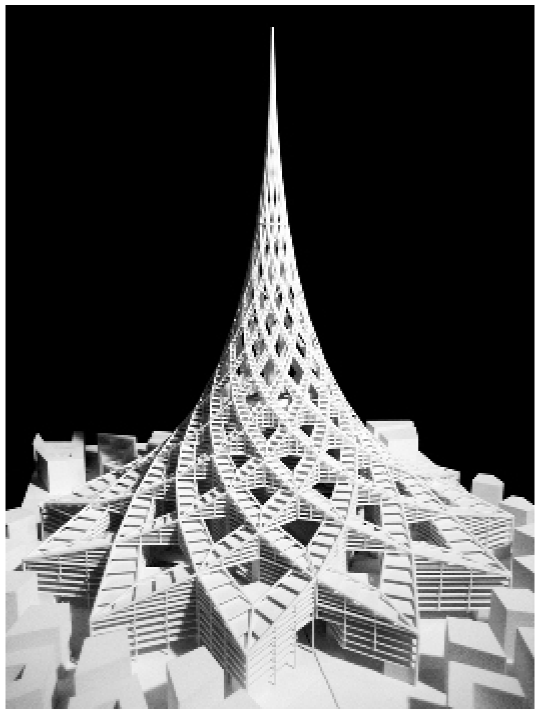


Figure 2. 52: An architectural model built by using an RP machine of Z Corp. [74]

When students interact with physical models, learning is enhanced. Based on this reality, the RP technology has been used effectively in educational institutes such as high schools and universities for several years [13, 77, 78]. The produced models are used in mathematics, anatomy, molecular biology, aeronautics, chemistry and archeology courses [77, 78]. For example, a caffeine molecule and an adenosine molecule could be compared side by side to demonstrate their similar shape, which allows caffeine to act as a competitive inhibitor for adenosine receptors in the brain. Also, Maria Terrell, a mathematics professor at Cornell University states that the students had difficulties imagining what the object actually looked like when they had 2D representation of a 3D object, such as an image of an abstraction of what a mathematical equation represents [77]. Before RP technology, some of the institutions could not afford to buy models which are used in courses. Because these models are most of the time very expensive, i.e., an anatomical model of heart can cost up to $600. However, with RP technology, today, these models can be manufactured with much less costs by the institutions. There are some non-profit projects aimed to provide STL files of educational models and allow institutions to reach these models easily. For example, Knapp et al. [77] from Cornell University created a website (3Dprintables.org) as an archive of printable models for education. A mathematical model and a DNA strand from this website can be seen in Figure-2.53. The STL file of this model can be obtained from this website. The website also includes tools allowing creation of printable models from various sources such as date files, equations, and Protein Data Bank (PDB) files.

Figure 2. 53: A Lorenz attractor model (left) and a DNA strand model (right) which were produced by using an RP machine
[http://www.3dprintables.org/printables/index.php?title=Image:Lorenz.jpg]
[http://www.3dprintables.org/printables/index.php?title=Image:3cro.jpg]

Besides the foregoing explained applications, there are some specific application fields which deserve special consideration. These are medicine, rapid tooling and rapid manufacturing.

2.6.1 RP applications in Medicine

In medicine, RP technology is used for pre-surgical planning, surgery rehearsal, implant pre-contouring, custom implant manufacturing, custom prosthesis design, medical student education and communicating with patients to achieve patient's agreement prior to surgery [12, 74, 79, 80] (See Figure-2.54).

Figure 2. 54: Use of RP models to plan surgery and design titanium mesh implants to correct facial distortion. [12]

RP has become very popular in medical applications because many medical applications require some level of personal customization, and RP technology has capable of supplying this demand. For example, by using SL machines, Align Technology Company has developed more than one million RP models to produce invisible plastic aligners (Figure-2.55) to straightening adult teeth [11, 81, and 82]. Another indirect use of RP models in medicine was presented by Key et al. [83]. In their method, the RP model of the nasal defect is used to produce a custom bung. Moreover, Lohfeld et al. [84] presented a route for designing and manufacturing of customized maxillofacial implants. In the method, both indirect and direct use of RP technology is presented (respectively, as a biomodel and as an implant), and it is stated that titanium and titanium alloy (TiAl6V4) prosthesis models can be manufactured by using SLS method.

3D Ultrasound, computed tomography (CT) scans or magnetic resonance imaging (MRI) scans are used to obtain the necessary data for constructing a particular anatomic structure. A sequence of images is captured, and then by using interactive software, such as MIMICS® software developed by Materialise, the scanned images are segmented and STL file is generated [80]. After the STL file is generated, the rest of the process is straight forward; the generated STL file is used to create the subjected medical model in RP machines. In most of the cases, the built RP models are used as tools for direct molding of implants.

Figure 2. 55: An aligner manufactured using a combination of RP technology and thermoforming - [http://www.vporthodontics.com/images/img_invisalign.gif]

Currently, the most important limitation on the medical applications of RP technology is the production material. For now, RP technology is being used as an assisting technology in medicine, because there is no approved bio-compatible material which can be used in RP systems. There are experimental researches in which scaffolds are produced by using RP method, are tested in vivo applications. However, these researches are done on test animals.

Due to this reason, RP models have not been able to be used directly in vivo applications for humans. The material processability is very important because each RP technique requires a special form of input material and the biocompatible material should not loose its properties during the RP process.

In tissue engineering, there are extensive researches about using RP technology while producing scaffold, artificial organs and tissues. Mainly these researchers are focused on the bio-compatible materials that can be used in RP systems. In the light of these researches, it can be said that in the near future, RP machines can be used directly to build implants or artificial organs that can used in vivo applications. According to Hutmacher et al. [70], development of solvent-free and aqueous-based RP systems which allow inclusion of bioactive components, such as growth factors, cells and drugs is a milestone in scaffold fabrication, and these systems offer new opportunities in tissue engineering and regenerative medicine. For example, Wang et al. [41] showed evidences about how RP technologies have potentials about enabling manufacturing of bio-artificial human livers.

Moreover, there are successful researches which show that rapid manufacturing of biocompatible scaffolds and tissues can be possible in the future. But recently, only small scaffolds are produced and tested in experiments. For example, in the research of Lopez-Heradia et al. [43], titanium scaffolds were produced and implemented in syngenic rats' bones. However, in this research, instead of manufacturing scaffolds directly, wax patterns were produced by using an RP method. Then by using these patterns, ceramic moulds were prepared to use in cast investment of titanium scaffolds. Another successful research was performed by Ang et al. [10]. Chitosan-hydroxyapatite scaffolds were produced and by making in vitro tests, it was proved that the produced scaffolds are biocompatible. A similar deposition system used by Ang et al. has been built in the content of this thesis study. That is, as a future work, studies to produce biocompatible structures will be conducted.

Another interesting approach about tissue engineering was proposed by Cohen et al. [45, 73, 85] from Cornell University. In the proposed method, they built a robotic hydrogel deposition system and various implant samples were fabricated by using pre-cell-seeded alginate hydrogels (Figure-2.56). Short-term cellular survivability was verified by the viability test.

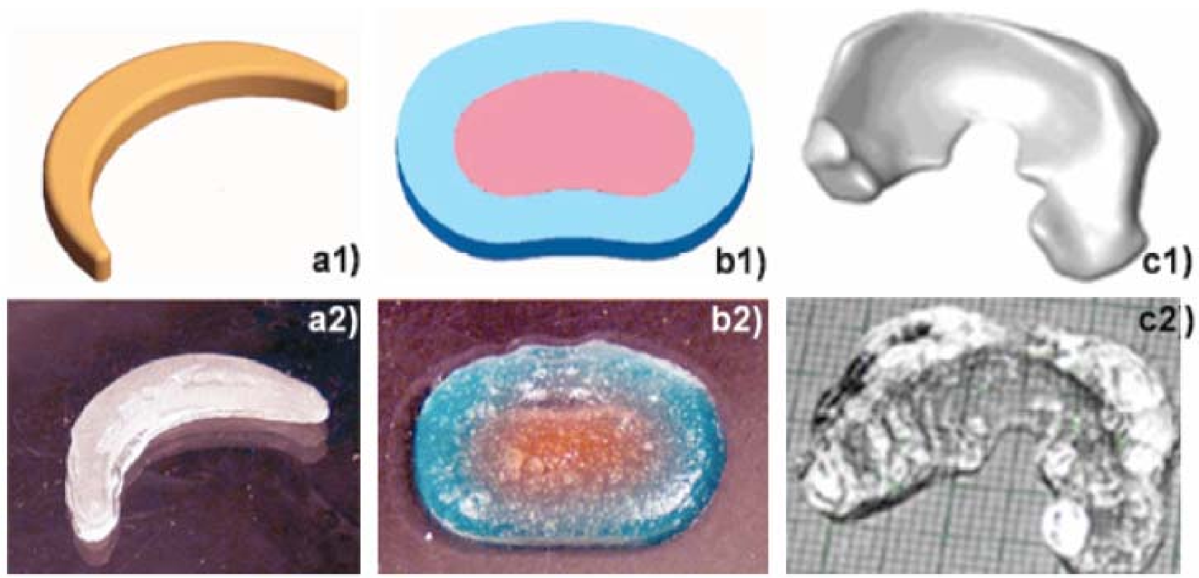


Figure 2. 56: CAD models and photographs of printed samples [73]

Also there are some researches in which the researchers are directly focused on rapid production of porous cartilage and bone scaffolds. Bases of these studies are mainly the different porous structures [86, 87] and mechanical properties of these structures [88].

The foregoing studies and developments prove that the importance of the RP technology is going on to increase in medicine, and direct manufacturing of implants and artificial organs will be able to possible.

2.6.2 Rapid Tooling

As its name implies, rapid tooling (RT) is the process of fabricating tools by using the RP technology. In the literature, the RT methods are divided in to two different categories: direct methods and indirect methods. Karunakaran et al. [50] made this categorization based on the RP methods used in RT processes (Figure-2.57). Levy et al. [48] also used RP processes to make this categorization but, in addition, they added material of the produced tool as a second element in their categorization table (Figure-2.58). Moreover, Levy et al. provided a statistical data about which RT category and material is preferred in the industry most. Rosochowski et al. [21] made a different classification mainly for foundry industry because RT technologies are mostly used in this industry. They proposed a classification of RT techniques based on practical aspects (Figure-2.59) and they concentrated on processes such as producing patterns for the foundry industry, using patterns for soft and hard tooling, and manufacturing tools directly on RP machines.

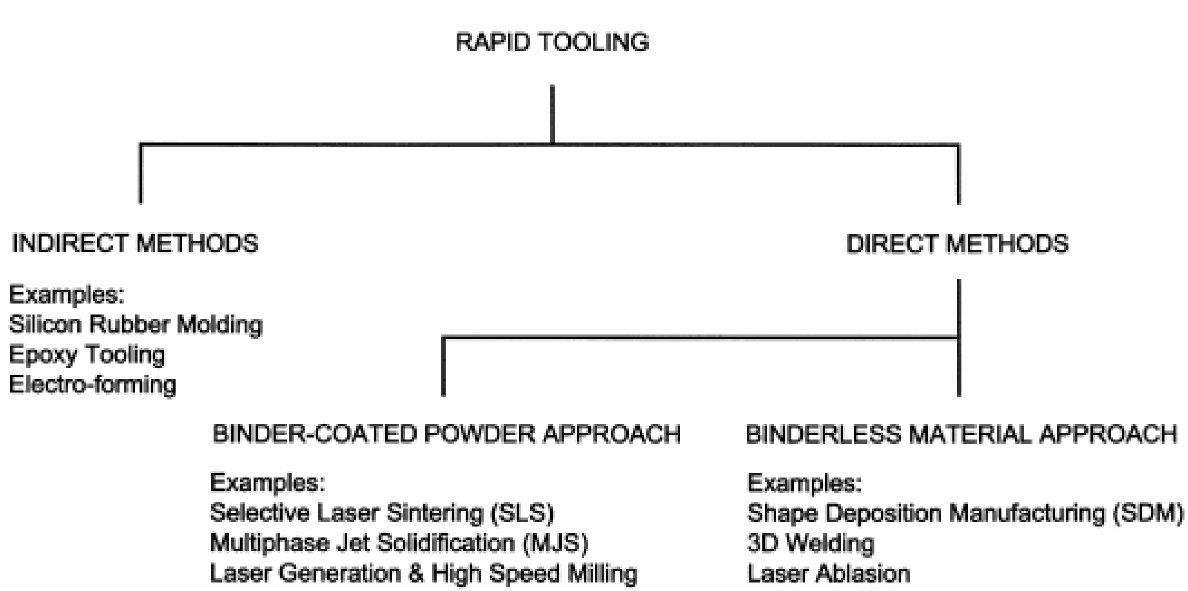


Figure 2. 57: Classification of RT processes according to Karunakran et al. [50]

Material	Direct technologies	Indirect technologies
Polymer	Bridge Tooling, CuPA-SLS (3D-Systems) SLS/SLA soft shells	Silicon rubber pattern RTV Swift™ Tooling (SWIFT™ Tech.)
Metal	DMLS™ (EOS) Rapid Steel 2 LaserForm (3D-Systems) 3D Printing (ProMetal™)	KelTool™ (3D-Systems) Cast tools Metal spraying (HEK) Metal deposition

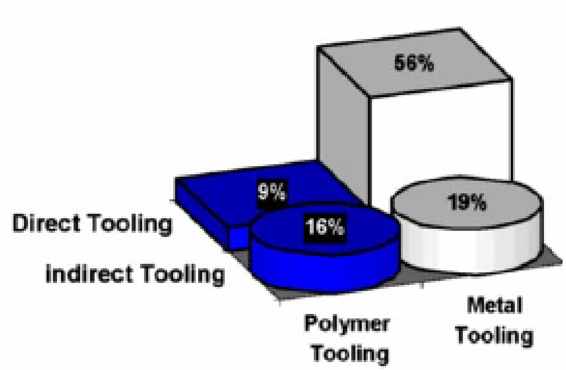


Figure 2. 58: Classification of RT processes according to Levy et al. and the provided statistical data about the preference of the RT methods [48]

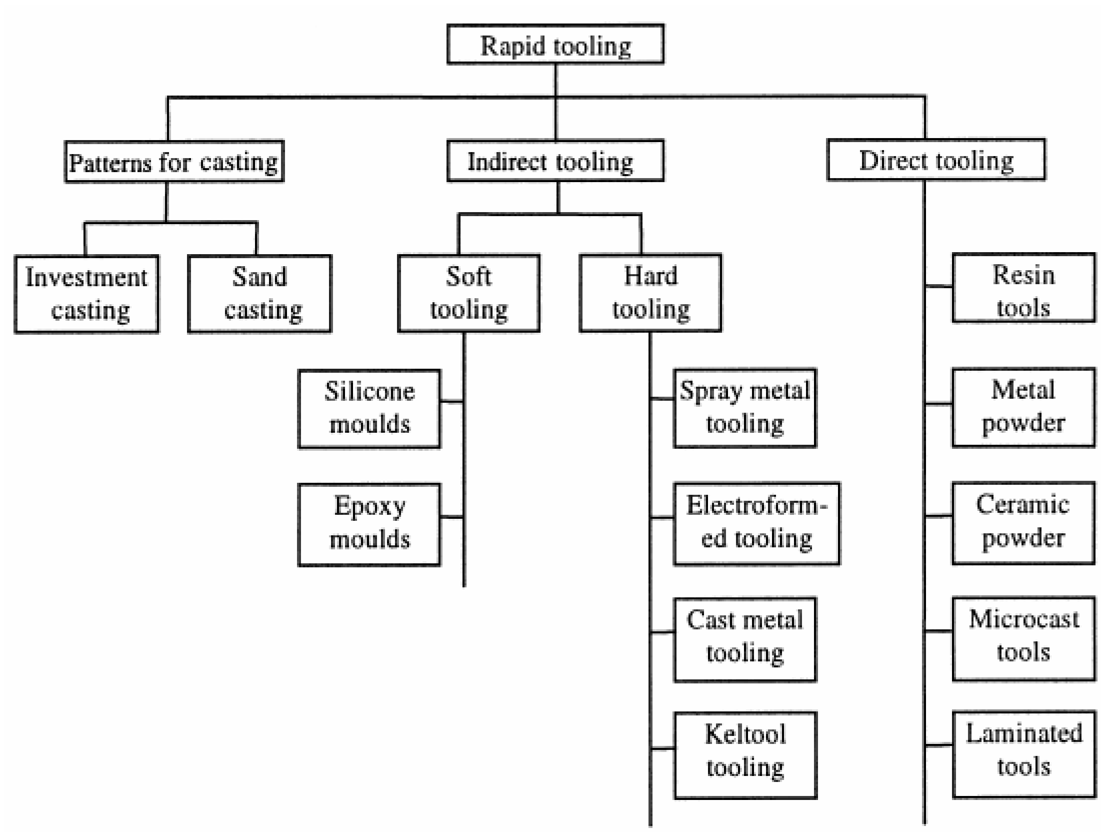


Figure 2. 59: Classification of RT techniques according to Rosochowski et al. [21]

In direct methods, the produced part in RP machine is as used as the tool itself such as cavity mold inserts. In indirect methods, the produced part is used as a master pattern in a secondary operation in which the real tool is produced, such as creating master patterns to produce a mold.

There is a great demand for faster and less expensive tooling solutions and consequently an impressive number of RT methods being developed worldwide. RT has some advantages over conventional tooling methods. For example, the high cost of labor and short supply of skilled patternmakers can be overcome. Hollow designs can be adopted easily so that light-weight castings can be produced more easily [11]. Moreover, RT techniques are faster than the conventional methods, and therefore, tooling time can be below one-fifth that of conventional tooling. Also, tooling costs are much less that the conventional tooling methods. Cost can be as low as the five percent of the conventional tooling cost. However, the tool lives of the tools produced with RT methods are considerably shorter than conventional tools, and the tolerances are wider than the conventional tools [89]. Properties of tools produced by using RT methods make them very suitable for one case or low volume production.

To show how RP technology is used in RT, room temperature vulcanization (RTV) silicone rubber molding process which is one of the most popular tooling applications for RP can be as an example. This process is popular because it provides fast and inexpensive molds, and the resultant parts have excellent surface quality. Moreover, the process is suitable for both large and small parts [90].

Steps of this process can be summarized as follows [89]: (Illustrations of the steps of this process is shown in Figure-2.60)

a) An RP pattern is used to create a male master pattern. The RP part is sanded to a suitable cosmetic finish and can be sealed.

b) The master pattern is fitted with a sprue and gate, and then surrounded by a parting surface which establishes the parting line for the mold. Alternatively, the cured mold can be cut carefully to form the parting line.

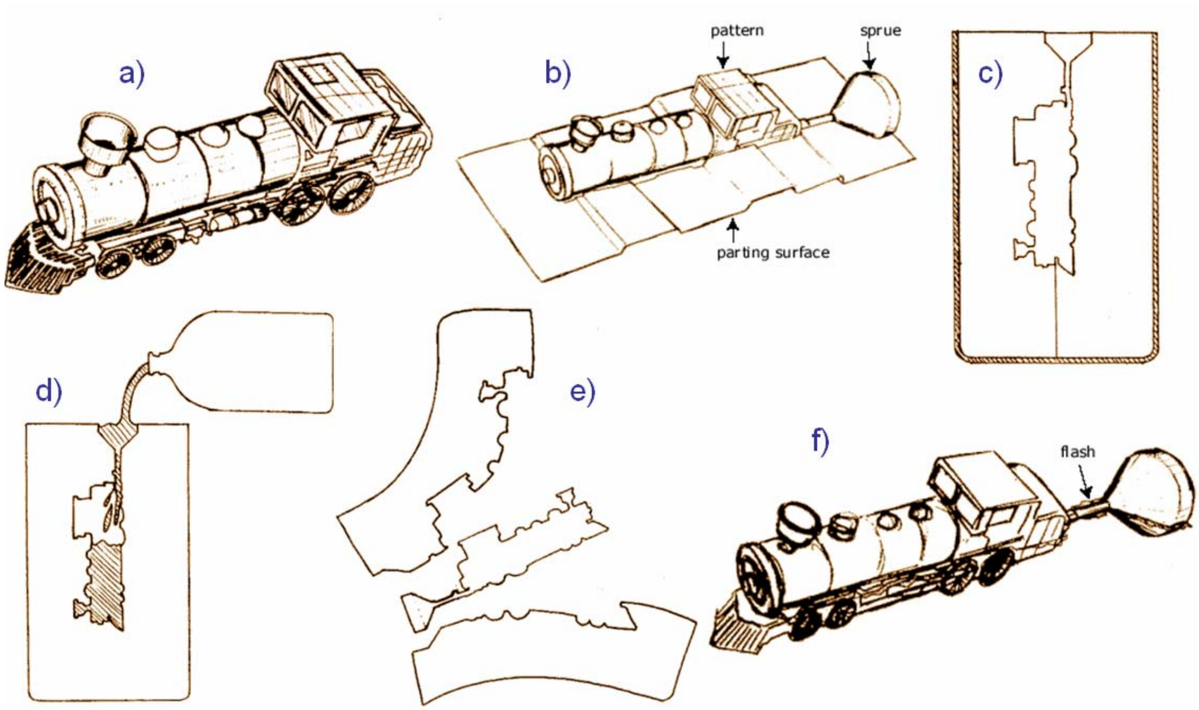


Figure 2. 60: Use of RT technology in RTV silicone rubber molding [89]

c) The assembly is fixtured in a vat, and liquid RTV is then poured over the pattern and parting surface combination as shown below.

d) Once cured, the RTV is removed from the vat and separated from the pattern and parting line surface to yield the two halves of the molding tool. RTV air-cures, so that the cure time depends on the geometry, the RTV type, and the environment. Cure time can range from .5 to 40 hours. Aging of the mold after cure for up to three days can improve mold life. Thermoset resin such as urethane is poured or injected into the mold, as shown below.

e) Finally, the finished part is removed from the mold. Undercuts are overcome by distorting the mold, which springs back to its original shape as long as distortion is not too severe.

f) The part must then be post-processed by trimming any flash, as shown below, and possibly sanding. The gate and sprue must also be removed.

The process explained above is categorized as indirect tooling (Figure-2.57, 2.58, 2.59) and although the used methods are differ, the steps of processes are similar.

Dimitrov et al. [91] analyzed three typical process chains: vacuum casting, indirect sand casting and investment casting. They compared the conventional and RT involved versions of these processes. In conventional versions of these processes, CNC machines are used to produce the moulds and core boxes. They produced some parts by following the routes for both conventional production route and the route involving RT, and presented their observations in their study. For example, for sand casting process it was reported that the development of the productions patterns, once the negative were done, took only seven working days. Beside the time saving, another advantage of the RT route was that this new method allowed testing of the core system and performing systematic checks along the process chain. Furthermore, an estimated 60 per cent cost reduction was achieved by using RP techniques.

RT technology is not only used to produce molds directly or indirectly, but also is used to produce hand tools. At the BMW AG plant in Regensburg, Germany, the plant's department of jigs and fixtures uses FDM technology of Stratasys to build hand tools for automobile assembly and testing (Figure-2.61). It is reported that besides the advantage of cost reduction, the use of RT technology improved productivity, worker comfort, ease-of-use and process reliability.

Figure 2. 61: This tool is used to affix the rear name badge

Since the RP methods provide freedom of design, engineers can create configurations that improve handling, reduce weight and improve balance. As an example, BMW reduced the weight of a device by 72 percent replacing the solid core with internal ribs cut 1.3 kg from the device. At first, this improvement may not seem as an important one, however, it makes a big difference for a worker who uses this tool hundreds of times in one shift [25].

RT has been most successful in casting and injection molding applications. Its use in metal forming applications is very limited due to the normally high requirements regarding surface finish, strength and abrasion resistance of metal forming tools [21]. However, as the surface quality and the strength of the parts produced by RP machines are improved, the use of RT will increase drastically in the following years.

2.6.3 Rapid Manufacturing

The term of rapid manufacturing (RM) is used to define the process of fabricating parts or products directly for end-use from a rapid prototyping machine. This process is also known as direct manufacturing, digital manufacturing and direct fabrication. As the material options for RP operations have been increasing, the use of RP technology in manufacturing has also been increasing proportionally. Especially, when only a small number of products are needed, RM can replace conventional production techniques.

There are numerous reasons why RP is used in manufacturing. First of all, there is almost no limit to the complexity of the products in RP. There is a wide range of material options. Since the parts are directly produce from CAD files, tooling which is necessary in conventional manufacturing methods is eliminated in RM. Elimination of tooling results in enormous saving in time and money. Parts and products can be fabricated at the point of use and in the exact quantity required. For example, parts may be manufactured at the location of the final assembly line, or at a replacement part distribution site, or on a ship at sea or in outer space. It will only be necessary to inventory the requisite materials rather than many parts or sub-assemblies, or even the final product itself. May be the most important advantage of the RM is that it allows mass customization. Conventional manufacturing methods are feasible for high volume productions. Therefore, producing a single part is both time consuming and costly. However, for RM it is the opposite. Since manufacturing time and the cost of a single product is always same in RM no matter how many parts are produced, the quantity of the production is not important. If it's possible to economically make as few as a single unit of an item, then it's hypothesized that there will develop a significant demand for products created by and for individual consumers. Such products might be expected to satisfy consumers' needs more precisely than mass-produced goods. For example, the shells of hearing aid devices are produced by using SL machines for several years by some companies (Figure-2.62). These devices are very small and their shapes are complex. Moreover, each person’s ear canal is unique in shape and size. So the traditional method of producing a mold for each hearing aid is time-consuming, expensive, and prone to error. The use of laser digitizing, special software, and additive processes results in a custom product that is superior in many ways.

Figure 2. 62: Hearing aid shells produced by using SL machine of the 3D systems [http://www.3dsystems.com/newsevents/newsreleases/pdfs/102004_3D_Systems_Introduces_New_Hearing_Aid_Shells_MFG_System.pdf]

Each year Wohler Associates survey many RP service companies which provide service hundreds of customers. One of the questions is “How do your customers use additive parts?” Still the form, fit and functional applications are the most popular answers. But the results show that the percentage of RM is increasing as an answer. 2003, respondents said that 3.9 percent of their activity was rapid manufacturing. It grew to 6.6 percent in 2004 and 8.2 percent in 2005 [92]. This means that in following years, RM will be a popular manufacturing option especially for low volume productions.

2.7 Economical Perspective

“Time”! This tetragram defines the most important concept in today’s global competition arena. Companies and manufacturers try to develop and produce new products as fast as possible because it is the only way to gain a competitive advantage in recent market. In product development cycles, there are four key objectives: product cost, product performance, development program expense and development speed [1]. Also there are other factors like quality and reliability which have to be considered. Until 80s, product cost and performance had been the dominant factors in product development cycles. Throughout the 80s, the quality of the product became more important. After 90s till now, the product development time has become the dominant factor because the criteria like performance, cost, quality, and reliability have been satisfied by most of the leading companies [1]. This is the main reason of rapid product development (RPD) necessity. Global companies have been discovering that reduction of product development time is a great source of competitive advantage (Figure-2.63).

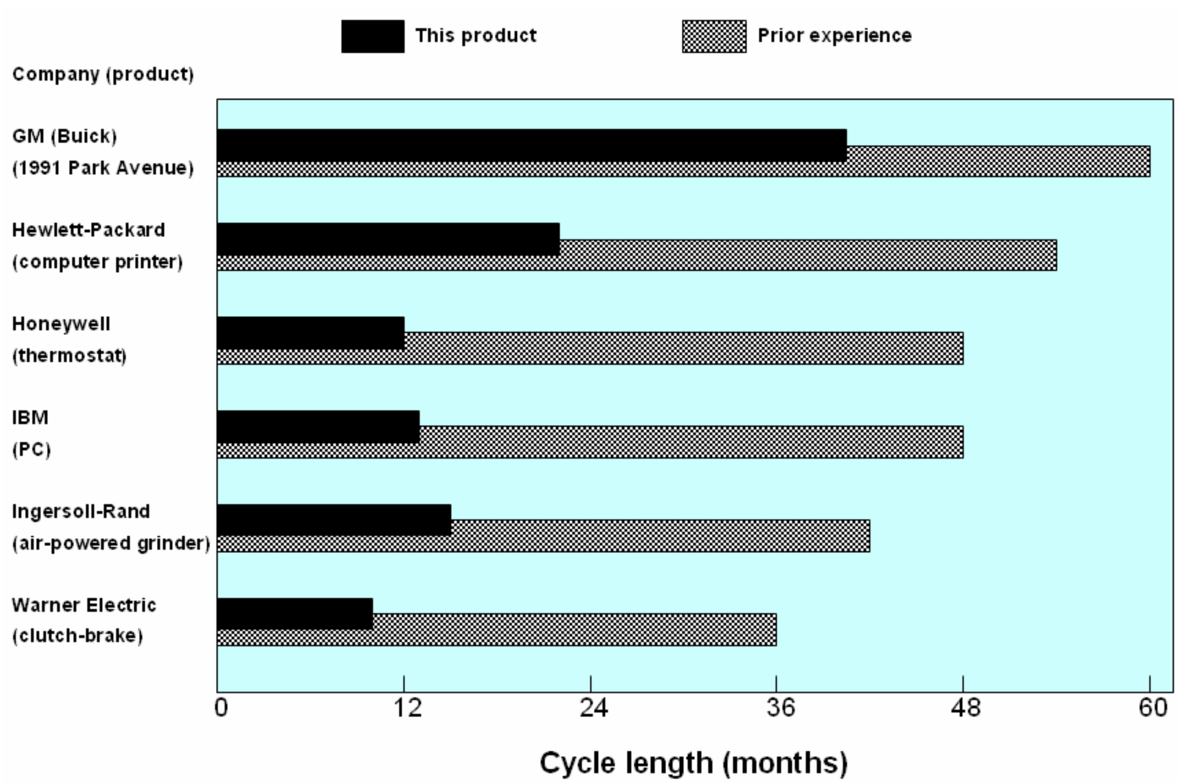


Figure 2. 63: In many industries, companies have been able to remove roughly half of the time formerly needed for product development. [1]

The data in Figure-1 belongs to 90s and it is obvious from the figure that the big companies in different industries realized the importance of the reduction of the development cycle. There are several advantages of a short production cycle and may be the most obvious one is that the sale life of the product is extended (Figure-2.64). That is to say, if a product's development cycle is shortened one month, sales life of this product is one month extended resulting an extra month of revenue and profit. The result of early product introduction is increased market share and this is the second benefit of short development cycle. Even at the beginning, the first product in the market has 100% share of the market, as illustrated in Figure-2.63. Moreover, for some specific industries like the personal computer industry or the software industry, if the product is the first in the market, the user can get locked to the product and it may be difficult or costly for them to switch to another product. [1]

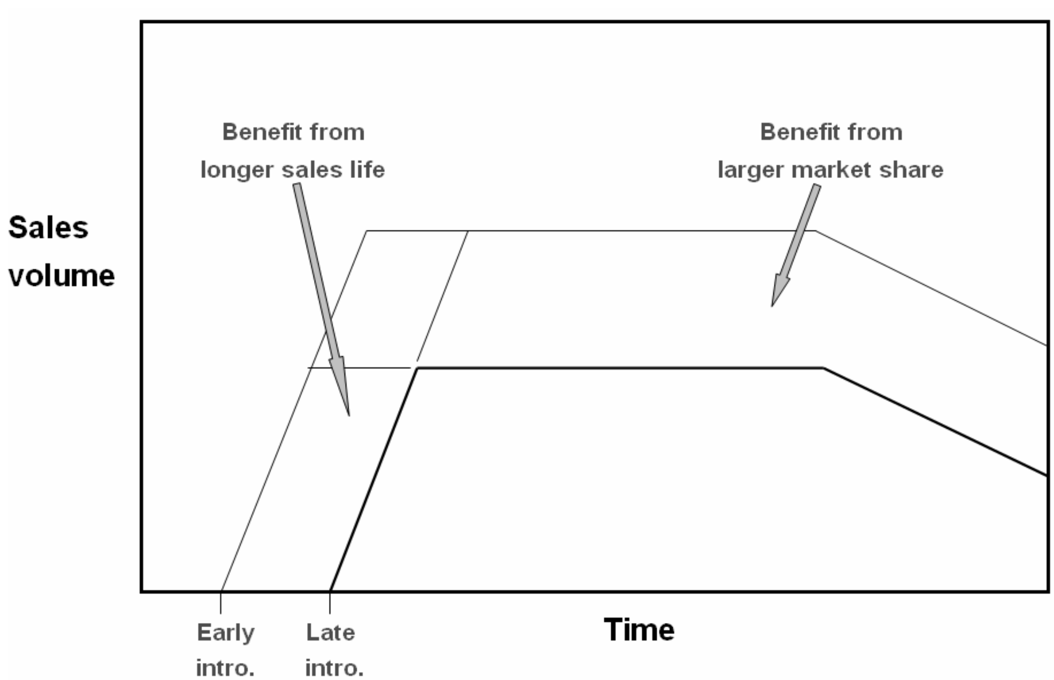


Figure 2. 64: Early introduction of a product can increase its sales life and market share [1]

Third benefit of the short product development cycle is higher profit margins. The company which introduces its product to the market first has the freedom of pricing and making higher margins if it is possible. After competitors' products enter the market, the price can decrease but this time the first company can benefit from the manufacturing cost advantage since it is producing the product for a longer time than the competitors (Figure-2.65).

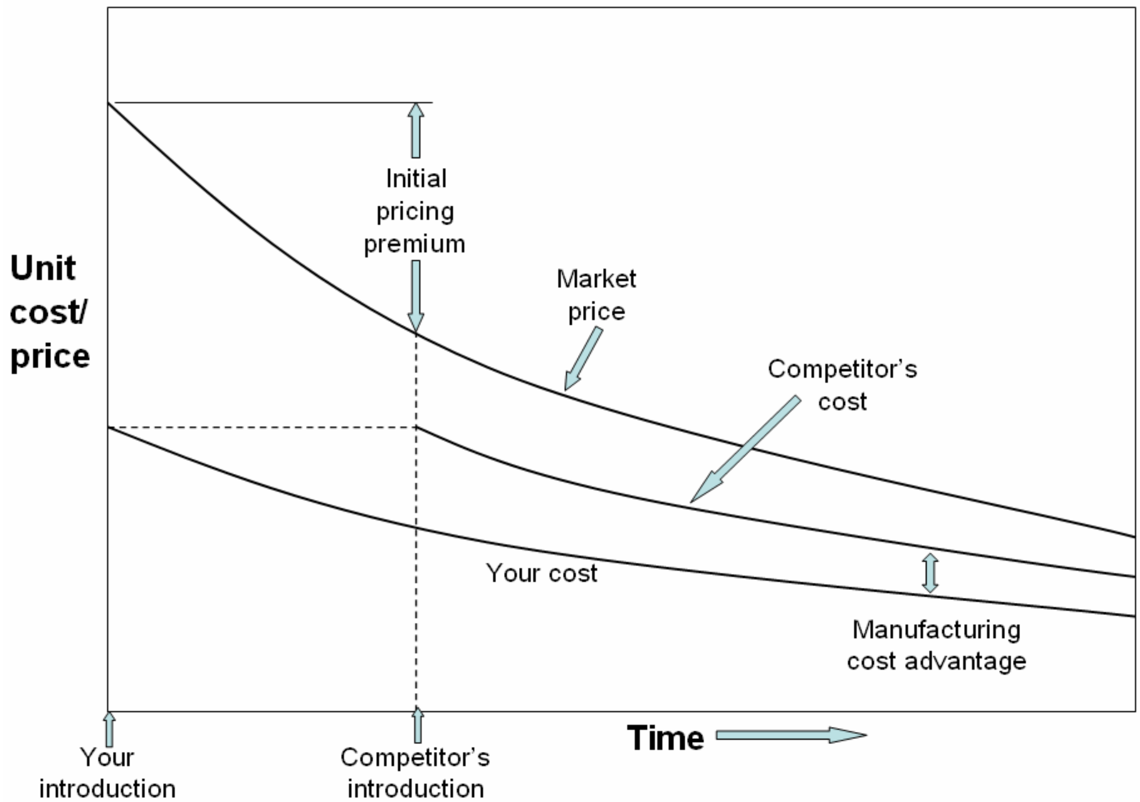


Figure 2. 65: Early entrance gives the company opportunity of benefit from the premium price and cost advantages from the manufacturing learning curve. [1]

Short time-to-market period, short product development cycle and rapid product development, all these terms refer the same thing; to be able to decrease the production period of a new product which begins with conceptual design and finishes with first real end-product which reaches to the end of assembly line. And for about two decades, RP technology is one of the key factors used by the companies to decrease the production time and consequently affect the profitability directly. In fact, the effects of the RP technology on the economical perspective of the production are not limited with the “time” of the production. There are some other indirect influences of the RP technology which decreases the costs of a new product.

Besides the prototyping, RP technology has also being used for manufacturing for several years. For low-volume or custom productions, RP technology is very attractive since the cost of a single product is fixed. For conventional manufacturing techniques, it is well known that, if the number of the produced product is increased, fixed cost per product is decreased. Consequently, more production means decrease in the cost a single product. Therefore, for low-volume productions, usually the limit is defined as 5000 products; the RP technology is very profitable compared to conventional production methods.

Chapter 3

DEVELOPED SYSTEM

3.1 HARDWARE

3.1.1 Mechanics and Kinematics

The system is a 3-axis table that is carried by an aluminum structure. There are two moving platforms; one of them moves along Y-axis and other moves along X-axis (Figure-3.1). Some basic information about the system is given on the Figure-3.2. Each platforms moves on two guides by help of one ball screw mechanism (Figure-3.3).

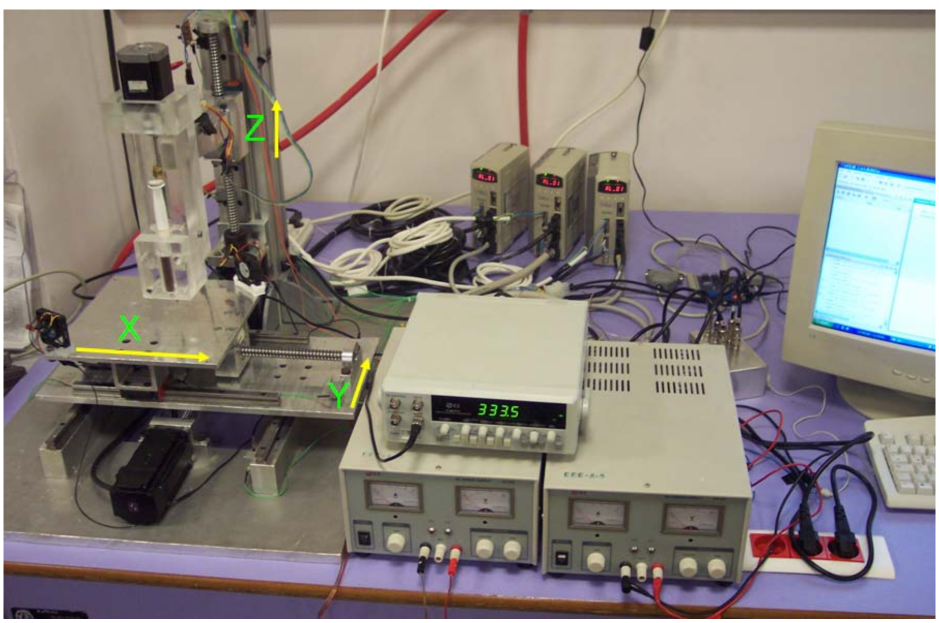


Figure 3. 1: A general view from the system

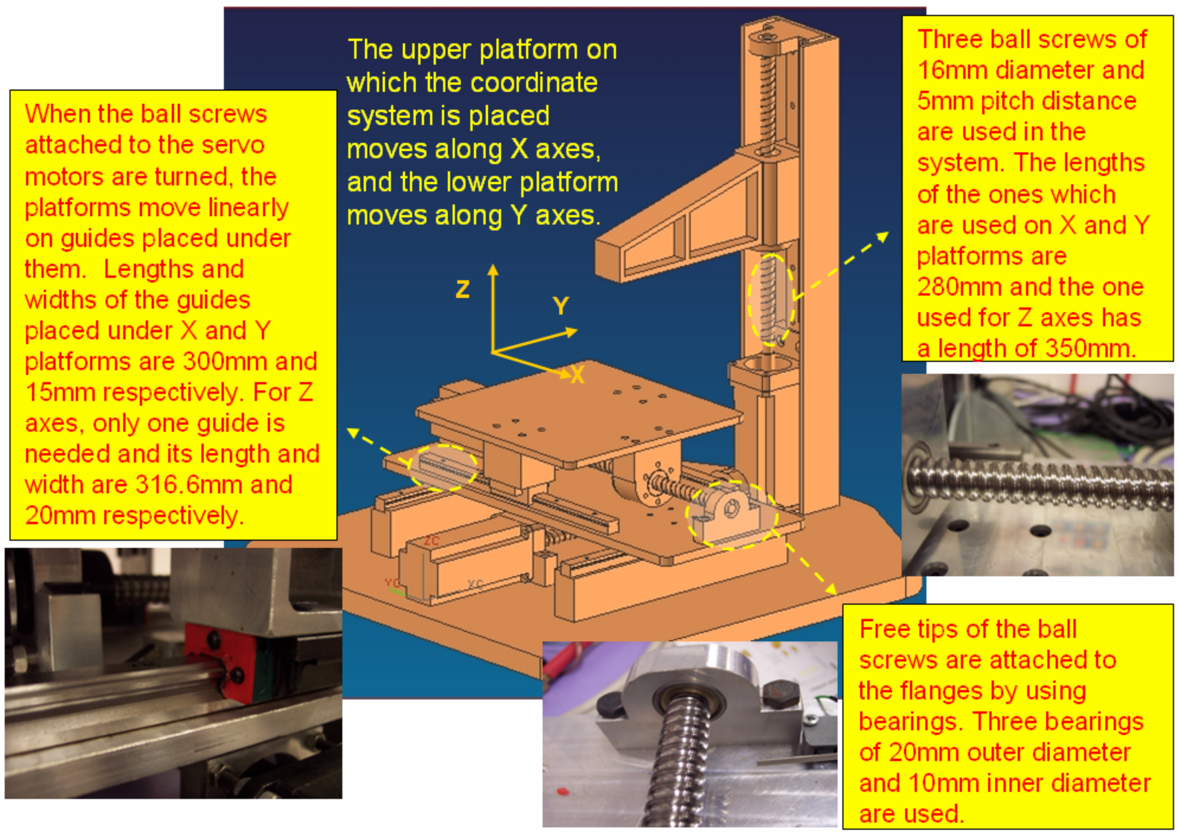


Figure 3. 2: Basic information about the mechanical system

The movement along Z direction is directly transmitted to the deposition system over a ball screw mechanism. The maximum kinematic resolution of the machine in all three directions is 5µm/pulse. However, currently used kinematic resolution is 50 µm/pulse because the resolution of the current deposition system is much lower than the kinematic resolution of the 3-axis machine. Translational kinematic accuracies in all axes are calculated with repeated measures. For X- and Y- axes, the table is moved 100 mm for 10 times and traveled distance is measured with a digital caliper. For Z-axis, measurements are done in only +Z direction since only upward translation occurs during production. 10 different measurements are done in +Z direction for a translation of 60 mm. Error is calculated as the difference of set translation and measured translation. It is found that the average translational kinematic accuracies are -0.04 mm, -0.04 mm, -0.12 mm, -0.11 mm and -0.03/+0.06 mm respectively for +X, -X, +Y, -Y and +Z directions. The measurement data can be found in Appendix-6.

There are two emergency switches on the platforms for each direction. The emergency switches on Y platform are shown in yellow boxes in Figure-3.3. In a case of an undesired situation, switches shuts the energy goes to motors.

Dimensions of the whole mechanical system are given in Figure-3.4. In Figure-3.4, red cube in big rectangular prism represents maximum space in which tip of the deposition system can reach every coordinate. That is, this cube represents the workspace of the system, and its dimensions in all axes are 220mm. These dimension values also defines maximum dimensions of the part that can be built with this machine.

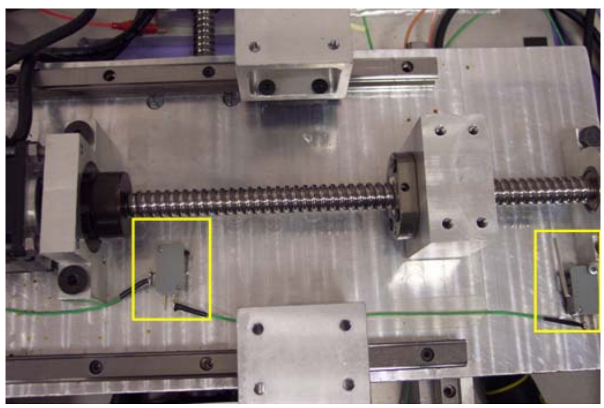


Figure 3. 3: X and Y platforms moves on two guides

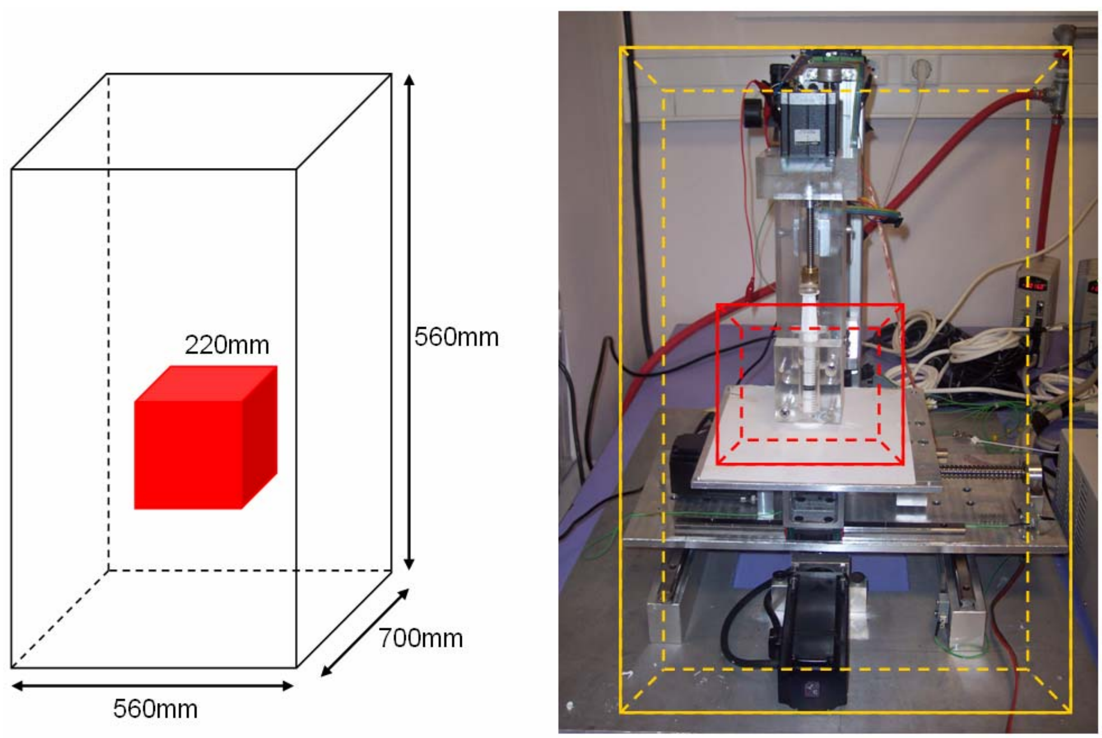


Figure 3. 4: Main dimensions and the workspace of the system

Fundamentally, developed RP system's kinematic system composed of three servo motors, and ball screws attached to shafts of these servo motors with bearings of 37mm outer diameter and 10mm inner diameter (Figure-3.5).

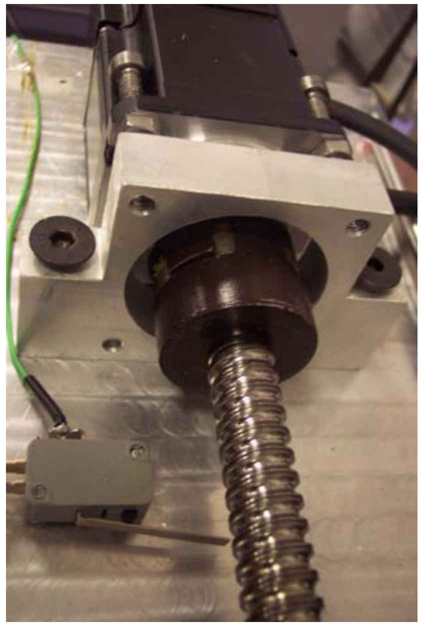


Figure 3. 5: The servo motor maintains motion along Y axis and the ball screw attached to this motors shaft with a bearing

Servo motors are driven with signals sent from their drivers. This process is explained in Section-3.3 in detail. Current rotational speed of the servo motors is 15 rev/min. Since the pitch distance of the ball screws is 5 mm, then the translational speed in all directions is calculated as 75 mm/min. Servo motors and their drivers used for Y- and Z-axes are identical, and motors have capacity of 400W, and the driver capacities are also 400W. Their encoder types are incremental 2500 [P/R]. The only difference for the servo motor and its driver for X-axis is that they have a capacity of 100W. Pictures of the drivers of the system and the servo motors of X- and Y-axis are shown in Figure-3.6.

Some basic technical specifications of the RP system are given in Table-3.1.

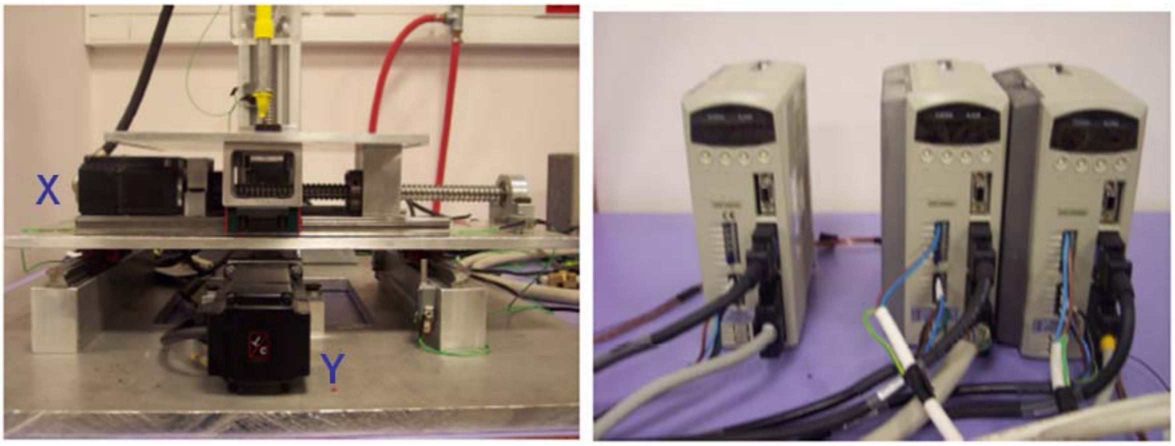


Figure 3. 6: Servo motors of X- and Y-axis and the drivers of the system

Table 3. 1: Technical Specifications of the RP system

			X	Y	Z
Dimensions of Machine	*Height*	560mm			
	Needed Ground Area	560mmX700mm			
Carrier Platforms	*Length*		245mm	460mm	
	Width		245mm	205mm	
Workspace Dimensions			220mm	220mm	220mm
Motors	*Capacity*		100W	400W	400W
	Speed		3000Rev/min	3000Rev/min	3000Rev/min
Ball Screws	*Pitch Distance*		5mm	5mm	5mm
	Length		280mm	280mm	350mm
Load Capacities			21kg.f	21kg.f	7kg.f
Kinematic Resolution		5µm			
Electrical Requirements		AC Power Supply			
		200-230V			
		50/60Hz			
Current Feed Rate			15rev/min	15rev/min	15rev/min

3.1.2 Deposition System

One of the most important units of an RP system is deposition system. Any fault in the deposition system directly affects quality of produced product. An acute deposition system should maintain continues flow of production material at a constant rate. It is desired that the production material conserve its physical and chemical properties during the production process. A case in which the chemical properties of the production material change can be encountered in RP systems where polymers are melted to be used as production material, such as in FDM systems. If the polymer is overheated during the melting, thermal degradation occurs, and consequently, the properties of the used material changes undesirably. Solidification of the production material before the production process is over can be given as an example for undesirable change of the physical properties of the material. Therefore, to maintain surface quality of the produced part, and to be able to have parts which always have identical chemical and physical properties, the deposition system should work seamlessly.

In this study, four different deposition units were designed and tested, and among them the best one were chosen. A continuous and constant material flow, prevention of the flow when desired, and maintaining fluidity of the production material until the end of the production are criteria of design.

3.1.2.1 Design A

This first design was composed of a temperature controller unit, a pressure vessel in which the polymers are melted during production process and a pressure regulator which allows controlling pressure level of pressurized air that flow into the vessel. This system is shown in Figure-3.7.

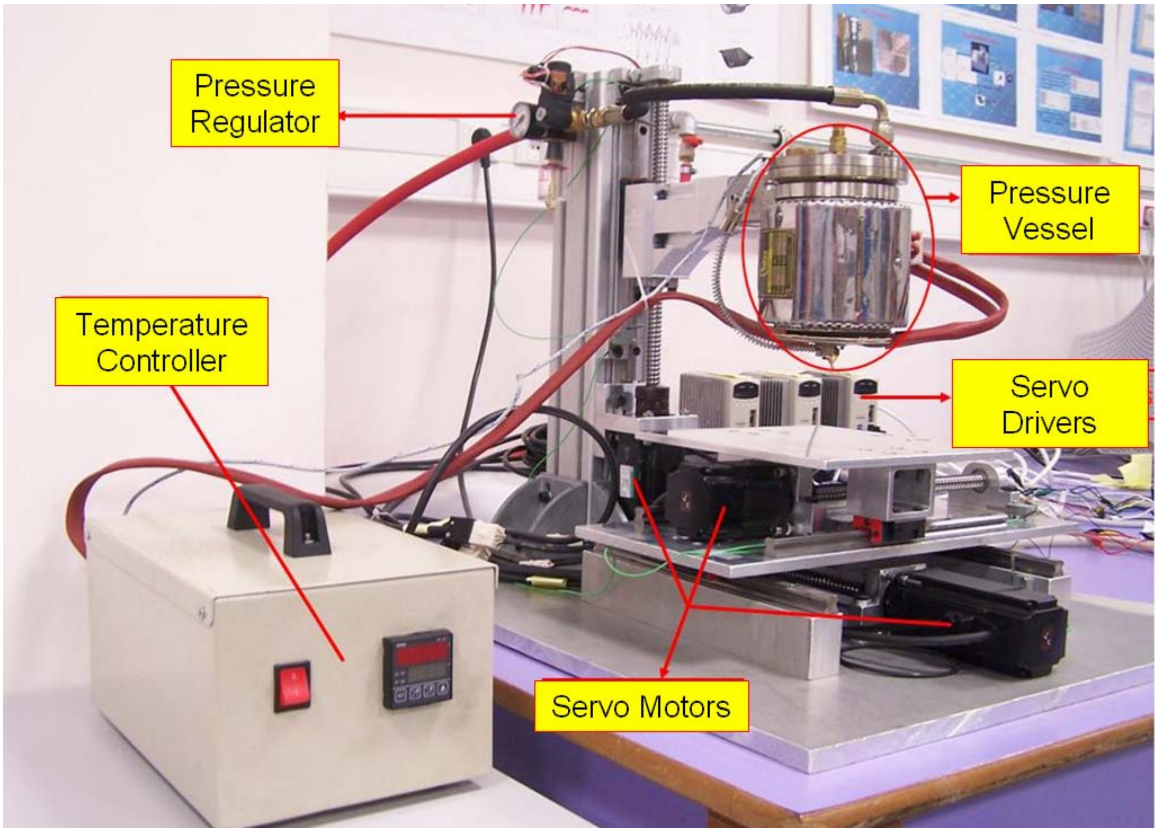


Figure 3. 7: System integration of the first deposition system design

Thermoplastic polymer in form of small granules is put into the vessel. Then the cover of the vessel is closed tight. A temperature set value is entered to temperature controller unit as input. This set value is determined based on the melting point of the used thermoplastic. Temperature controller unit is connected to the bottom surface of the pressure vessel by a thermocouple (Figure-3.8). The inner volume of the pressure vessel is heated with resistance heaters embedded into the bottom and side surface of the vessel. Current sent to these resistances is also controlled by the temperature controller. If the inside temperature of the vessel is measured lower than the set temperature value, by the mean of resistances the temperature is increased until the desired set value is reached. After the set temperature is reached, the temperature control unit goes on working to keep the temperature level at this specific value.

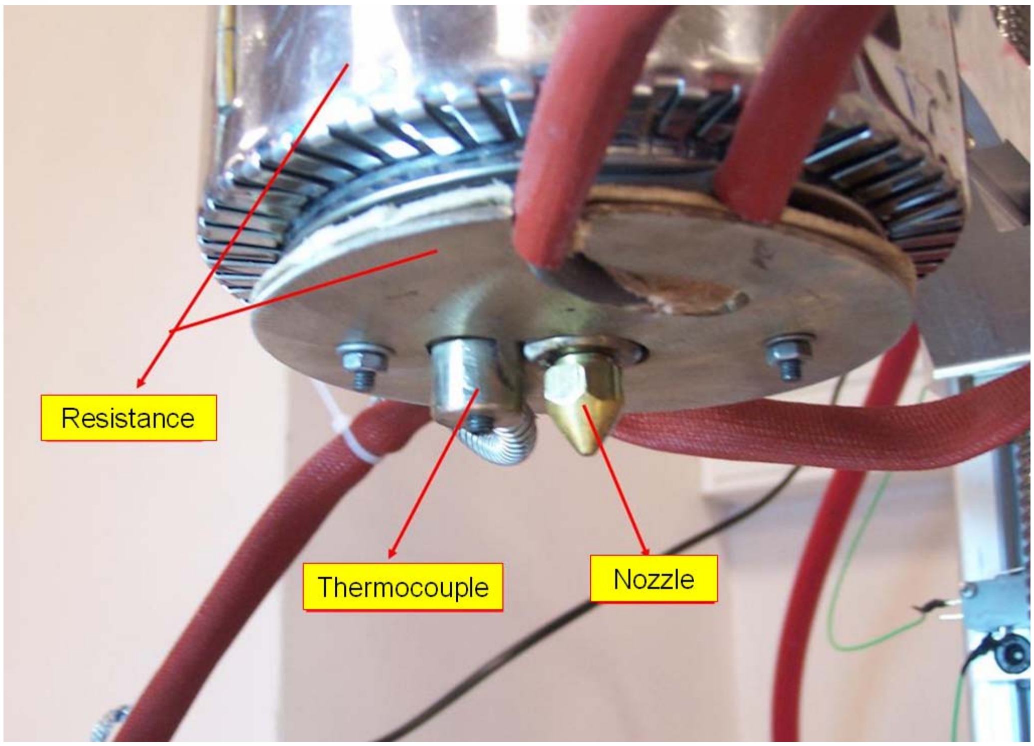


Figure 3. 8: The components at the outer bottom surface of the pressure vessel

After the polymer melts down, the pressure regulator is adjusted according to type of the polymer used, and the pressurized is filled into the vessel. As soon as the pressurized air fills into the vessel, the melted material runs out from the nozzle. In Table-3.2, some of the materials used in tests, and corresponding melting points and pressure levels that are needed to stream the molten material from the nozzle are given. At that instance, the system is driven and the tip of the nozzle begins to follow a path. Consequently, the material is deposited onto surface at a specific pattern to form the desired part.

Table 3. 2: Some of used materials, and corresponding process temperatures and nozzle pressures

Material	**Process Temperature (°C)**	**Nozzle Pressure (Bar)**
SLM TPSE 140 (Wacker)	170	2-2.5
%5 SLM TPSE 140 + %95 ABS	212	2
%8 SLM TPSE 140 + %92 ABS	220	2.3
105.45 E (Neotek Kimya)	215	1-1.5
105.43 (Neotek Kimya)	212	1
PP (Polypropylene)	180	2
%80 ABS + %20 PP	215	2

Some sections of the part which is going to be produced may be empty. That is, the part may have hollow sections. In this case, material flow should be stopped when these empty sections are reached while the path is followed. A subsystem is designed to stop the flow of the material when needed. This subsystem is attached on the nozzle (Figure-3.9), and the system is composed of a small blade which is driven by a pneumatic mechanism.

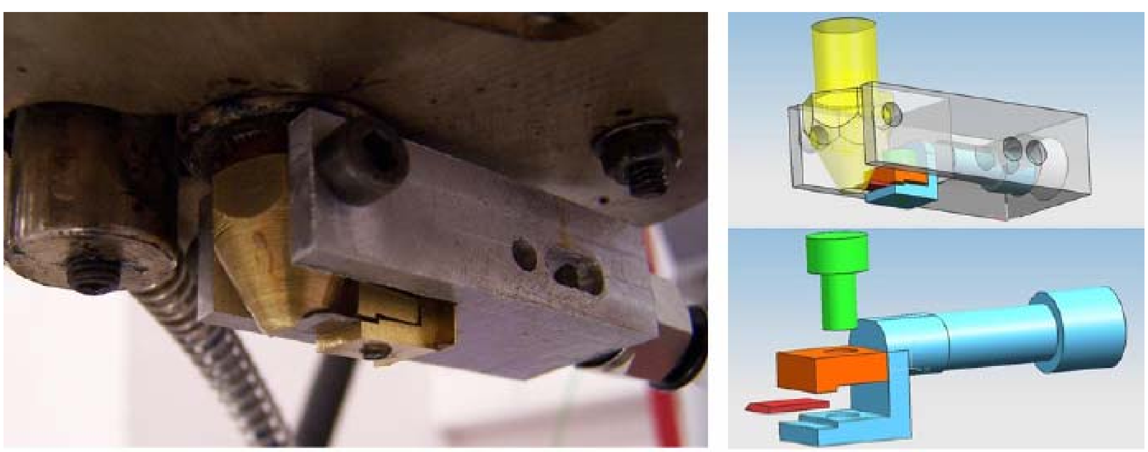


Figure 3. 9: Location of the designed and manufactured subsystem on the nozzle, and CAD files of the system used in manufacturing

Although this deposition system, design A, satisfies most of the design criteria, it has four main problems. The first one is that the temperature control must be very precise during the melting of the material and the production process, because the degradation temperature and the processing temperatures of the materials are very close to each other. Thus, a small increase in the temperature during the process results in degradation of the material chemically, and al of the material in the vessel becomes useless. The pressurized air fed into the vessel can also cause temperature changes in the vessel, and sometimes sudden decreases in temperature occur because of this reason. Since the temperature of the material is affected from these variations, properties of the flowing material changes and the process is negatively affected. Even sometimes, the flow stops when the temperature of the material at the tip of the nozzle decreases below the melting point.

The second main problem is about the stopping of the material flow. Even though the designed pneumatic subsystem works well and stops the flow, the melted polymer sometimes sticks on the blade. Thus, solidified material accumulates at the tip of the nozzle, and this situation affects the flow quality. It is hard to stop the flow because at the mentioned processing temperatures, the polymers yield excessively.

The third problem is the cleaning of the system. Thermoplastics stick on inner surfaces of the vessel, and these waste materials must be cleaned before the next production process. The cleaning process is hard and time consuming. Because of this reason, this system is not practical and does not allow serial productions. The last one is a health problem. If the polymers are burnt, they release carcinogenic smokes.

Two of the parts produced by using this deposition system design are shown in Figure-3.10.

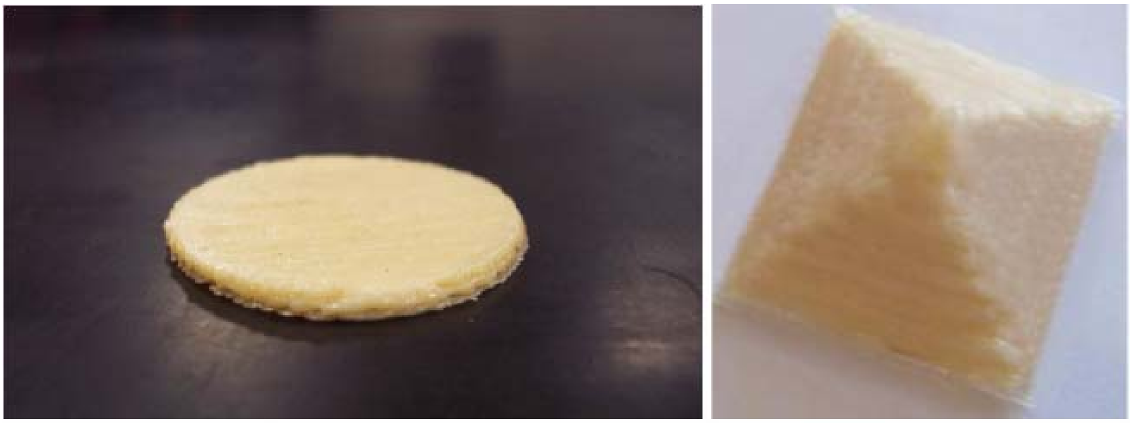


Figure 3. 10: A 4-layer cylindrical part and a square based pyramid

3.1.2.2 Design B

In this design, silicone sticks are used as production material. These silicone sticks are melt down about 70 C and are used as adhesive or sealant materials by means of hot glue guns which are also known as hot melt stick guns (Figure-3.11).

Figure 3. 11: Silicone sticks and a hot glue gun

Basically, deposition system Design B is composed of two subsystems (Figure-3.12 a). The first subsystem is melting unit, and for this subsystem, standard melting mechanism of the hot glue gun is used as it is. The second subsystem is composed of a DC motor and an extrusion screw attached to the motor with a coupling. This extrusion subsystem pulls silicone sticks placed inside the deposition system and feed them into the melting unit of the deposition system. Whole system is carried by a two-piece plexiglas casing which was manufactured in MARC by using CNC vertical machining center.

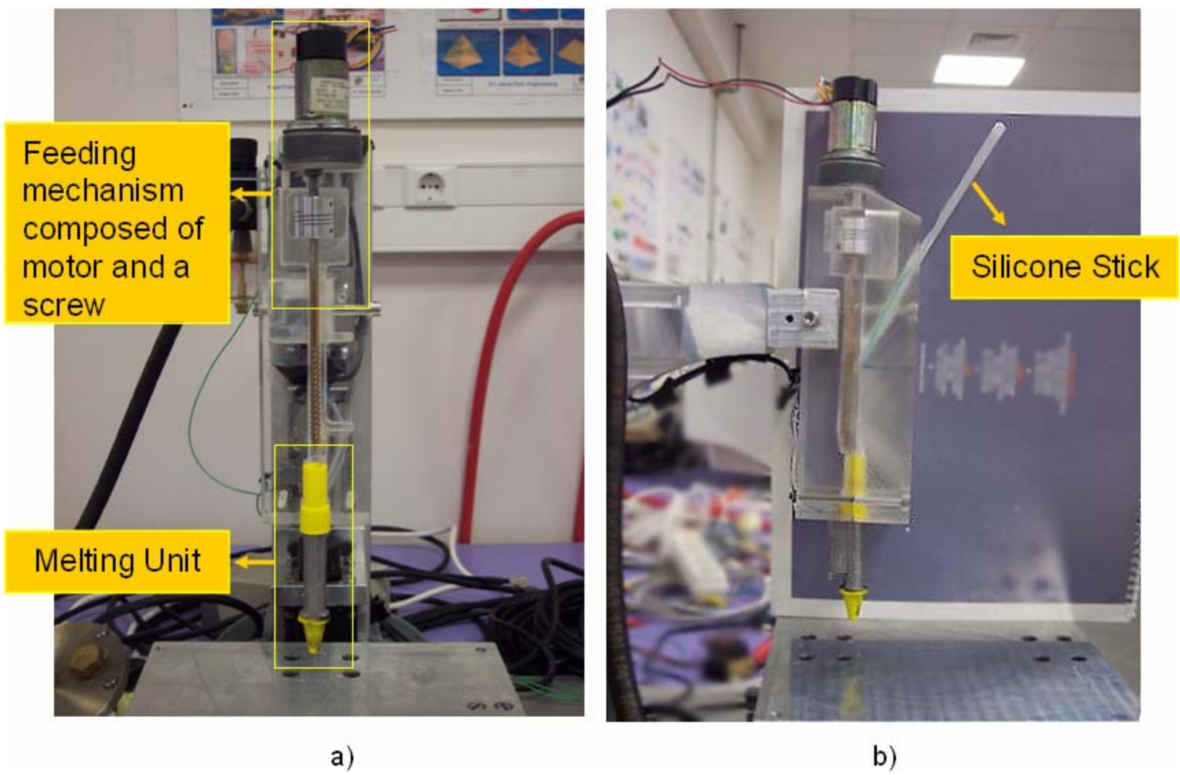


Figure 3. 12: a) Subsystems of the Design B, b) Side view from the system and feeding of the production material

As seen in Figure-3.12 b, a silicone stick is manually fed in to the system from the front part of the casing of the system. Once the silicone stick get in contact with teeth of the screw, it begins to move towards the melting unit. After that moment, no manual action is needed. When the silicone stick reaches to the melting unit which is kept always at a constant temperature, it melts down. Melted silicone is pushed out from the nozzle because of the solid section of the silicone just entered in to the melting unit.

Some problems are encountered about the feeding mechanism of this design. Also melting unit does not work at expected efficiency. A continuous flow of melted material is not obtained. Either the continuity of the flow is lost or the viscosity of the melted material is too low and can not preserve its initial form which is an undesired situation.

Because of the problems and difficulties caused from temperature control process, it is focused on materials and designs which will provide production of parts without a heating unit and temperature control action. It is decided that liquid silicones mostly used as sealant in everyday use are one of the most ideal materials to use in next design. They are called polysiloxanes technically. They are sold in special cartridges (Figure-3.13) and very cheap. After these materials get in contact with air, they solidify in very a short time. In addition to that, the material at lower layers can carry the weight of the material on top of them, and they can preserve their form during production. Thus, liquid silicone is a very suitable material for layered manufacturing.

Figure 3. 13: Liquid silicones are sold in cartridges

It is decided to transfer the silicone in to a standard medical syringe, and to use this syringe as a reservoir during the production. It is planned to design a mechanism to push the piston of the syringe, and consequently, to obtain a controlled flow of material from the tip of the syringe.

3.1.2.3 Design C

This deposition system does not include a heating and a temperature control unit as mentioned before. It is designed to allow the use of liquid silicone. In this design, a rack and pinion couple is used (Figure-3.14).

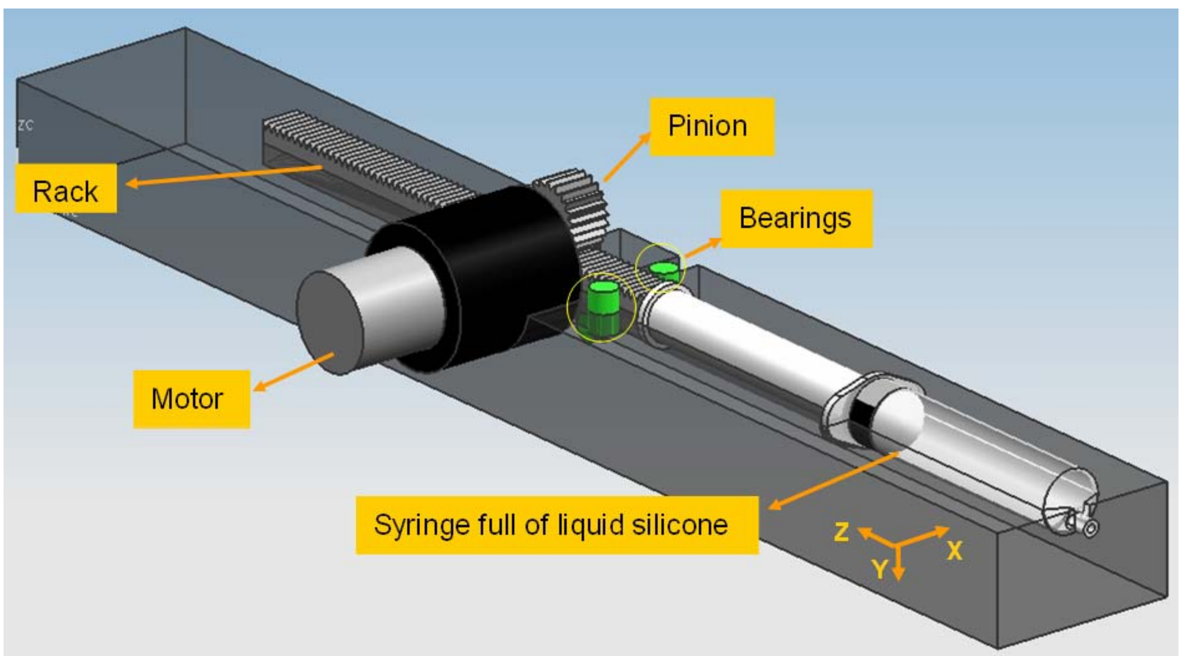


Figure 3. 14: CAD model of the system designed in Unigraphics NX-4 software

The pinion is attached to shaft of a motor, and the rack is supported with four bearings from both sides and bottom to smooth the motion of rack on the plexiglas casing. When the pinion begins to rotate, the motion is transferred to the rack from the teeth of pinion and the rotational motion is converted to translational motion. So, the pinion makes rack slides on the bearings as shown in Figure-3.15. Since the bottom surface of the rack is in contact with the piston of the syringe, it pushes the piston (Figure-3.16). Therefore, the material inside the syringe is squeezed and get out of the tip of the syringe.

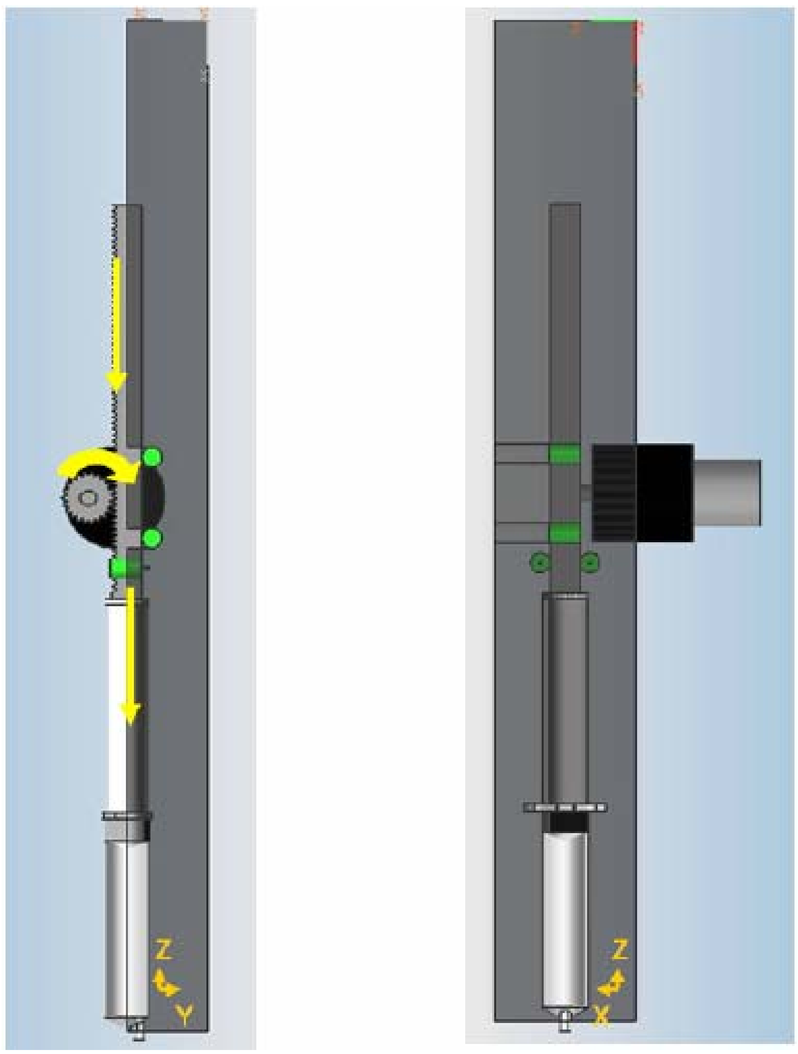


Figure 3. 15: Right and back views of the CAD assembly of the system

In design, module-1 rack and pinion couple is used. Although the module-1 rack and pinion couple is the smallest one in standards, it is too heavy to control properly. Therefore, it is decided to replace this rack and pinion mechanism with another mechanism while keeping the syringe in the system.

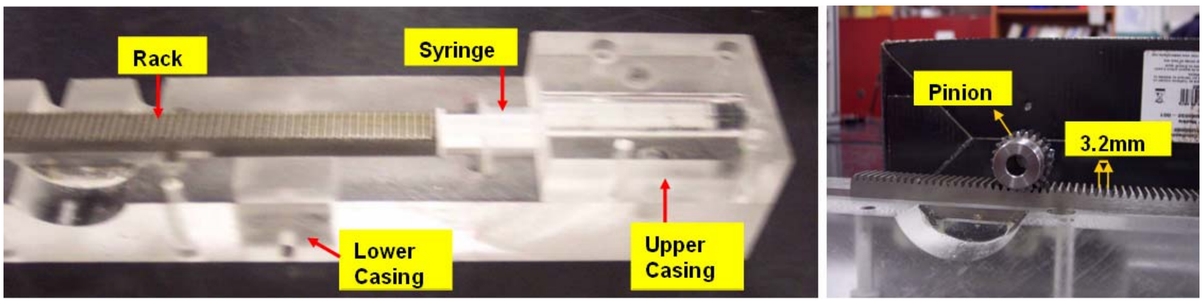


Figure 3. 16: Pictures taken during assembly of the deposition system

3.1.2.4 Design D

This is the last design which is currently in use and this system is shown in Figure-3.17. In this deposition system design, instead of a rack and pinion mechanism, a linear actuator mechanism is designed which performs the same aimed task with the rack and pinion mechanism.

The stepper motor can be driven either by signals sent from PC or signals generated from a signal generator. When the motor is driven, the ball screw attached to it with a coupling begins to rotate. There are two nuts on the ball screw. One is the ball screw mechanism's nut which carries ball bearings in it and the other one is a hexagonal nut. Between them, a plexiglas part is attached which is in direct contact with the piston of the syringe, and pushes it while the system is working. This trinity, two nuts and a plexiglas part between them, can move linearly on the ball screw freely (Figure-3.18). But under normal conditions, they move along the ball screw by making a rotational motion. This is not desired for designed deposition system. A grove in the exact form of the hexagonal nut is created on the casing of the system. Because the nut is fitted in to that grove, it can not rotate (Figure-3.19). Consequently, it moves linearly along the ball screw according to the rotational direction of the stepper motor without revolving around itself.

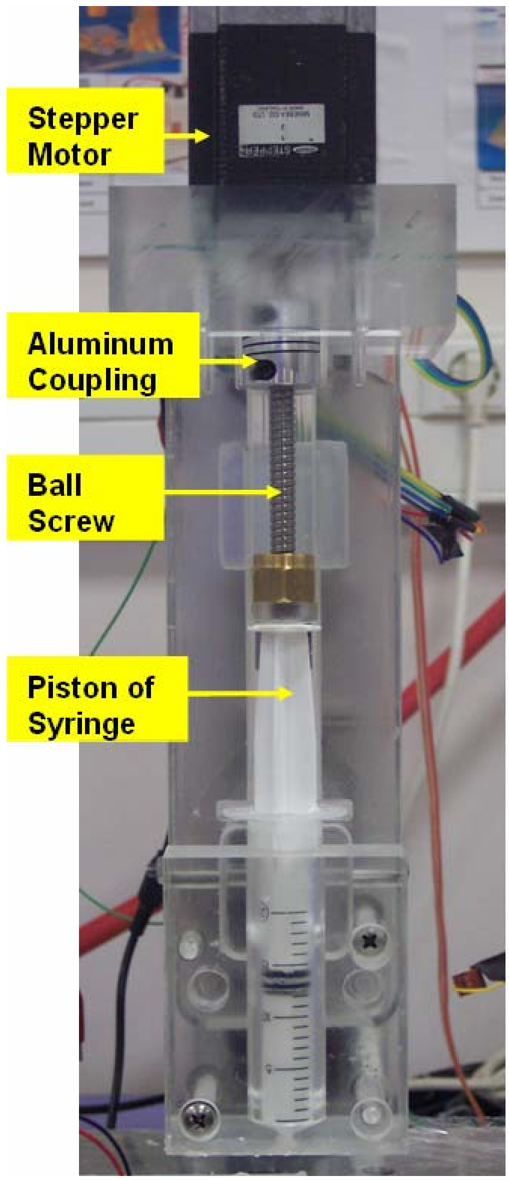


Figure 3. 17: Some of the components of the Design D

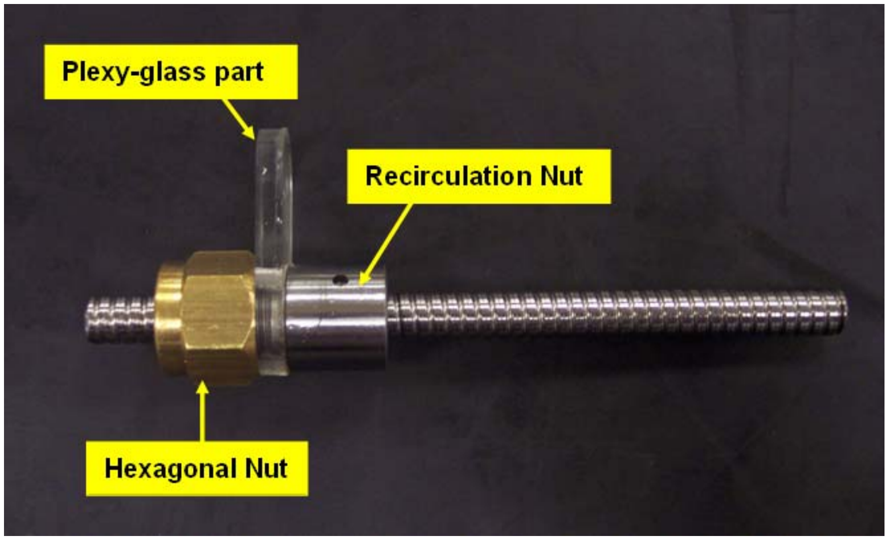


Figure 3. 18: A plexiglas part is placed between hexagonal and recirculation nuts

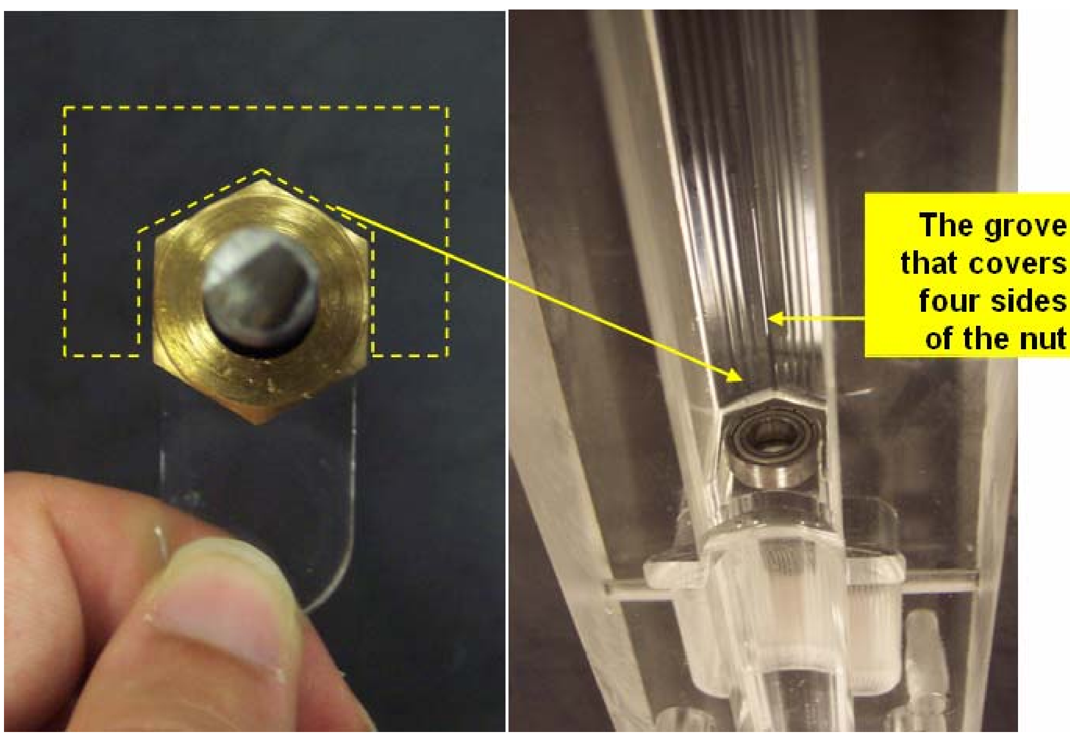


Figure 3. 19: The hexagonal nut is fitted into a grove in the same form

When the system is on, the nuts and the plexiglas part is moves downward along the screw and plexiglas part pushes the piston of the syringe and material is come out of the tip of the syringe (Figure-3.20). The flow of the production material is controlled by adjusting the signal frequency sent to the stepper motor. If the rotation speed of the motor is increased, the flow of the material is increased too. For the sake of sustainability and to create a standard for this deposition system, it is designed based on the dimensions of a specific syringe. Hayat Syringe Company's three part syringe of 20 ml is used in the system. A syringe can be replaced with a new one by simply removing the upper casing (Figure-3.20).

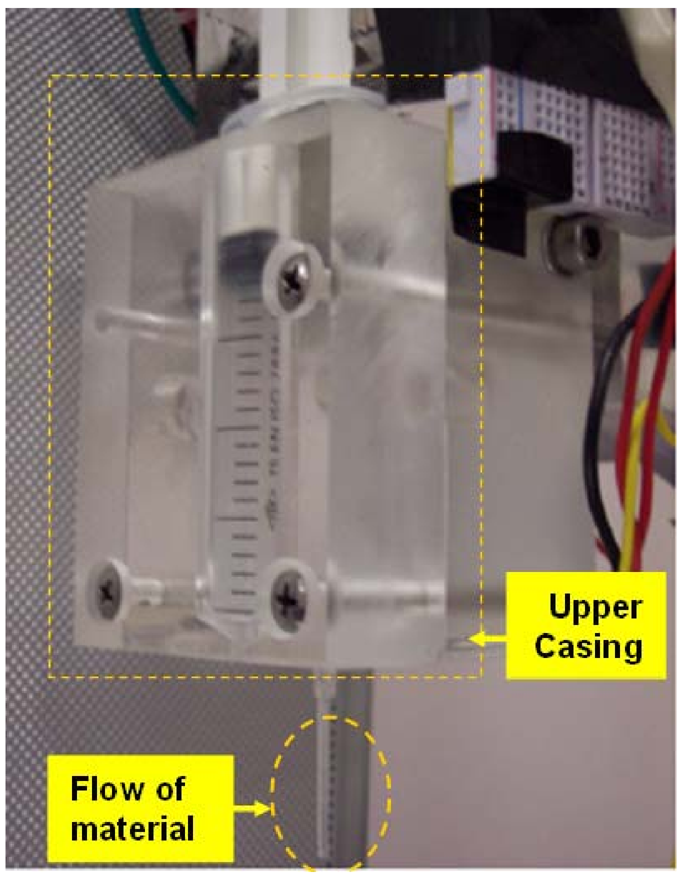


Figure 3. 20: Upper casing should be removed to replace the syringe

Silicone can be kept in the syringe for three days without losing its properties. After the third day, viscosity of the silicone begins to increase gradually, but still the left material can be used for almost one week. Then it solidifies. The life of a syringe is approximately two weeks. After that period, gasket of the syringe is deformed and could not be used.

Tip diameter of the syringe is 1.9mm (Figure-3.22). This dimension determines the thickness of the layers of produced part. If a better surface quality is desired, needle of the syringe can be plugged on the tip, and the layer thickness can be decreased to 0.6mm (Figure-3.21 & Figure-3.23). The needle must be shortened to use on the system. By plugging needle of different diameters or producing nozzles of different diameters which can be plugged on the tip of the syringe, the layer thickness can be varied.

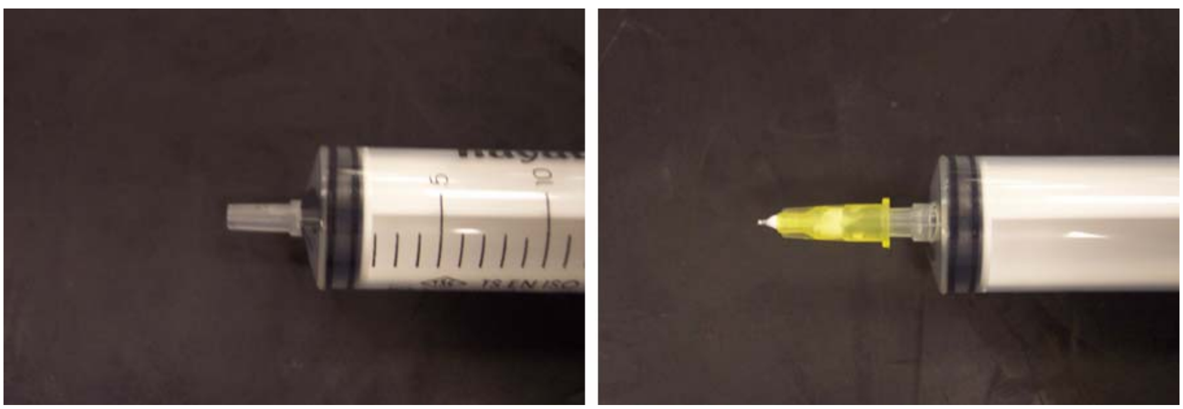


Figure 3. 21: The diameter of the flowing material can be decreased by plugging needle of different sizes on the tip of the syringe

There are several advantages of using silicone as production material. Most important one is that silicone can be easily provided and easy to use. Also, it has a lower price compared to the price of materials which are commercially used in the market. Since heat treatment or melting of the material is not needed during or before the production process, the deposition system is not very complex. Moreover, material and surface quality of the produced part are always same. In the deposition system such as the Design A, the material should be melted and kept in a specific temperature, and if a fluctuation occurs at the temperature, the material properties and surface quality of the produced part can be affected and changed. One more advantage of silicone is that it is not inimical to health.

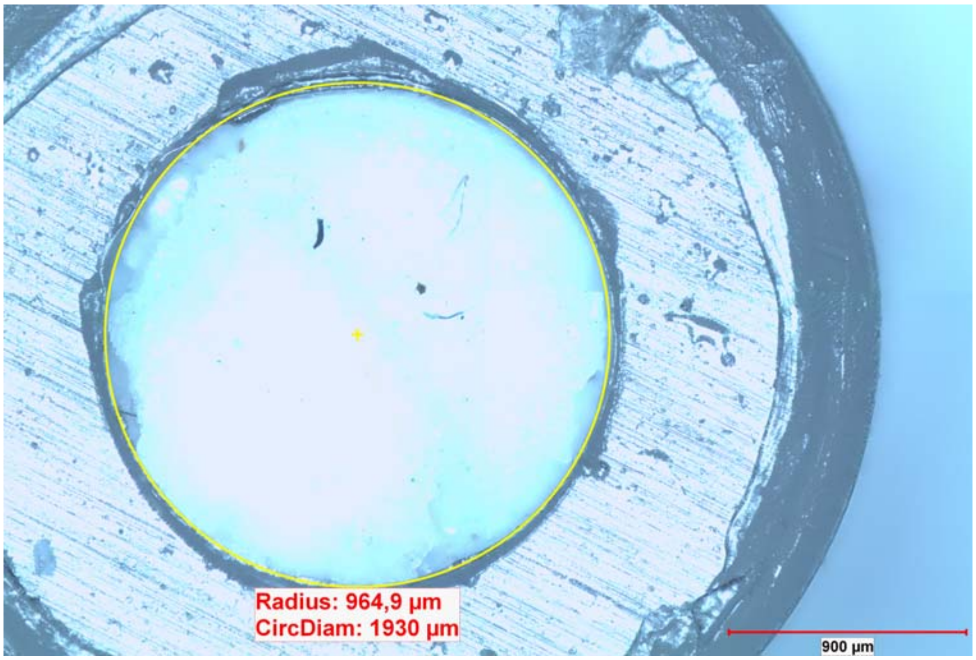


Figure 3. 22: Inner diameter of the tip of the syringe is measured as 0.19 mm with Nikon Eclipse 3x2 stage microscope

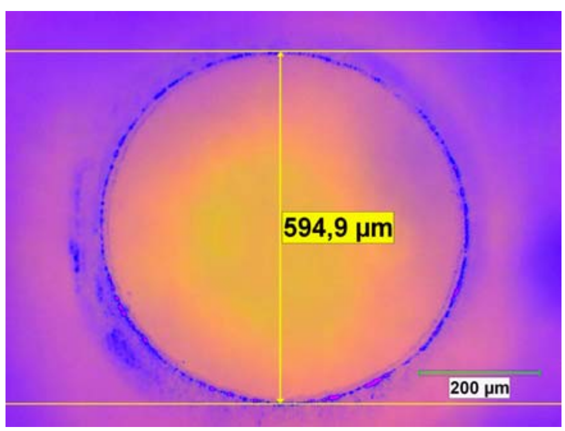


Figure 3. 23: Inner diameter of the needle is measured as 0.6 mm with Nikon Eclipse 3x2 stage microscope

It is very important that the lower layers of the part can carry the weight of the upper layers during the production. It is observed that the silicone can carry the load results from material deposited during the production of upper layers, and the lower layers do not deformed. Technical properties of the silicone material which is used in the tests are given in the Table-3.5. As in the case of syringe, always the silicone from a specific company is used (Figure-3.13).

Table 3. 3: Technical data of the silicone used in this study

Density	0,97 g/ml
Working Temperature	-5°C & 40°C
Temperature Resistance	-50°C & 250°C
Vulcanization Speed	15-20 minutes (23°C at 50% R.H.)
Curing Speed	1,5 mm/day (23°C at 50% R.H.)
Losing Volume	5,5%
Shore A Hardneww	20 (ISO 868)
Steady Elasticity	25% (DIN 52451)
Elongation at Break	400%
Power of Breaking Potential	2,3 MPa
Maximum Joint Measures	30 mm
Heat Insulation Quality	0,17 W/km (DIN 53612)
Elasticity	200% (ISO 8339)

Besides the advantages of this material, there are also minor disadvantages. First, silicone does not solidify immediately. Its vulcanization speed is 15-20 minutes, and only after about 30 minutes the produced part can be handled and removed from the production platform. Although slow vulcanization speed is a disadvantage, in some cases this disadvantage can be beneficial. The flow of the silicone can be increased by increasing the driving frequency of the stepper motor that drives the deposition system. As the rotational speed of the stepper motors increases, the flow of the silicone also increases. Since the silicone does not solidify immediately and the translational speed of the machine is constant in all directions (75 mm/min), width of the produced silicone lines can be changed by controlling the driving frequency of the stepper motor.

Ideal working frequencies are found as 500 mHz and 2.5 Hz for 0.6 mm and 1.9 mm tip diameters respectively. With these frequencies, hatch lines with approximately 1 mm and 2.2 mm diameters are obtained from 0.6 mm and 1.9 mm tip diameters respectively.

In addition, silicone can not preserve its initial circular geometry perfectly as it comes out of the tip of the syringe. When it touches the surface, it spreads a little bit since it does not solidify immediately. Its circular cross section becomes ellipsoidal as shown in Figure-3.24.

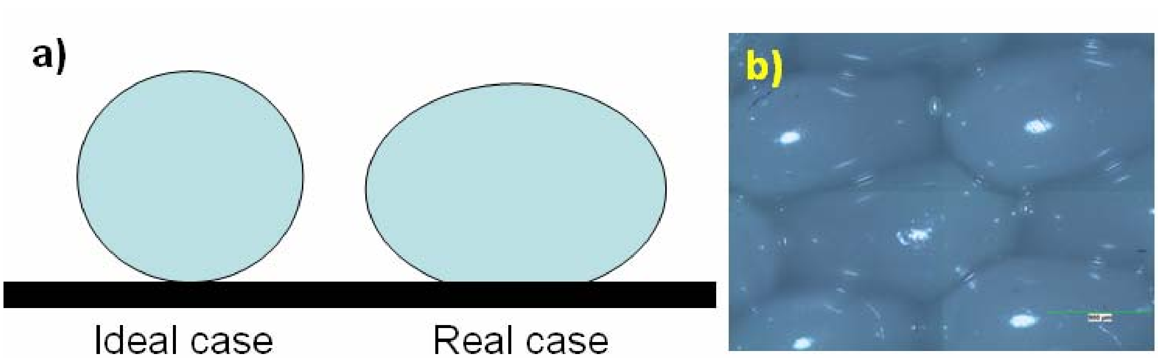


Figure 3. 24: a) Silicone rod loses its circular form and spreads on the surface and obtains an ellipsoidal cross section; b) a picture taken from a side of a produced part with Nikon Eclipse 3x2 stage microscope

Another measurement about the spreading of the material can be seen in Figure-3.25. In this figure it is obvious that the bottom face of the deposited material is wider than the top face.

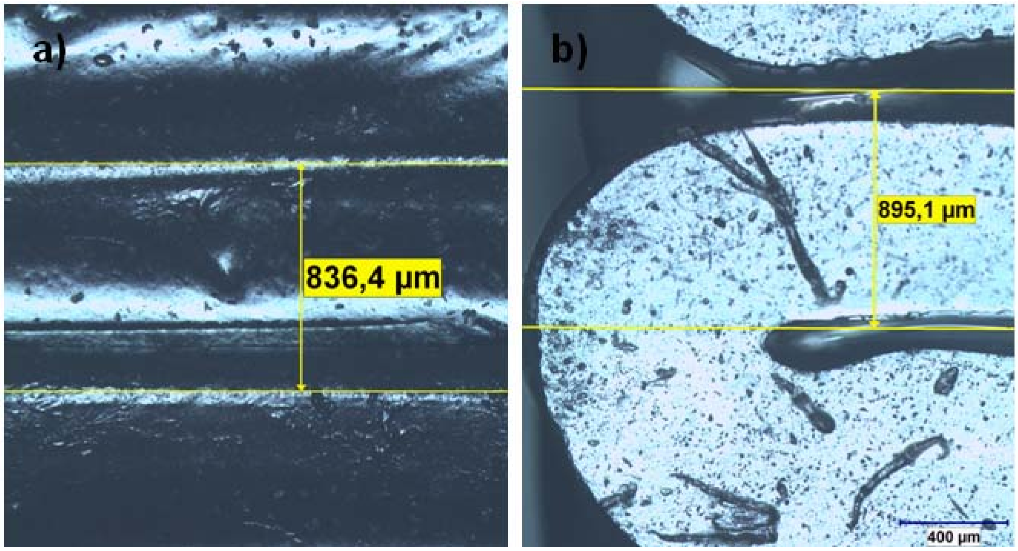


Figure 3. 25: a) Top face of a produced part; b) bottom face of the same part

Silicone is an elastic material, so produced part has some elasticity. But eventually after the applied load on the part is released, it turns back to its initial form. If it is desired that the produced part do not deform when a load is applied, its surface can be covered with another material to prevent its deformation. For just demonstration and validation of this proposal, two different materials were tested. These were Polia Poliester Company's Polipol 336 RTM type polyester resin and Polijel F-213 brush type gelcoat. Polipol 336 RTM type polyester resin did not make too much difference. However, for the part that was coated with Polijel F-213 brush type gelcoat, the deformation percentage was decreased in the case of a loading. Technical data of Polijel F-213 gelcoat is given in Table-3.4. Red one of the triangular prisms shown in Figure-3.26 is coated with gelcoat. Red color was added into the coating to make the differentiation possible.

Figure 3. 26: Two triangular prisms with and without coating

Covering a part with a secondary material after the production is technique that has several examples in the market. Products of some of the commercial RP machines have to be covered with materials to increase the strength. For example, the parts produced by using the RP machines of Z Corporation, which are called ZPrinters, have to be covered with resins that have similar function like the resin used in this study.

3.1.3 Tested and Used Materials

From the beginning of this study, a wide range of materials have been able to be tested to obtain the best result. Developed system has allowed so many materials to be used, because it is an open architecture system that has allowed different deposition systems to be tested. Some of the materials have been used so far is explained in the foregoing sections in which different deposition system designs are introduced. In this section, unsaid materials are explained.

It has to be well understood that the main purpose of this project is to develop an open architecture RP system in Manufacturing and Automation Research Center (MARC) of Koç University. Scope of the project includes developing all software and hardware of the system. Since production material development is not in the scope of this project, known materials have been tested and used in the development progress of the system.

At the first phase of the project, thermo plastic materials were experienced, because first design of the deposition system which is Design A is very similar to FDM method, and currently thermo plastics are used in the commercial FDM RP machines in the market. Some of the tested materials are given in Table-3.2. The most important material among the all tested ones is acrylonitrile butadiene styrene which is shortly known as ABS; because it is the most commonly used and preferred production material for FDM machines in the market. Stratasys Corporation that introduced the first FDM machine to the market uses ABS. ABS is preferred because of its strength and light weight. In this study, ABS in granule form was used. It is also mixed with other thermo plastics for different percentages (Table-3.2). At temperatures between 210 and 220 °C ABS reaches to its most suitable viscosity to be usable in Design A. Temperature values vary between 210 and 220 °C because of the other mixed materials in to the ABS. This temperature interval is very close to the degradation temperature of the materials, and this condition causes some problems in the temperature control process. In Design A, because the flow of the molten material is driven by pressurized air, sudden changes of may occur at internal temperature of the reservoir. Even the temperature increases a few centigrade degrees, the material can degrade and process is discontinued. Another disadvantage is that the upper surface of the material in the reservoir lost its chemical properties in a very short time because of the pressurized air in the reservoir (Figure-3.27). Therefore, all of the material put into the reservoir can not be used and the material close to the upper surface is wasted.

Figure 3. 27: Samples of materials that could not be used as they lost their chemical properties

Waste thermoplastics sticks on to the interior walls of the reservoir. It is very hard and time consuming to clean this waste material. For cleaning, a chemical called THF is had to be used, and respiration of the vapor of this chemical is harmful for health. Moreover, at high temperatures, some of thermoplastics release harmful gases. Because of all the foregoing listed disadvantages, another system was designed which is Design B. It is mentioned that silicone sticks are used in this design. But before the silicone sticks, injection wax and paraffin was tested which are injurious to health (Figure-3.28). Silicone sticks, wax and paraffin are very easy to use and clean, and melt down at low temperatures (60-70 °C).

Figure 3. 28: Injection wax (left) and paraffin (right) were also tested in Design B besides the silicone

Melted silicone, wax and paraffin have very low viscosities, so they could not preserve their forms when deposited on a surface. That is why they are not used.

While working with known materials, some trials were also done to create layers by applying glue on a surface of powdered materials (Figure-3.29). Starch was selected as material. Because, it is known that in some of the 3D printers it is used as a production material. The desired surface quality and material integration was not obtained. As a result, these experiments were stopped.

Figure 3. 29: a) Different types of glue tested with starch, b) formed layers after the solidification of the glue

Temperature control system increases the complexity of the whole system and it is very hard to deal with molten materials. Therefore, it is decided to design a deposition system which does not include a melting and temperature control subsystem. That is how Design C and Design D deposition systems are manufactured. Currently, silicone, a kind of thermoset polymer, is used as production material. It is a room temperature vulcanizing (RTV) material used as household sealant and is based polysiloxane. Its main advantage is that it is found easily, very cheap, and not harmful to health. It, also, is easily dispensed from the tip of the syringe. It has high temperature resistance (-50°C and 250°C). With the mechanism explained in section “3.1.2.4 Design D”, it is managed to deposit silicone from the tip of a syringe successfully. Silicone is a very elastic material, and if the produced part is wanted to be rigid, it can be covered with materials mentioned is Section 3.1.2.4.

Any pre- or post-process is not needed. The material is filled in to the syringe and can be used directly. After the production process, the produced part vulcanizes in a time period between 15 and 20 minutes depending on the size of the part, and it is fully cured in one day. The resultant part is elastic. Since the curing does not occur immediately, during the production, some supporting materials, such as wires, can be embedded into the part.

A wide variety of materials such as thermoplastic polymers, hydrogels and pastes which are initially in liquid, semi-liquid, gel form or soft enough to squeeze can be used in this system as production material. In this study, beside the silicone, chocolate and polymer clay have been used as production material, and it is demonstrated that the current deposition system is also capable of producing parts with these materials.

3.2 SOFTWARE

The main purpose of RP technology is to produce the prototype of a newly designed product as fast as possible and check its validity before the mass production, such as checking the dimensions of the part and controlling whether the part fits with other parts or not. Every RP application begins with modeling a part in a computer aided design (CAD) environment. In this study, Unigraphics® NX CAD/CAM program has been used to create CAD models. Three different algorithms have been developed to run this newly developed RP system. MATLAB program has been used to write and run the programs, and to send the created pulses to the system. Algorithms have been written as m-files. All of the algorithms have different capabilities.

First algorithm which is the primal one requires a Stereolithography (STL) file. By using this STL file, algorithm creates the path that the deposition head of the machine follows. Second program requires a Cutter Location Source File (CLSF) as input. This file is obtained from the manufacturing module of the Unigraphics NX-4 program and includes the path that cutter of Computer Numerically Controlled (CNC) milling machine follows while machining a part. Third program requires operator input. The operator enters X, Y and Z coordinates of nodes that are on the desired path. That is, this algorithm lets the operator to create his/her own path and make the machine follow this path. The mentioned algorithms are explained in detail in next sections.

3.2.1 Algorithm 1

In first algorithm, STL based slicing is applied. As it is well known, STL file format which was developed and published by 3D Systems Company to use in its RP system Stereolithography Apparatus (SLA), was found acceptance as de facto standard file format in RP industry. The CAD model is converted to STL file format in which the 3D model is meshed with triangles sharing common sides and vertices. This process is called tessellation. The 3D model is not defined as a solid object but a closed surface like a shell without thickness. STL file format is explained in detail in Section-2.3.2.1. Almost all of the CAD programs are capable of producing an STL file. For this study, Unigraphics NX-4 CAD program has been being used. But other well known CAD programs such as ProEngineer, SolidWorks, AutoCad (Versions R14-2000i), Mechanical Desktop can also be used to design a 3D model and to produce the STL file of this model.

There is one important thing that has to be considered. In engineering CAD programs, designed parts are positioned based on X-Y-Z coordinate system. For the developed algorithms within the context of this study, base of the designed part must be placed on X-Y plane and it must be heighten along +Z direction.

After the model is designed by taking into account the warning mentioned above, the part is converted to STL file format (Figure-3.30). The surfaces of the model are defined by using adjacent triangles. For this surface definition, the corner coordinates and the normal vectors of these triangles are used. These normal vectors are directed from the surfaces through the outside of the triangle. The directions of these normal vectors are determined according to the right-hand-rule. Below, there is an example expression for one of the triangles which define the surface of the model in STL format:

```
facet normal +0.0000000E+00 -1.0000000E-00 +0.0000000E+00
       outer loop
              vertex   +1.0407910E+01 -6.8891950E+00 +2.5000000E+01
              vertex   -3.5920898E+00 -6.8891950E+00 +2.5000000E+01
              vertex   -3.5920898E+00 -6.8891950E+00 +0.0000000E+00
       endloop
endfacet
```

In the first row which begins with “facet normal”, the normal vector of the triangle is defined. On the rows which begin with the word “vertex”, the corner coordinates of the triangle are given which are ordered based on the right-hand-rule.

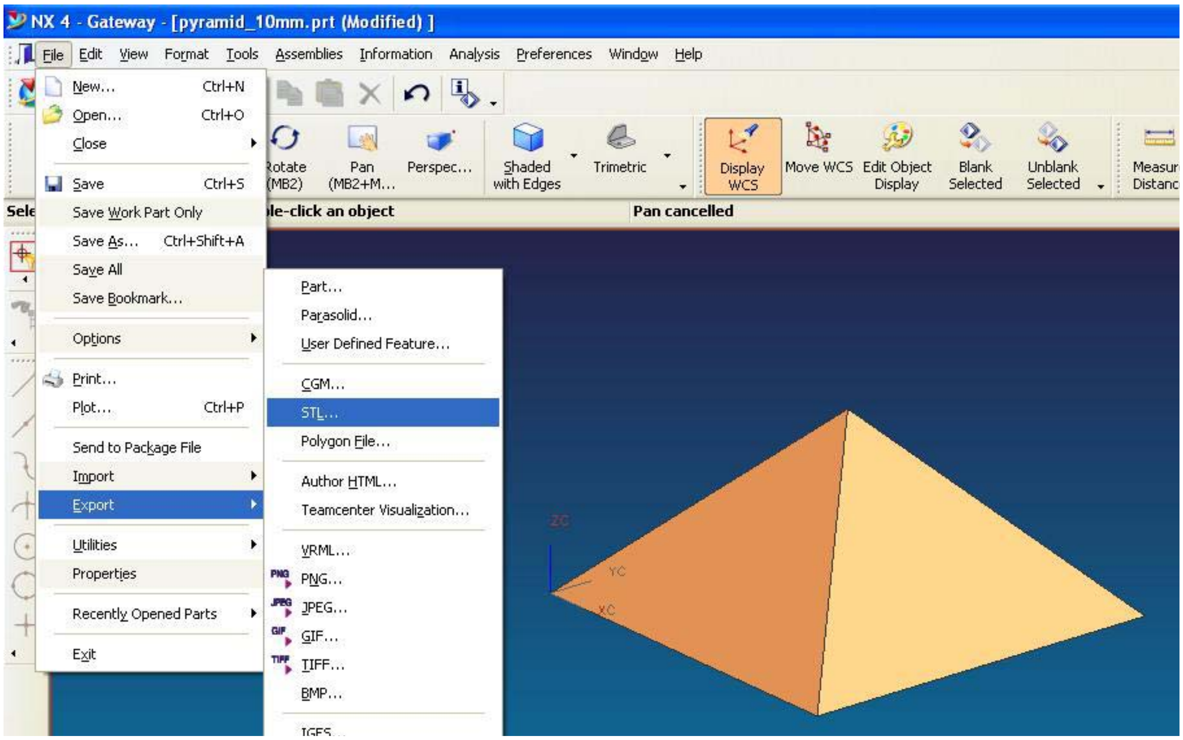


Figure 3. 30: Prepared model is exported in STL format

As can be understood easily, the models which does not have curved surfaces or the ones whose side surfaces are triangles, squares or rectangles can be more easily converted to the STL file format and resultant files are not very big in size. For instance, six of the foregoing triangle expressions are sufficient to define a pyramid with square base (4 of them for the side surfaces and 2 of them for the base). But, tens of triangles are needed to define sphere.

After the 3D model is exported as STL file format, the words of "facet normal", "outer loop", "vertex", "endloop" and "endfacet" are erased from the STL file. By this way, the file is converted to new format of which column number is always three but the number of the rows can increase according to the complexity of the model.

STL file which is cleaned from the words is loaded in to the MATLAB program. Two inputs must be entered in to the program. The first one is the layer thickness which is, at the same time, the hatch distance between two consecutive vectors on the layers. That is, the distance between two adjacent lines which are created by the deposition system while producing a layer of the prototype (Figure 3.31), and the other one is the STL file name which is going to be processed by the program, i.e., “cube.txt”.

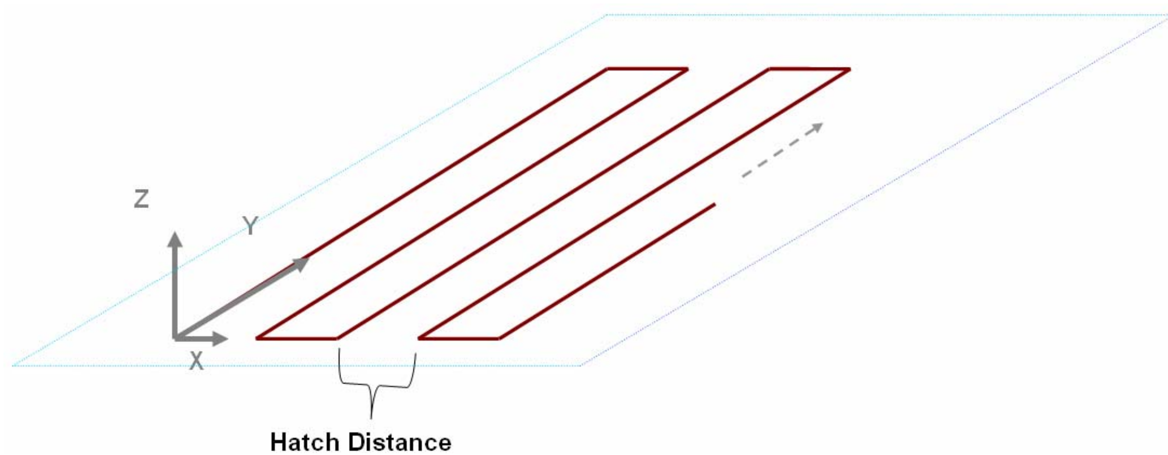


Figure 3. 31: The hatch distance between two consecutive lines

The kinematic accuracy of the produced machine is 5µm. That is, the minimum available hatch distance or the layer thickness can be 5µm. Smaller the layer thickness, smoother the surface obtained. As the layer thickness value is increased, the step wise structure gets more distinct. As the result of this situation, the appearance of the prototype can be bad or if the model is a small one, some details can be lost.

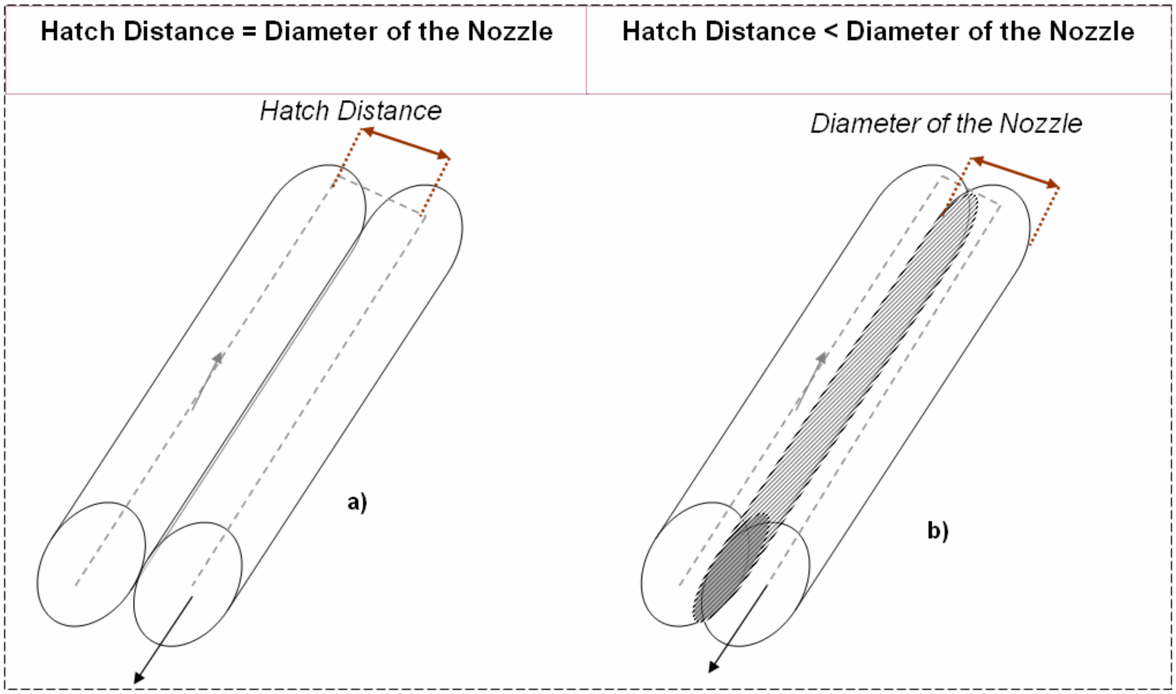


Figure 3. 32: The hatch distance must be equal or greater than the diameter of the nozzle

The determining factor for the hatch distance and the layer thickness is the resolution of the deposition sub-system which depends on diameter of deposition system's nozzle. Both the layer thickness and the hatch distances can not be smaller than the diameter value of the deposition nozzle. Otherwise, during the production, when the deposition of material is passed to the next line, the new material is deposited on to the previously deposited hatch line. Therefore, formations of the previously created hatch lines and the layers can be deformed. This situation is shown in Figure-3.32. The relation between the hatch distance and the diameter of the deposition head, and the effect of this relationship on the hatch lines can be seen figuratively.

As a result, the hatch distance and the layer thickness values should not be chosen smaller than the deposition nozzle diameter. In the situation where the hatch distance or layer thickness is chosen too much greater than the nozzle diameter size, there can be big vacancies between the hatch lines and the consecutive layers. This situation is also not desired.

After the layer thickness value (hatch distance) and the name of the STL file is entered in the program, it is run. First, the algorithm determines the workspace by finding maximum and minimum coordinates of the model in each +X, –X, +Y, –Y, +Z and –Z directions (Figure-3.33 a). According to the layer thickness value entered to the program as an input by the operator, virtual planes are created along the +Z direction. That is, the distance between each plane is equal to the layer thickness and this thickness value depends on the tip diameter of the dispensing system. Areas of the planes are same and calculated by using the extreme coordinate values found in the previous step. By using the intersection points of the created planes and the surface of the model defined by the triangles, the boundaries of layers are determined. Virtual vectors are created along Y-axis on each layer. Coordinates of the cross section points of these vectors and the boundary of the corresponding layer give the necessary nodes for path creation. Algorithm creates a zig-zag path by joining these nodes with lines. This is one of the disadvantages of this algorithm: it can only create zig-zag paths. But the accuracy of the created part is very good.

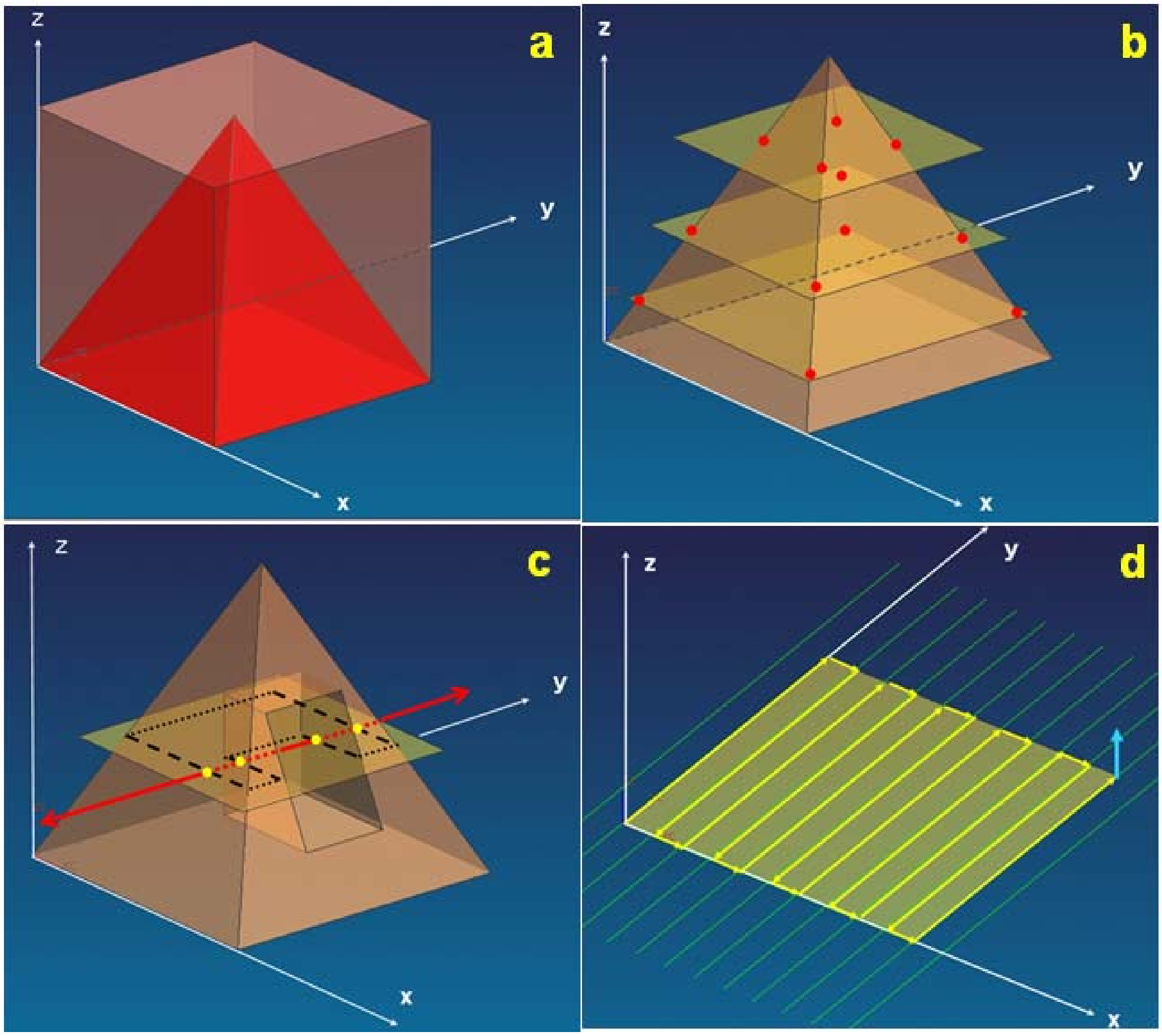


Figure 3. 33: a) workspace is determined, b) virtual planes are created, and cross sections of these planes and the model is found, c) by combining the cross section points, outer boundary of each layer is created, d) by crossing vectors along Y axis for each layer, the necessary nodes for path creation are found.

Since the lengths of the lines are known and it is known that the distance traveled in all axis for one pulse is equal to 50µm, the required number of pulses is easily calculated for each line segment by simply dividing the line lengths to 50µm (Figure-3.34). The algorithm creates five arrays for each direction; +X, –X, +Y, –Y, +Z and. Since the motion in Z-axis is always in +Z direction, there is no need for an extra array to keep the information about +Z direction. After the material is deposited for current layer, the machine always moves in +Z direction for the next layer. For each pulse, one couple of "1-0" is placed in corresponding arrays. Consequently, all line segments in the path are composed and the arrays are filled. The process of sending these arrays to the system is explained in Section-3.3.1.

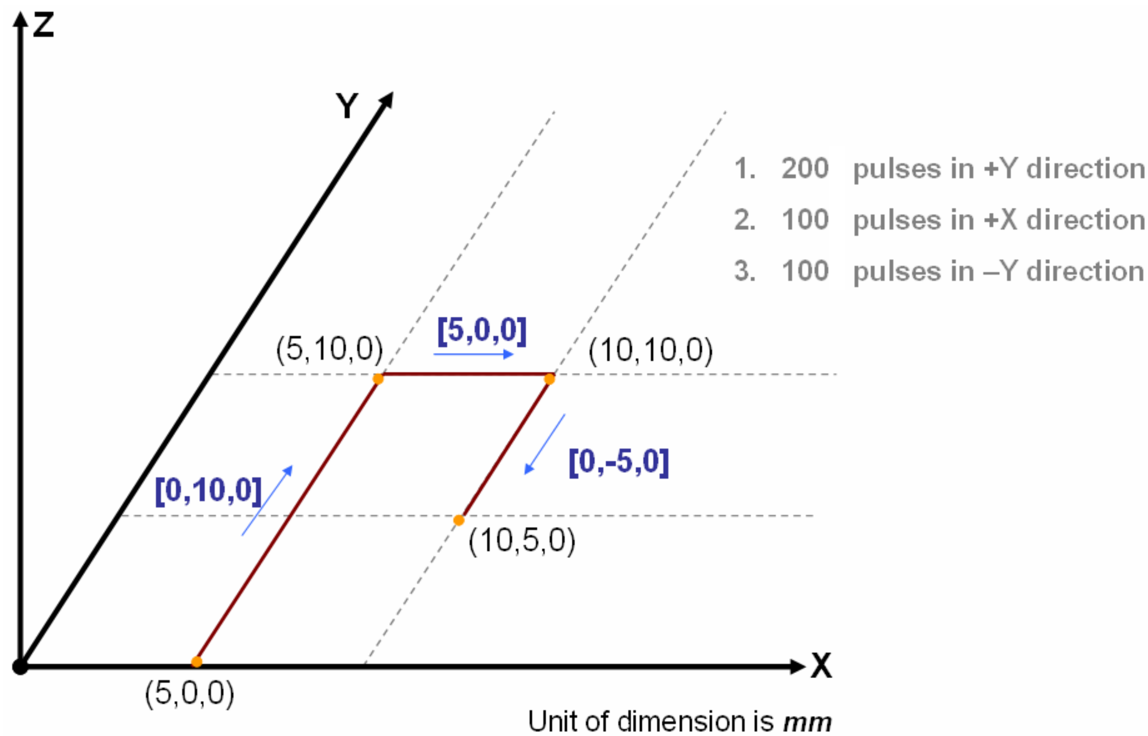


Figure 3. 34: The necessary number of pulses is calculated for each line segment and by combining the pulses final five arrays are composed

A summary of how this STL based algorithm works is given in Figure-3.35. At first a part is designed in a CAD program (Figure-3.35 a). Then, this part is converted into STL file format, and after some changes are applied on this file it is loaded in to the algorithm. Algorithm performs the slicing operation and generates a zig-zag path for each layer

(Figure-3.35 b and c). The information of this path is saved as pulse data into 5-arrayed matrix. When these data is sent to the servo drivers of the machine, it produces the desired part (Figure-3.35 d).

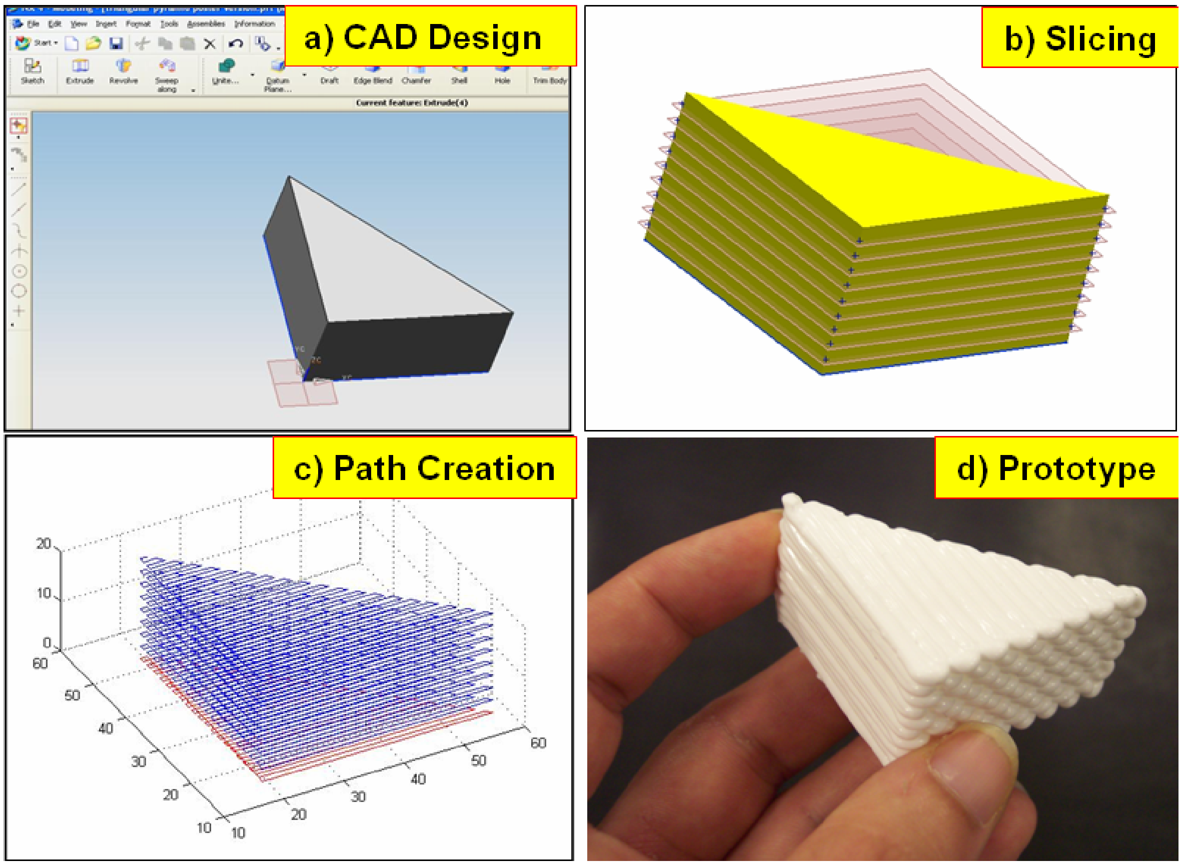


Figure 3. 35: Summary of part production by using STL based algorithm

3.2.2. Algorithm 2

Second algorithm is a kind of direct slicing algorithm because the CAD model data is not converted to another file format such as STL file format. Algorithm uses a cutter location source file (CLSF) as input. The idea of using CLS file to create a tool path for an RP machine is a novel idea. CLSFs are the files that contain information about the milling process for CNC machines; such as, coordinates of the nodes that the cutter visits during machining, machining conditions like feed rate, or information about the motion of the cutter like whether it is linear or circular. RP is a layered manufacturing process and so does CNC milling. Both operations are performed layer-by-layer. In milling process, a cutter follows a path to clean the whole layer just like creating a layer in RP process. A milling operation can be classified as layer-by-layer subtractive operation to produce the desired product from raw or pre-milled block of material. In CNC milling operation, the cutter moves along –Z direction, that is, it moves downward when it passes to the next layer. However, in RP operations, the moving head of the system, this can be a deposition head or a laser, moves along +Z direction, that is, it moves upward from the current position when it passes to the next layer. Consequently, if the signs of the Z coordinates in CLS file are reversed, this path file can be used for RP operation. This is the main idea of the algorithm 2.

The main advantage of this algorithm is that it is more accurate than the STL-based slicing algorithm because the STL file format approximates the surface of the CAD model with triangles, and this first order approximation causes geometric inaccuracies and errors called chordal error. However, in second algorithm, the slicing operation is done by the CAD program it self while creating CLSF.

Unigraphics NX CAD program's manufacturing module is used in this study to create the needed CLSFs. First step is the modeling of the part, but this time the part is modeled as a vacancy in a block (See Figure-3.36 a and b). Then, in the manufacturing module of the CAD program, tool path for milling operation is created (Figure-3.36 c). The most important thing that has to be taken into consideration is that the step over value, depth of thickness and the cutter diameter has to be chosen equal to the tip diameter of the dispensing system. In algorithm-1, parts are produced only by following a zig-zag path, but in algorithm-2, different path options can be chosen like peripherical path. Moreover, the material dispensing direction on the layers can be specified such as inward and outward.

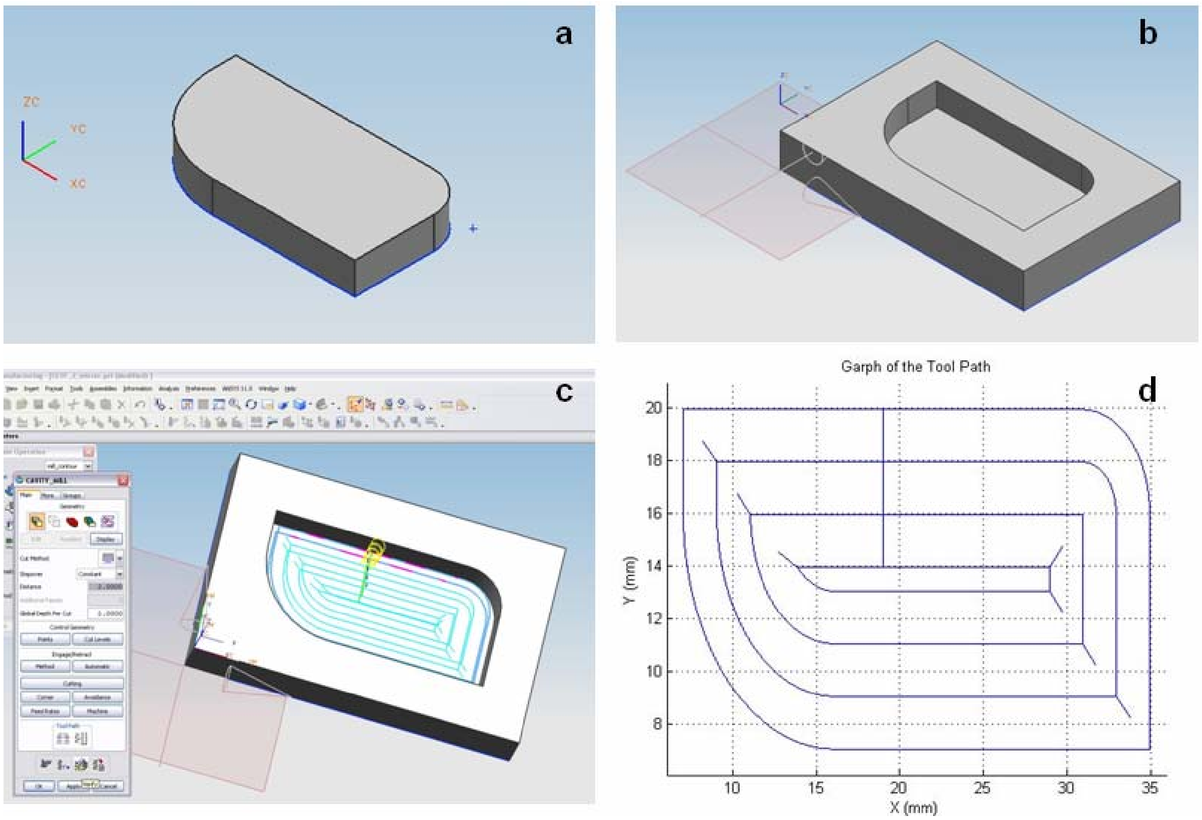


Figure 3. 36: a) The part that is desired to be produced, b) the part has to be modeled as a vacancy in a block, c) from the manufacturing module of the CAD program, the CLSF is obtained, d) CLSF is loaded into the MATLAB program, and the program produce the path going to be followed by the system and gives the path as a plot

CLS files contain instructions and the node coordinates that form the tool path for milling operations. For example;

GOTO / 7.05, 16.00, -2.00

GOTO / 7.05, 19.95, -2.00

The foregoing expressions mean that from the current position which is 7.05, 16.00, -2.00 (X, Y and Z coordinates respectively) the cutter is going to move linearly to the following X,Y and Z coordinates which are 7.05, 16.00, -2.00 respectively. Or the expressions can be like as following;

GOTO / 31.00, 17.95, -2.00
CIRCLE / 31.00 , 16.00 , -2.00 , 0.00 , 0.00 , 1.00 , 1.95 , 0.06 , 0.50 , 2.10,0.00
GOTO / 32.95, 16.00, -2.00

These three expressions define a circular segment of in the path. This expression group means that, two nodes (X_1=31.00, Y_1=17.95, Z_1=-2.00 & X_2=32.95, Y_2=16.00, Z_2=-2.00) are connected to each other with a circular path of radius of 1.95 mm and the direction of this circular path is clock wise (CW). The sixth number in the expression which begins with the word of "CICRLE" defines whether the circular path is in CW direction or in counter clock wise (CCW) direction. Since it is "1" for this case, this means that the path is in CW direction. If it was "-1", the direction would be in CCW direction.

After the CLSF is obtained (Figure-3.37 a), some modifications are done on the file and only the needed data is kept in the file to turn it into a form that can be accepted by the MATLAB program (Figure-3.37 b). Because, CLS files do not only contain necessary node coordinates, types of the motions and instructions but also contain information such as feed rate and type of the milling operation. However, this information is not needed in the case of creating a tool path for PR operations. Therefore, to be able to use this file format, unnecessary data must be cleaned from the file. Also, because the MATLAB is used for programming, the file also must be cleaned from words, i.e. the words of "GOTO" and "CIRCLE" are replaced with "1" and "2" respectively. And the word of "RAPID" is deleted from the file completely. The necessary changes that must be done on the file to make it ready to load the algorithm are explained in Section-A3-B in details.

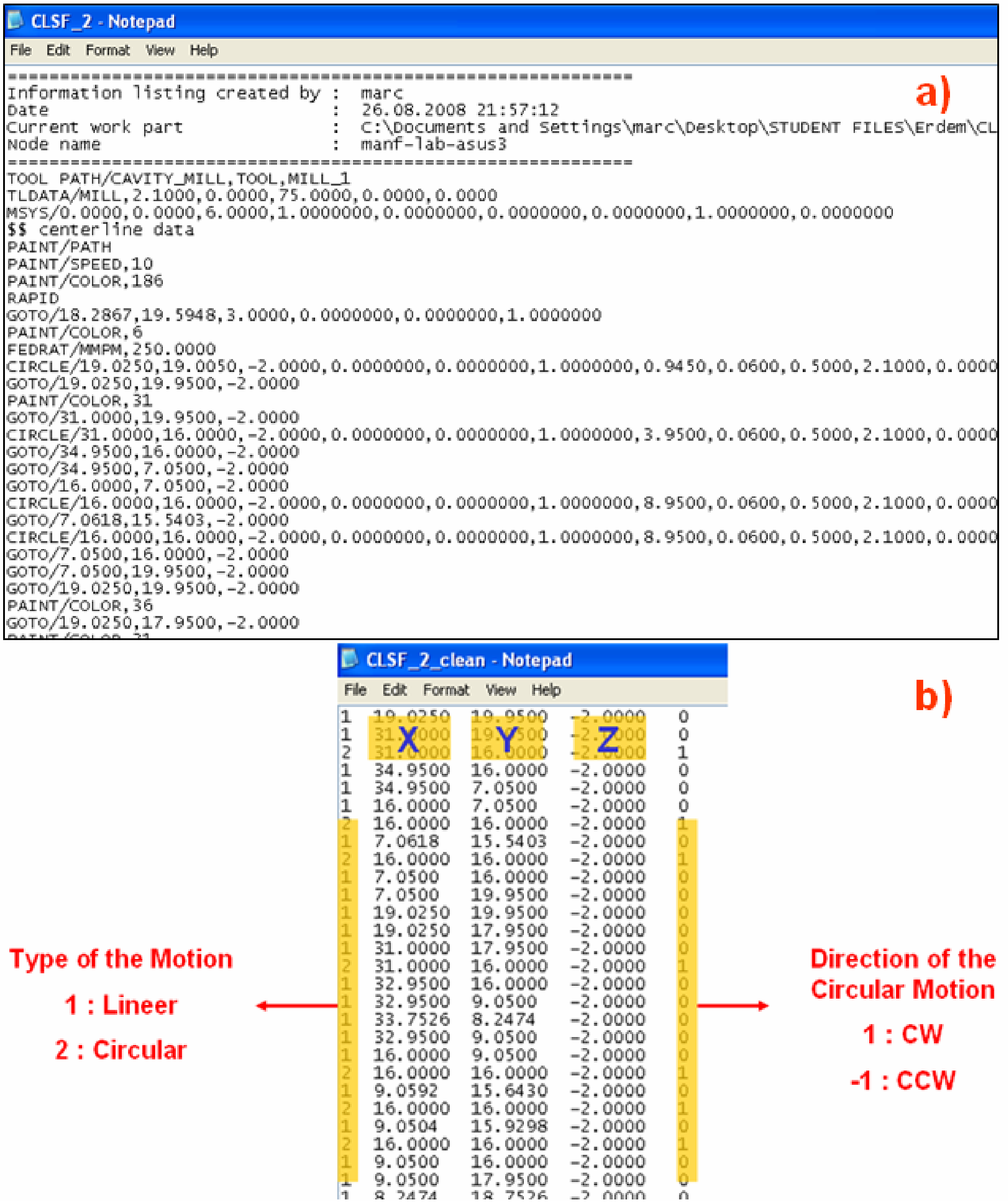


Figure 3. 37: a) Obtained CLSF contains unneeded data; b) the file is modified and unneeded data is cleaned

After the unnecessary parts are taken out and the words are cleaned from a CLS file, a .txt file including five columns of numbers is obtained as shown in Figure-3.37 b. In this file, first column represents the type of the interpolation. That is, if the number in this column is “1”, there will be a linear interpolation from the current position to the coordinates follow the “1”. If the number is “2”, there will be circular interpolation. Second, third and forth columns are X, Y and Z coordinates of the nodes respectively. Finally, fifth column represents the direction of the circular motion for the circular segments of the path.

This text file is loaded in to the algorithm-2 and path of the production process is generated by the algorithm (Figure-3.36 d). Pulses for corresponding line segments are calculated almost in the same way as done in the algorithm-1. Also, this algorithm is capable of creating circular paths (Figure-3.36 d). Circular portions of the path are divided into small line segments. Virtual nodes are created between the beginning node and the end node of the circular segments.

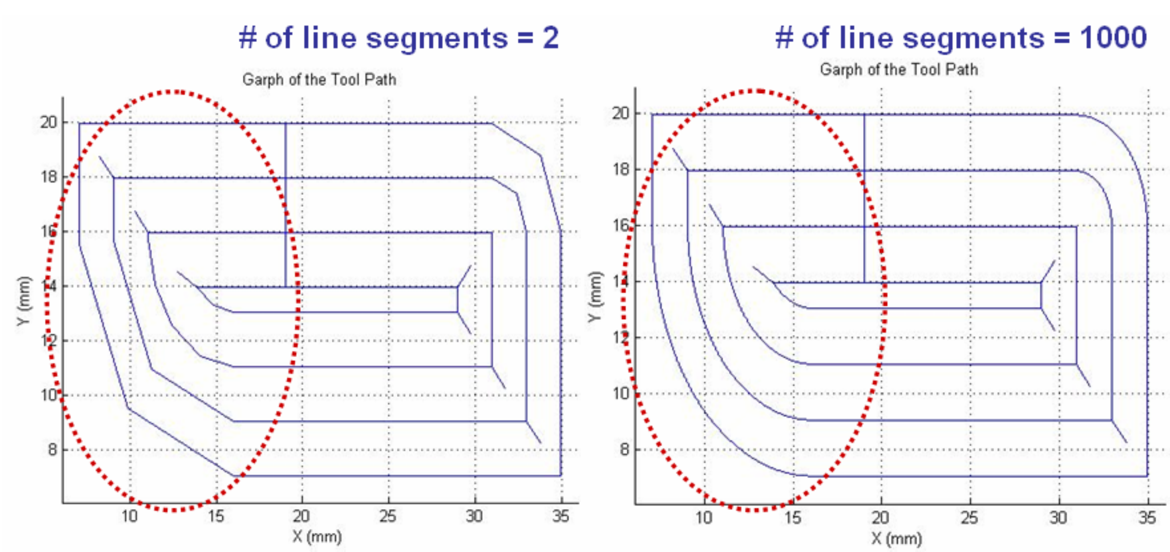


Figure 3. 38: Circular portions of the path are defined as line segments

The number of virtual nodes is decided by the operator, and defines the smoothness of the curve as shown in Figure-3.38. Converting a circular segment into a series of lines is one of the important properties of this algorithm. To define a circular segment in cutter location source files, three different points are needed as shown in Figure-3.39.

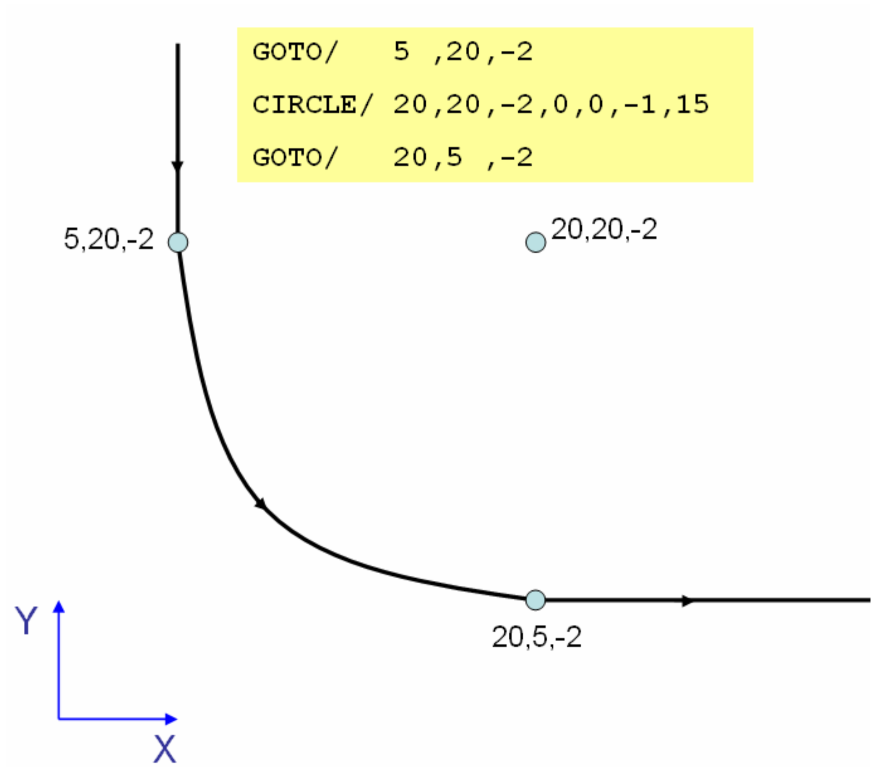


Figure 3. 39: Three points are needed to define the circular paths

The expression begins with the word of "CIRCLE" contains the coordinates of the center of curvature. It also contains the direction of the rotation and the radius of the curvature. In this case rotation is CCW since the number is –1 as it is mentioned before, and the radius of the curvature is 15mm.

Operator decides how many intervals this circular segment is divided into. As shown in Figure-3.38, higher the number of intervals, smoothest the curvature. If the algorithm finds that the loaded file contains circular segments, it warns the operator to enter the number of intervals. For all circular segments in the path, the same number of interval is used. First, algorithm finds the angle between lines which connect the center of the curvature with the first and second nodes (Figure-3.40).

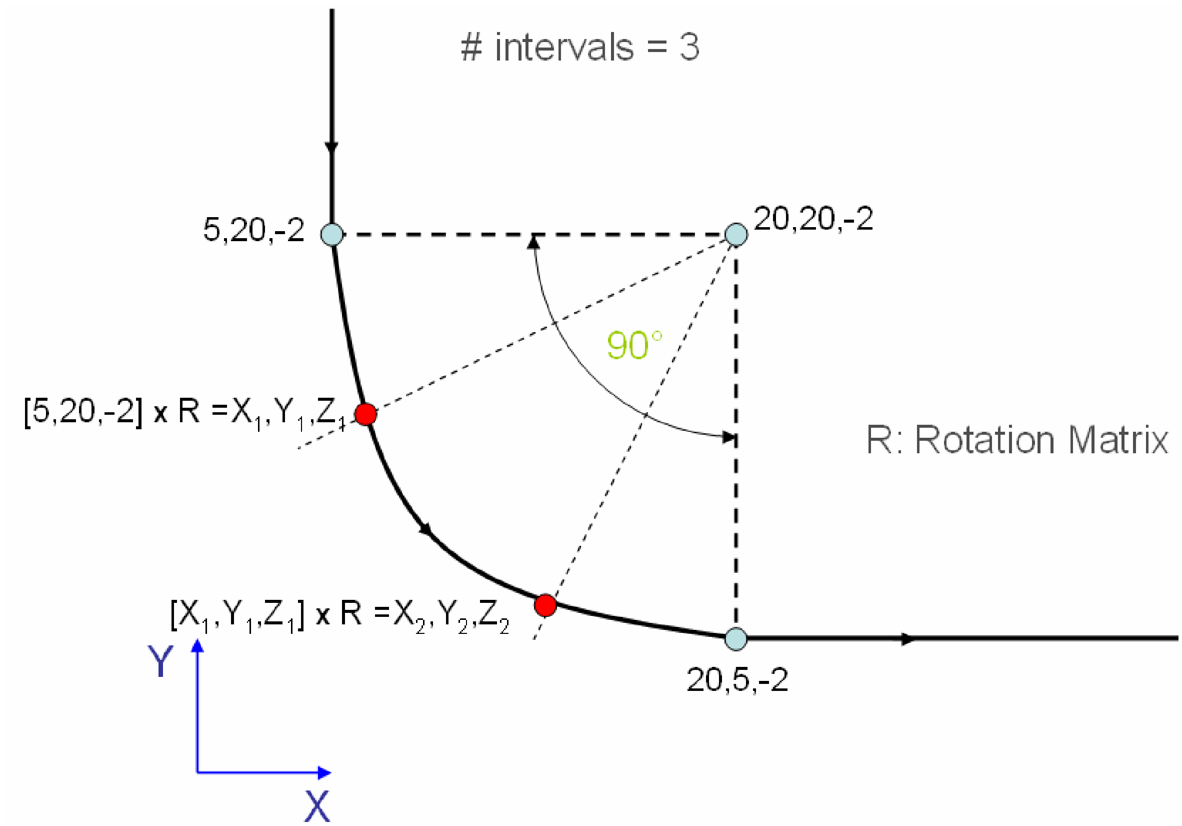


Figure 3. 40: Calculation of new nodes

By using the desired interval number entered by the operator, algorithm calculates the angle for intervals. In this case, it is 30°. Then, the first node is multiplied by rotation matrix to find the coordinates of the first of the imaginary nodes on the interval. After its coordinates are found, this time, this newly found coordinates are multiplied by the rotation matrix to find the last imaginary node on the interval.

Since the coordinates of the imaginary nodes are found, they are replaced with the expression which defines the circle. As a result, circular segment of the path is converted into a series of lines as shown in Figure-3.41.

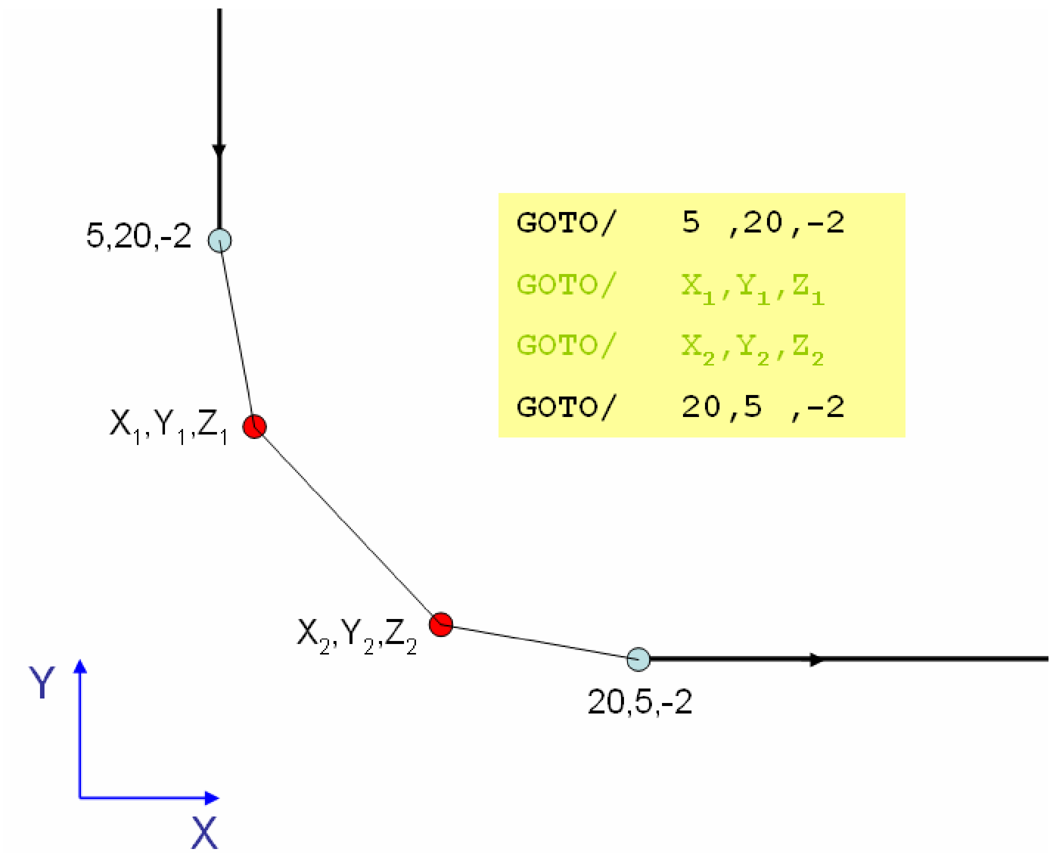


Figure 3. 41: Circle expression is replaced with two line expression

After the circular segments of the path are converted to the series of lines, the pulses for +X, –X, +Y, –Y and +Z directions are created and composed in five arrays corresponding to each direction, as in the first algorithm. Sending process of these pulses to the servo drivers are explained in Section 3.3-System Integration.

3.2.3. Algorithm 3

The aim of the third algorithm is to allow the operator to create his/her own path without using a CAD program. The third algorithm can be very useful while creating grid-like structures (Figure-3.42); such as different types of scaffolds.

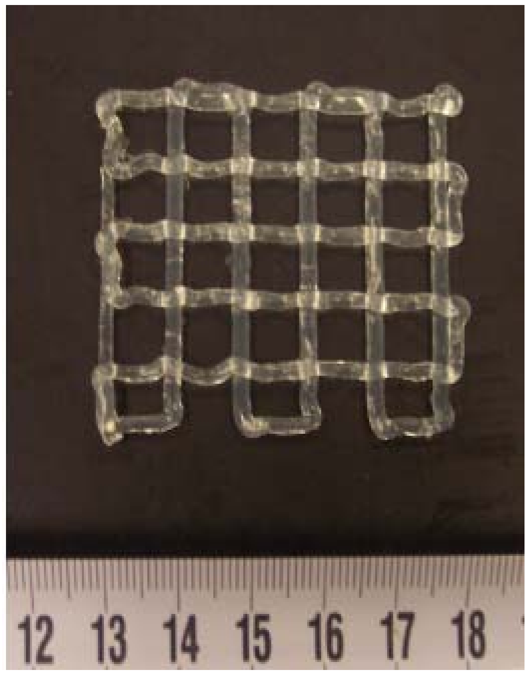


Figure 3. 42: A grid-like structure produced by using Algorithm-3

Operator just enters the distance values – in mm- to be traveled for each interval for X, Y and Z directions. That is, operator teaches the machine how long it will travel for each segment of the path. For example, assume that the machine is desired to move 10mm along X direction and to not move in both Y and Z directions at first segment of the path. In second segment of the path, it is desired to move 5 mm along X direction, 2mm along Y direction and to not move in Z direction. For such a scenario, operator must enter 10 when the program asks the distance for X direction and 0 for Y and Z directions. Similarly for second array of data, operator must enter 5, 2 and 0 for X, Y and Z directions respectively.

After an array of data is entered, program asks operator whether the path is completed or not. If operator chooses to go on, s/he enters the new array of data for the next segment of the path. If operator chooses to finish the path, algorithm calculates the necessary number of pulses for each direction in each segment and creates pulse arrays for each segment. Finally, these pulse arrays are combined successively to create 5 necessary pulse arrays – X forward, X reverse, Y forward, Y reverse and Z forward- which include all necessary pulse data to define the whole path.

3.2.4. Advantages and Disadvantages of Algorithms

First algorithm which is an STL based algorithm is the most accurate program of all. However, it only generates zig-zag paths. For some parts, different types of paths are needed. For example, if the part is small and it is desired that the surface quality is to be good, a peripherical path is a better choice. Another disadvantage of the first algorithm is that, for only some of the cases it can generate circular paths, and although the zig-zag path is generated, the algorithm gives error if the part has too many curvatures. The main advantage of this algorithm is that it requires STL files as input. Almost every CAD program can generate STL files of the designed CAD model. That is, operator can use any commercial CAD program available to create an input for this algorithm.

Second algorithm requires a cutter location source file to generate the pulses needed to run the system. As mentioned before, Unigraphics NX CAD program is used in this study. Since the structure of the CLSFs generated in different Cad programs may differ, it can be said that to sue this algorithm operator must need Unigraphics NX CAD program and manufacturing module of this program. Also some preliminary work is needed to create a CLSF, because some parameters must be set in the manufacturing module. The parameters such as type of the path, hatch distance and layer thickness is entered in this phase of the process.

For first algorithm, hatch distance and layer thickness values are equal to each other. However, for second algorithm, while the source file is prepared, different values can be set for these two parameters.

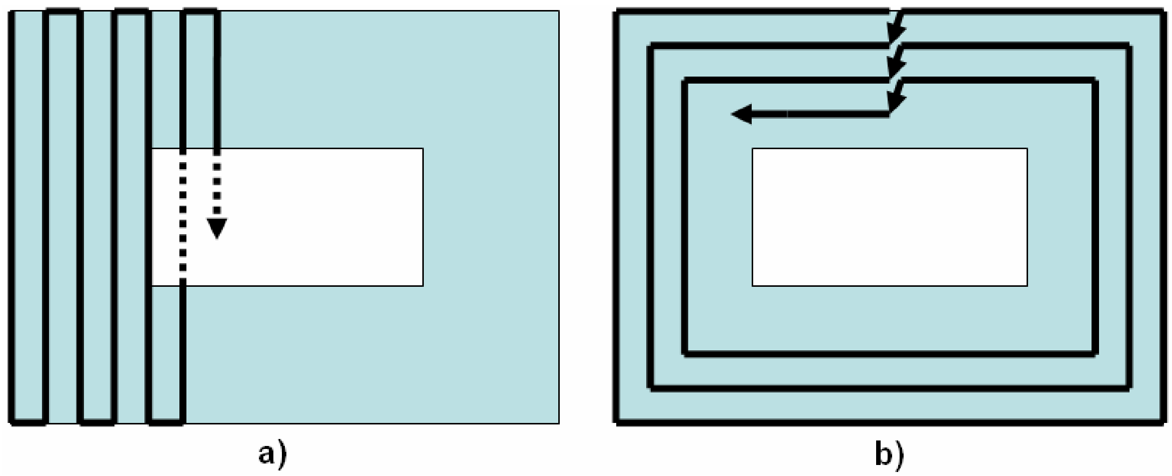


Figure 3. 43: a) For paths generated by first algorithm, the flow must be stopped when a hollow section is reached; b) Second algorithm can generate paths such that the flow is not need to be stopped

In first algorithm, if there is a hollow section the in part, the flow of the material should be stopped when this section is reached and after this section is passed the flow is started again. Stopping the flow during the production is hard and can not be performed successfully. A solution attempt which is not successful is mentioned in Section 3.1.2.1. That is why a new algorithm and deposition system have been developed. But in second algorithm, since it works based on a milling operation, the path is generated such that the tip of the nozzle does not pass though hollow section and material flow is not stopped. Instead, the path is generated such that the tip of the nozzle follows the contours of the empty section as shown in Figure-3.43.

For second algorithm different path options are available different than zig-zag path: peripherical path, circular path, path that in only contours of the part is followed and zig-zag path with different angles.

Main advantage of the second algorithm is that it can generate paths that have curves. Details of this process are explained in Section 3.2.2. Moreover, first algorithm can only create lines of 45°. In second algorithm, a new code is embedded to create lines other than 45° and 90°. Although this new option works, for some cases errors can occur because of the approximations done in this new part of the code. This is one of the problems should be solved about the second algorithm.

As mentioned before, third algorithm allows operator to create his own path. It is only beneficial for small path, since operator must enter all of the coordinates of the nodes in the path by himself. Codes of this algorithm and the second one are similar. Basic modules of the second algorithm are used while creating this one. The main difference is that a new module that allows entering input is added.

3.3 SYSTEM INTEGRATION

3.3.1 Data Packaging and Sending Program

All of the algorithms create five arrays containing the pulse data to drive the three servo motors of the system. These five arrays form a matrix and each row of this matrix represent one time increment. That is, each row of the matrix contains information about the corresponding direction for a specific time increment. As each row contains only ones and zeros, they can be treated as binary decimal numbers (BDC). By the help of this logic, five-columned data can be compacted in only one column as decimal numbers as shown in Table-3.4.

Table 3. 4: Compaction of five-columned data into one-columned data

2^4	2^3	2^2	2^1	2^0	Decimal
X_F	X_R	Y_F	Y_R	Z_F	New
1	0	1	0	0	20
0	0	0	0	0	0
1	0	1	0	0	20
0	0	0	0	0	0
1	0	0	0	0	16
0	0	0	0	0	0
0	1	0	0	0	8
0	0	0	0	0	0
0	0	0	1	0	2
0	0	0	0	0	0

Then, a MATLAB program sends this new array of data to a micro controller through RS232 serial port. Micro controller programmed as a decoder. This time, micro controller decodes the decimal numbers and sends the binary data to five different channels sequentially for each time increment. The program loaded in micro controller which performs this operation is given in Section A6-F.

3.3.2 Data and Signal Processing

Micro controller is connected to the drivers of the motors over an isolated BNC connection box as shown in Figure-3.44. The decoded data is sent successively and consequently, motors are simultaneously driven.

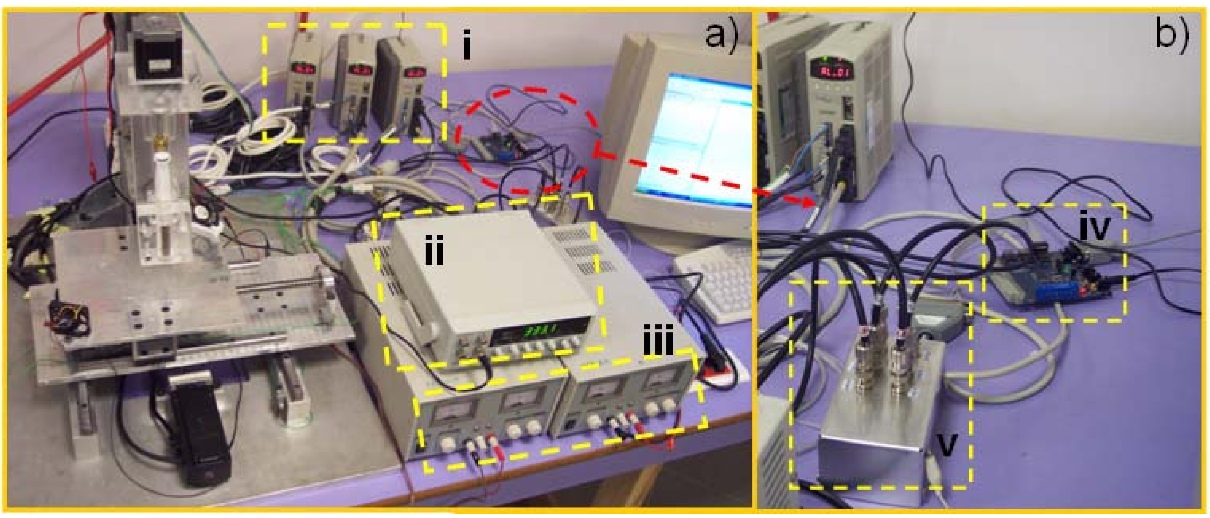


Figure 3. 44: A general view of the RP system; i) Servo drivers, ii) Function generator, iii) Power supplies of the system, iv) Micro controller, v) BNC connection box

Besides the micro controller and RS232 connection, the data can be sent over a controller board. In this study, a controller board of dSPACE Inc.’s 1104 R&D controller board is used. Five DA channels or digital I/O module of the controller board can be used to drive the system (Figure-3.45). This time, the pulse data is directly sent to the controller board over a specific PC board embedded into the computer. It is not needed to compact the five arrays of data. The data is send by using a Simulink module written in MATLAB which create real-time position data. These two methods were also utilized in the developed system successfully. According to the conditions of the application, one of these three options can be chosen.

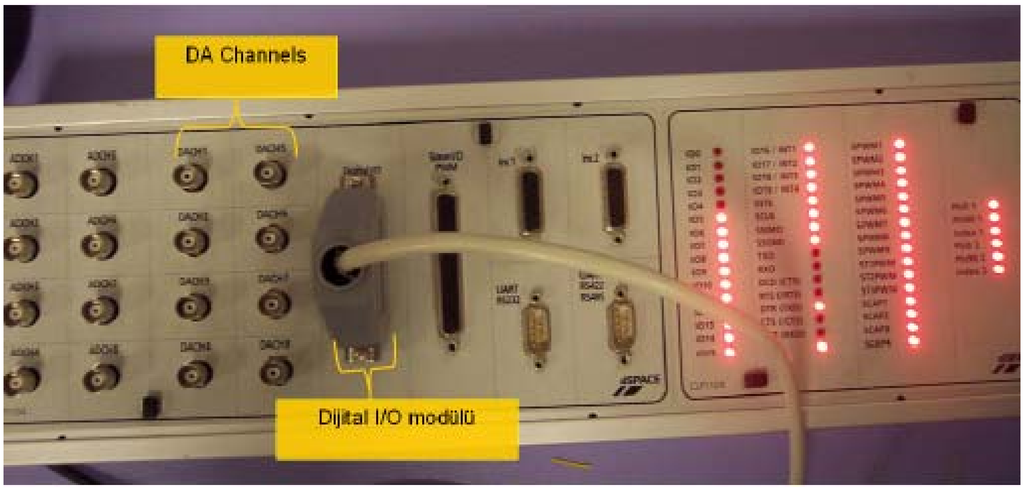


Figure 3. 45: dSPACE R/D controller board can also be used to send out the data to the system

When the sent data reach to the drivers of the servo motors, they are sent out to the servo motors under the control of gear ratio entered to the drivers. Numerator of the gear ratio is set as 10000 and denominator of it set as 100.

The stepper motor used in the dispensing system is driven from a function generator. In fact, the stepper motor can also be driven by creating a sixth pulse array in the program, and sending it over RS232 port and micro controller. However, in the laboratory, the tip diameter of the dispensing system is changed according to the research and the part that is produced. For different tip diameters, the stepper motor should be driven in different frequencies and for new tip diameters a tuning process must be done to find the proper frequency. Therefore, it is more convenient to drive the stepper motor from a function generator. The program loaded into the driver of the stepper motor to control it is given in Appendix A6-G.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Current Situation of the Developed System

Basically, whole mechanical system consists of two subsystems: a 3-axis machine and deposition system. The motion in each axis of the machine is driven by PC controlled servo motors. The system is robust and able to be controlled with a kinematic resolution of 5µm in each axis. However, currently used kinematic resolution is 50 µm, because the minimum resolution of the deposition system is 600 µm. obviously, it is meaningless to use the kinematic resolution as 5 µm without improving the resolution of the deposition system. Translational speed of the machine in all directions is 75 mm/min (1.25 mm/sec). With repeated measurements for 100 mm translation in X- and Y-axes and 60mm translation in +Z direction, kinematic accuracies of +X, -X, +Y, -Y and +Z directions are found as -0.04 mm, -0.04 mm, -0.12mm, -0.11mm and -0.1/+0.05 mm respectively. Currently used deposition system is composed of a ball screw mechanism, syringe and casing. A stepper motor is used as the driving component. Optimal working frequencies for 0.6 mm and 1.9 mm tip diameters are found as 500 mHz and 2.5 Hz respectively. With these frequencies, hatch lines with width of 1 mm and 2.2 mm are produced from 0.6 mm and 1.9 mm tip diameters. This deposition system does not contain any heating subsystem; therefore it is proper for thermoset materials.

Three different slicing and path generation algorithms are available and their validity is checked. First and second algorithms are STL and CLSF based respectively, and the third one requires operator input and allows operator to generate his own path. STL base program is capable of generating paths for any basic geometrical objects. However, it can only generate zig-zag paths. CLSF based algorithm is capable of generating paths other than zig-zag paths, like peripherical paths. Another advantage of this algorithm is that it can generate paths which have circular segments. Also this algorithm gives more satisfactory results while creating parts that have hollow sections. The first algorithm can generate paths only for line of 45° inclination. Second algorithm can generate paths for lines with any degrees of inclinations. However, for some cases, because of the approximations done in calculations, some errors can occur during the production of the part resulting the shifting of some of the layers. This is the only problem that has to be solved about the CLSF based algorithm. Third algorithm is tested with several grid-like paths and its validity is also proved.

Developed RP system allows production of parts which have layer thicknesses between 600μm and 1.9 mm. According to the part that is going to be produced, operator can choose a wide range of layer thickness and hatch distance options to choose.

Recently, silicone is used as production material but other materials such as polymer clay and cream chocolate are tested as production materials. Although it is very cheap and easy to use, silicone is not very proper for accurate production of the parts, because silicone looses volume and shrinks after it dries. This situation causes dimensional errors. Current deposition system allows any materials which are initially in gel form to be used. Moreover, this deposition system design provides a sterile working conditions since medical syringes are used as reservoir for production material.

4.2 Dimensional Errors on the Produced Parts

Some tests are done to find the accuracy of the produced parts. At first, it is tested whether the errors depends on the production direction or not. In order to find the dimensional errors, several identical lines in different scales and several identical parts are produced (Figure-4.1).

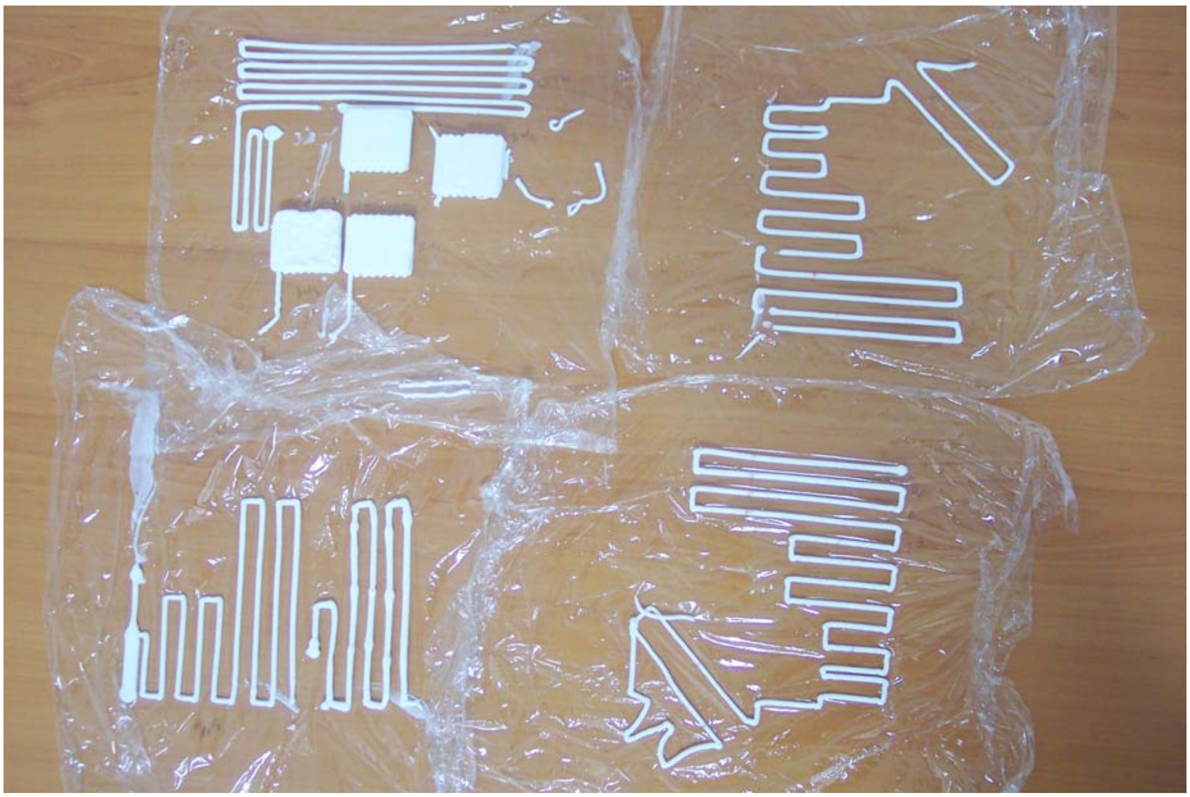


Figure 4. 1: Some of the identical specimens that are produced to find dimensional errors in different directions

The lines are produced along both X- and Y-axis. Measured dimensions of the specimens are compared with the expected dimensions. Along X-axis, 7 lines of 150 mm, 4 lines of 100 mm, 8 lines of 50 mm and 5 lines of 30 mm are produced. The lengths of these specimens are measured by using a digital caliper and it is found that average dimensional errors for specimens of 150 mm, 100 mm, 50 mm and 30 mm are %0.23, %0.36, %2.65 and %5.47 respectively. Weighted average of the errors in X-direction is %2.15.

Along Y-axis, 8 lines of 100 mm, 8 lines of 50 mm and 5 lines of 30 mm are produced. After measurements, it is found that the average percentage dimensional error of the specimens for 100 mm, 50 mm and 30 mm are %0.22, %2.64 and %2.92, respectively. Weighted average of the dimensional errors in Y-direction is %1.78. Average percentage errors in both directions are close to each, thus it can be concluded that the errors in the produced parts are not directional.

Since the production material, silicone, does not solidify immediately and is viscous enough to spread on the surface after it is deposited, some deformation occurs causing a produced line to lose its circular form tolerably. As a result, dimensional errors occur. These errors must be almost same and does not depend on the size of the produced parts, because from the results obtained for both axes, it is observed that as the length of the line decreases, percentage errors are increased. Hence, it can be concluded that if the dimensions of the produced parts are higher than 100 mm, the errors are within acceptable limits.

It is also observed that there are some errors that depend on the hatching position. They can be classified as the errors parallel to hatch lines and the errors perpendicular to hatch lines (Figure-4.2). 4 identical specimens of 30x30 mm^2 base area are produced for the identification of these errors. In addition to these four specimens, measurements are done on the other produced parts based on the foregoing error definitions. The collected data are given in Table-4.3. Moreover, the average percentage errors measured from the same parts are given in the Table-4.2.

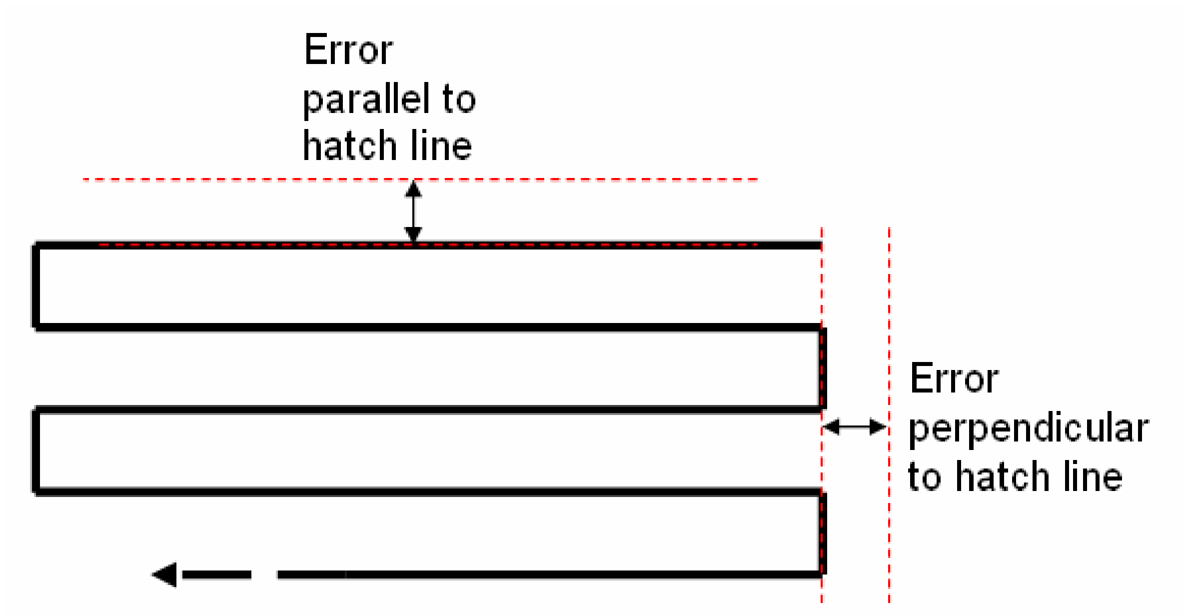


Figure 4. 2: Definitions of the non-directional errors

Table 4. 1: Measured errors that are perpendicular and parallel to hatch lines

	Error perpendicular to hatch line				**Error parallel to hatch line**		
	Expected	Measured	% Error		Expected	Measured	% Error
Specimen 1	30.00	29.41	-1.97		30.00	31.38	4.60
Specimen 2	30.00	29.32	-2.27		30.00	32.04	6.80
Specimen 3	30.00	29.21	-2.63		30.00	32.92	9.33
Specimen 4	30.00	30.29	1.00		30.00	30.08	0.27
Part 1	40.00	40.1	0.25		40.00	40.7	1.75
Part 2	40.00	41.6	4.00		40.00	40.8	2.00
Part 3	40.00	40.56	1.40		40.00	41.97	4.93
Part 4	30	30.47	1.57		30	30.77	2.57
Part 5	20	20.51	2.55		20	20.64	3.20
Average Error			**-2.29 / +1.80**				**3.94**

Table 4. 2: Measured height errors

	Errors on the heights of the parts		
	Expected	Measured	% Error
Specimen 1	10.00	9.87	-1.30
Specimen 2	10.00	9.89	-1.10
Specimen 3	10.00	10.42	+4.20
Specimen 4	10.00	9.60	-4.00
Part 4	27	25.8	-4.44
Part 5	41	40.13	-2.12
Average Error			**-2.59**

The given results in Table-4.1 and Table-4.2 are coherent. From the Table-4.1, it is seen that the errors perpendicular to hatch line and parallel to hatch line are most of the time positive. That is, the results prove that the material spreads on the surface by losing its circular form. As a result, the height of the each layer decreases some and the other two dimensions increases.

These are the tests done to get an idea about the dimensional errors on the produced parts. For more accurate results, more measurements must be done on different parts with different geometries.

4.3 Future Works

Primary objective of this study is to design and manufacture an open architecture rapid prototyping system, and to prove that this system works. Therefore, a specific production material development research does not take place during the study. Focal point of the study is to produce a part from its CAD data. As a future work, new materials can be developed or different materials besides the used ones can be tested.

Nowadays, RP technology is being used in medicine widely. Since current deposition system is very suitable for sterile medical applications, tissue engineering and tissue scaffolding researches can be performed by using biocompatible materials.

Support materials are needed to produce parts which have overhanging sections. A second syringe can be added in to the current deposition system to allow a different material to be used as support material. STL based algorithm is currently capable of generating pulse data for support material. This property of algorithm can be used to drive a deposition system with two syringes.

4.4 Some of the Produced Parts

Below, some of the parts which are produced by using developed system are given. It is proved that the system is capable of producing a part that is designed as a model in a CAD environment.

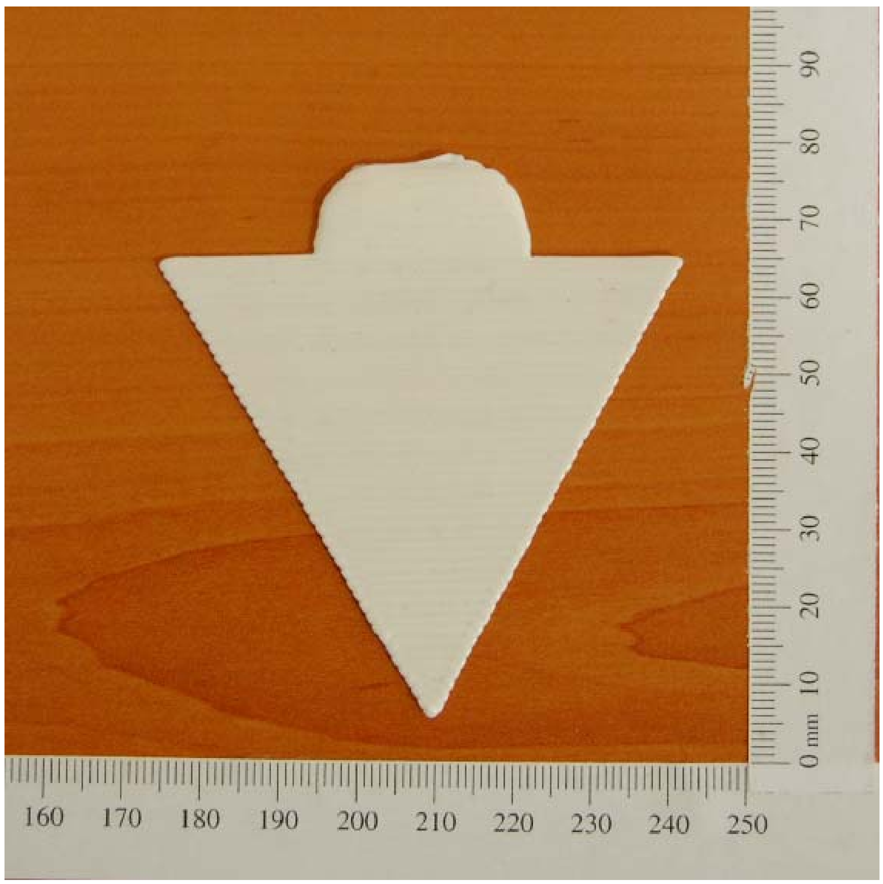


Figure 4. 3: One of the produced parts –Production time: 21min (one layer)

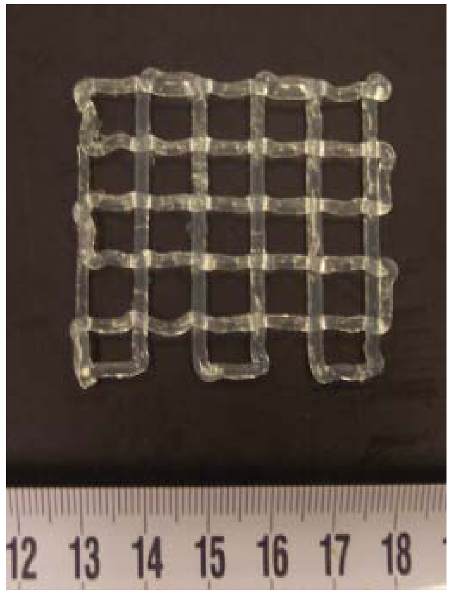


Figure 4. 4: One of the produced parts –Production time: 8.5min

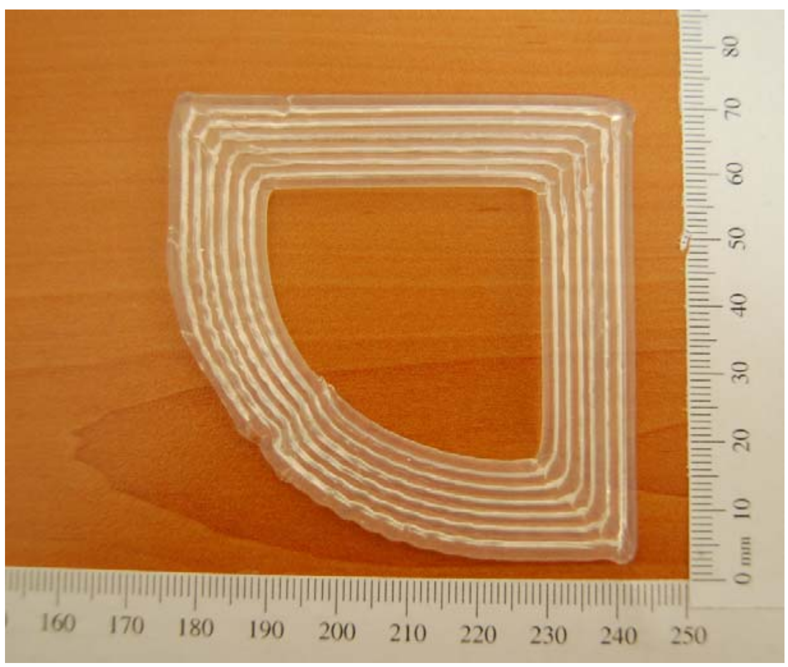


Figure 4. 5: One of the Produced parts (One layer)

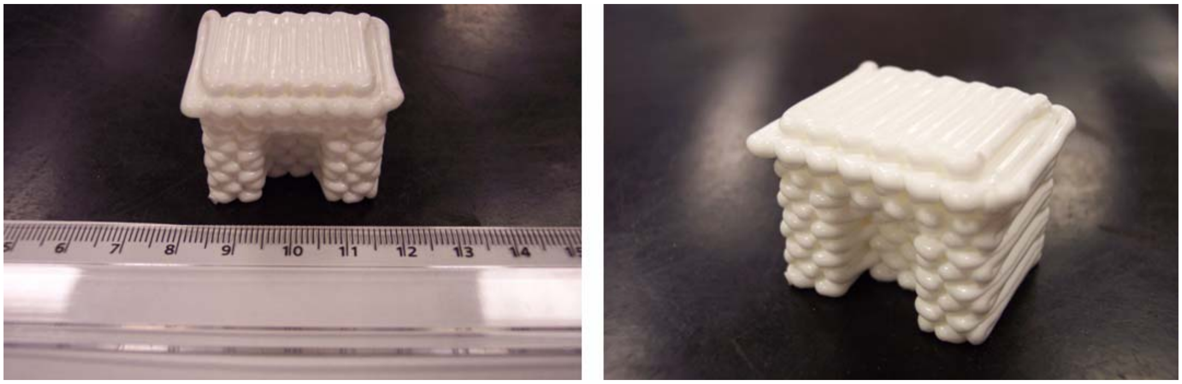


Figure 4. 6: One of the Produced parts (11 layers)

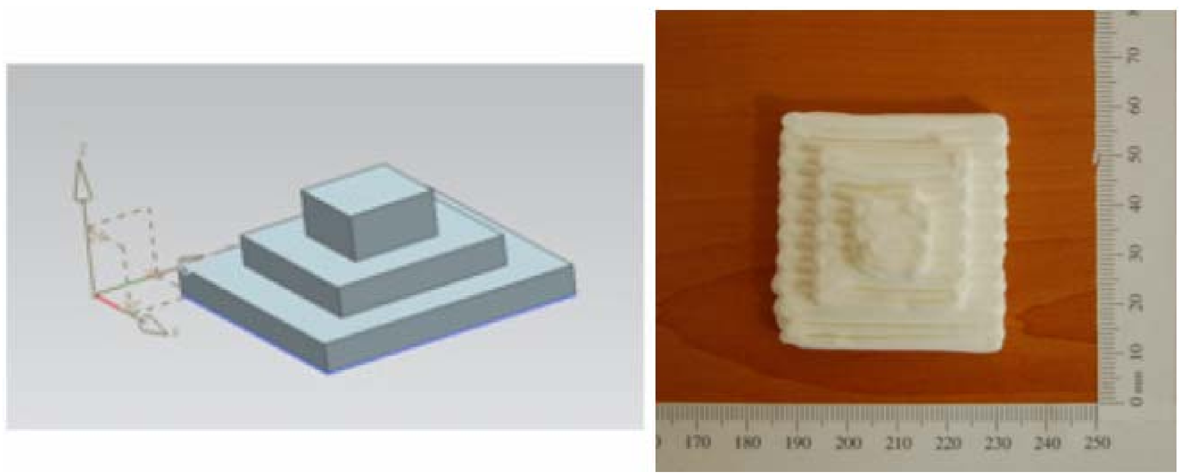


Figure 4. 7: One of the produced parts –Production time 33min. (7 layers)

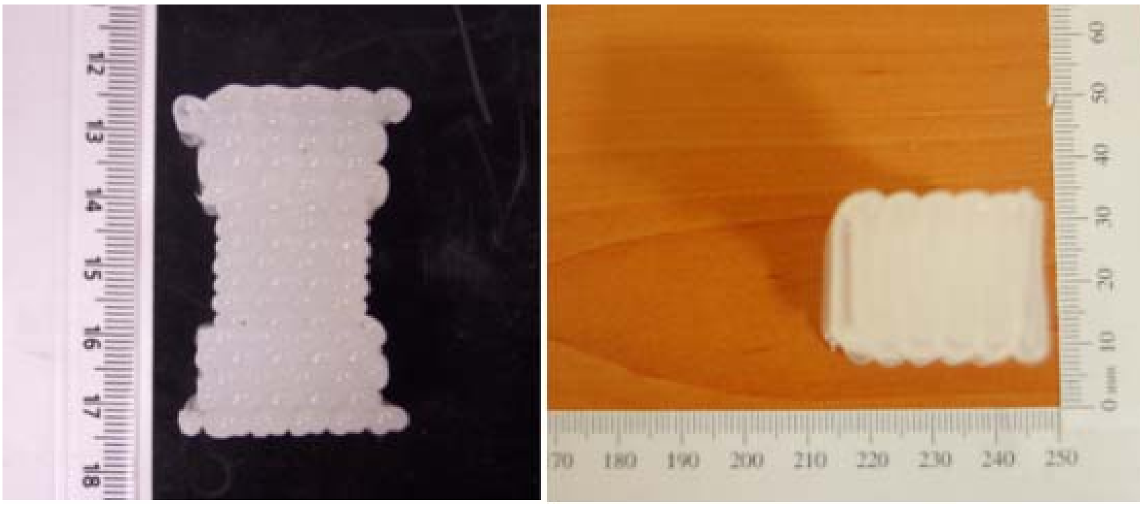


Figure 4. 8: One of the produce parts (17 layers)

Figure 4. 9: One of the produced parts (12 layers)

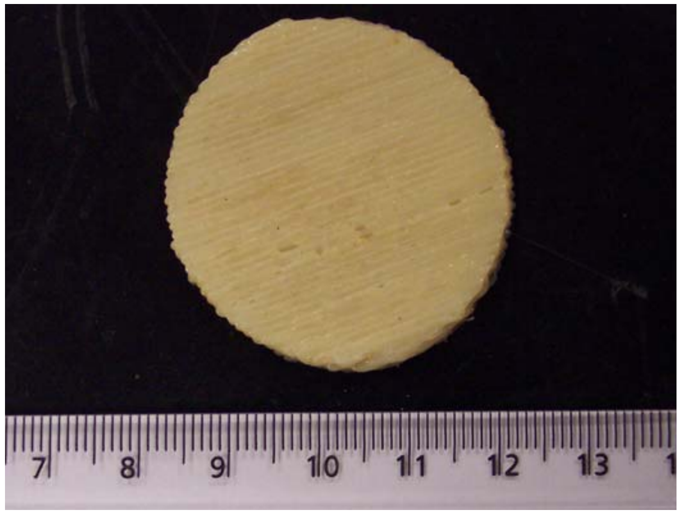


Figure 4. 10: One of the produced parts –This part was produced with Design-A deposition system (4 layers)

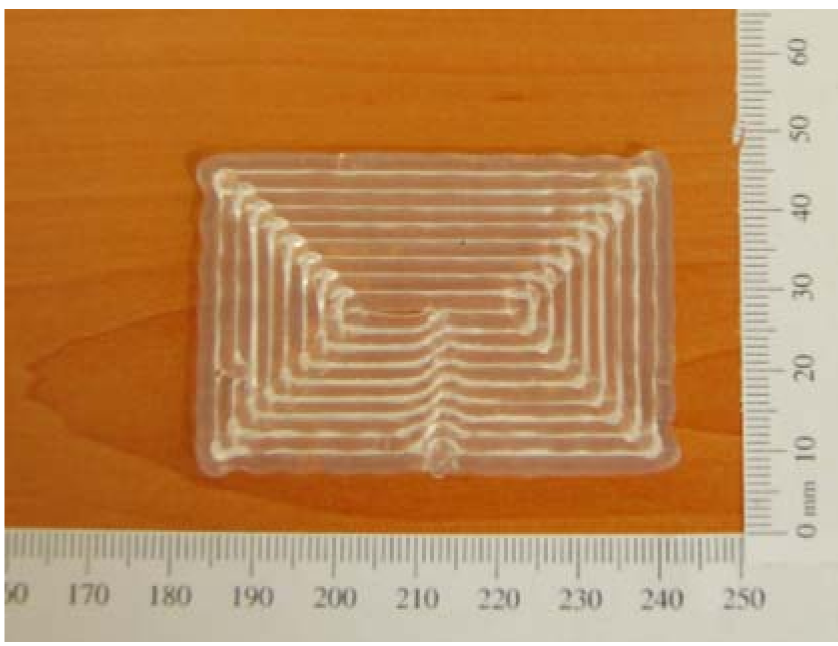


Figure 4. 11: One of the produced parts (1 layer)

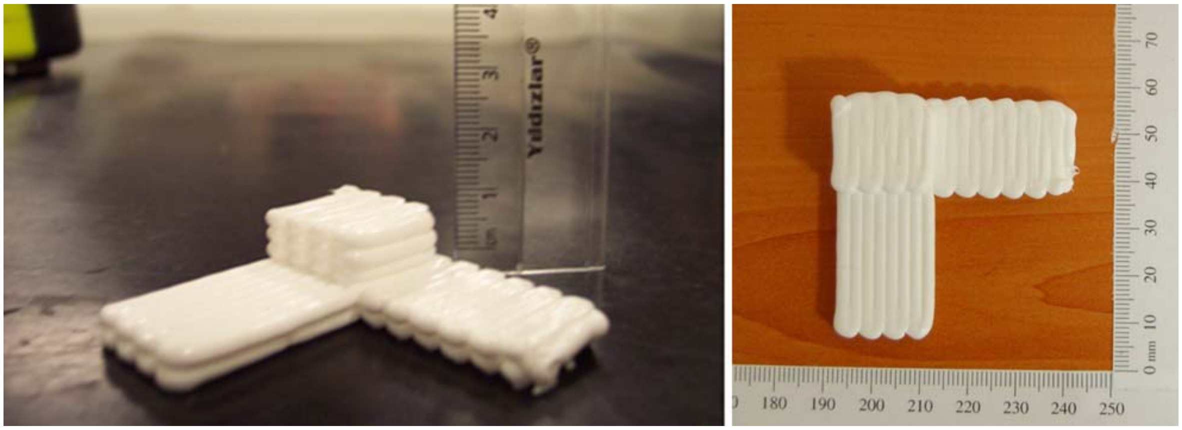


Figure 4. 12: One of the produced parts (5 layers)

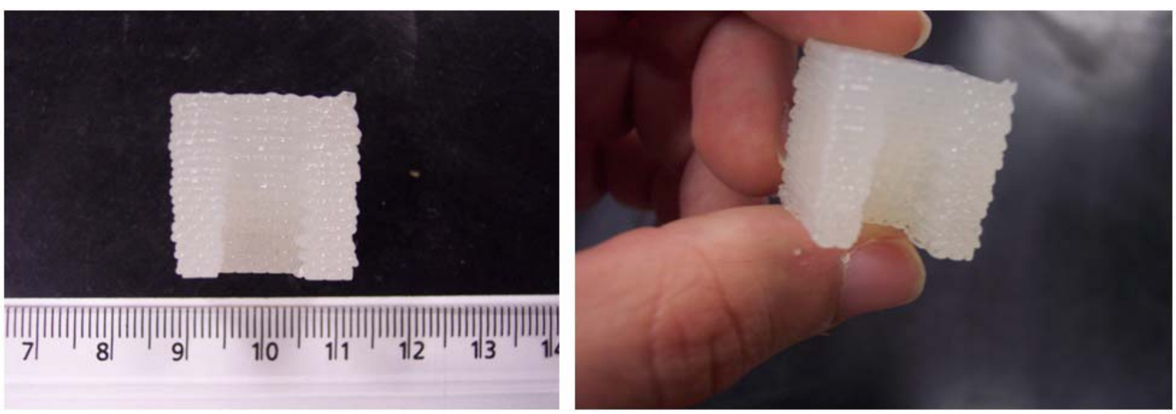


Figure 4. 13: One of the produced parts (21 layers)

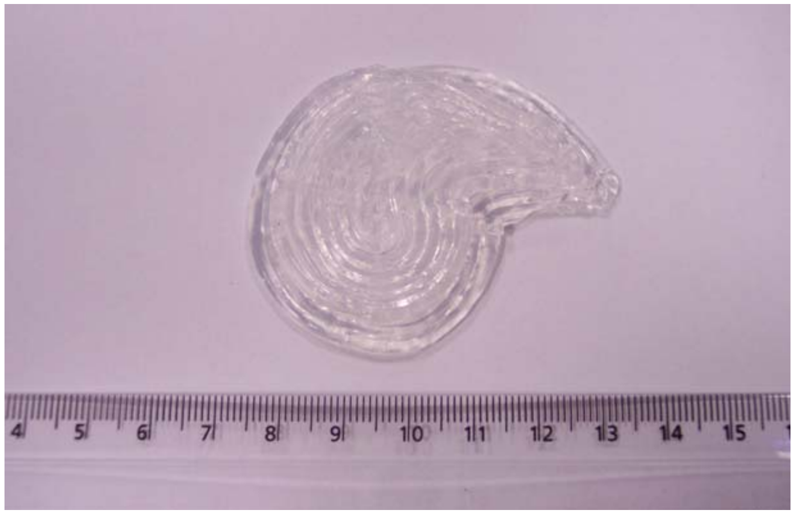


Figure 4. 14: One of the produced parts (2 layers)

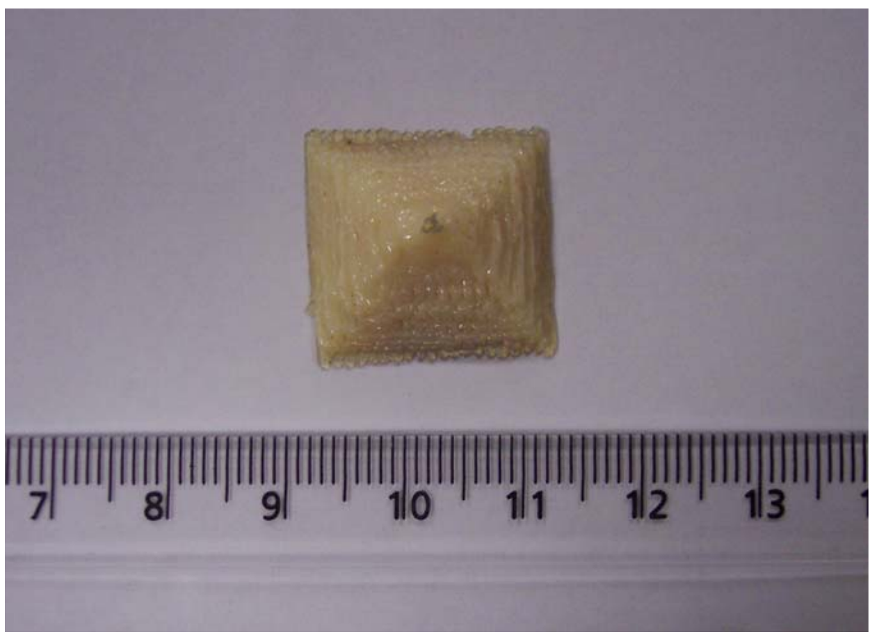


Figure 4. 15: One of the produced parts –This part was produced with Design-A deposition system

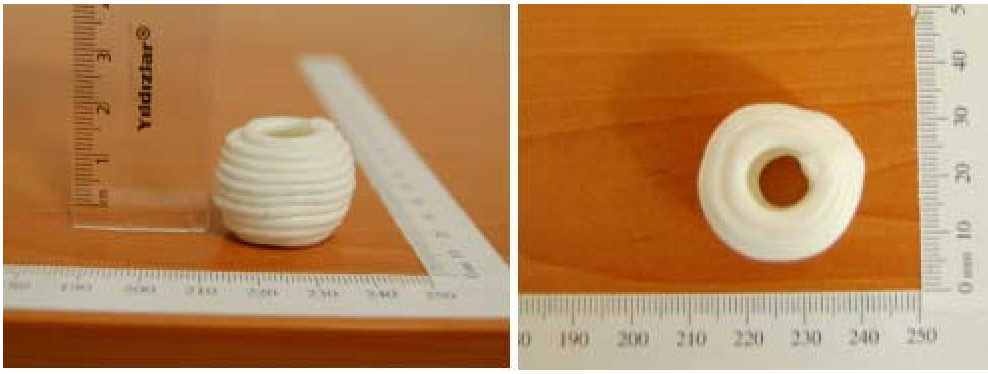


Figure 4. 16: One of the produced parts (12 layers)

Figure 4. 17: One of the produced parts (11 layers)

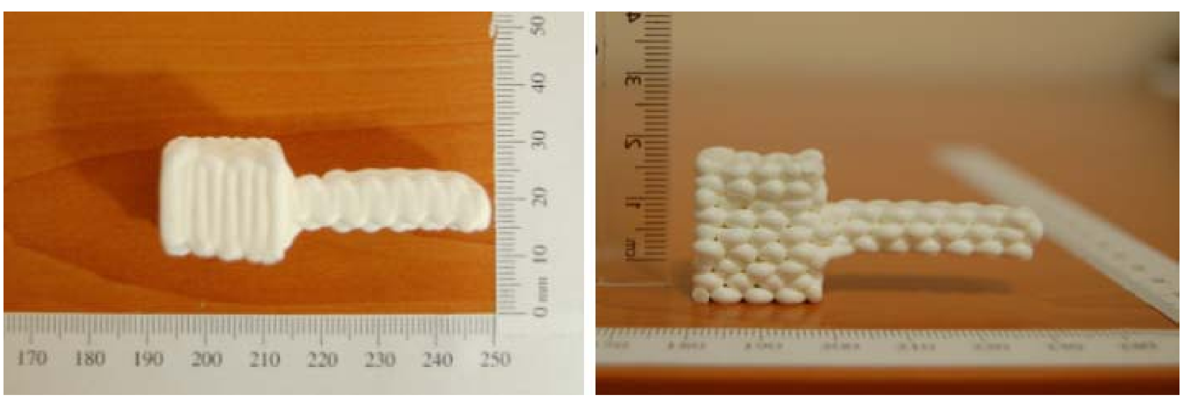


Figure 4. 18: One of the produced parts (9 layers)

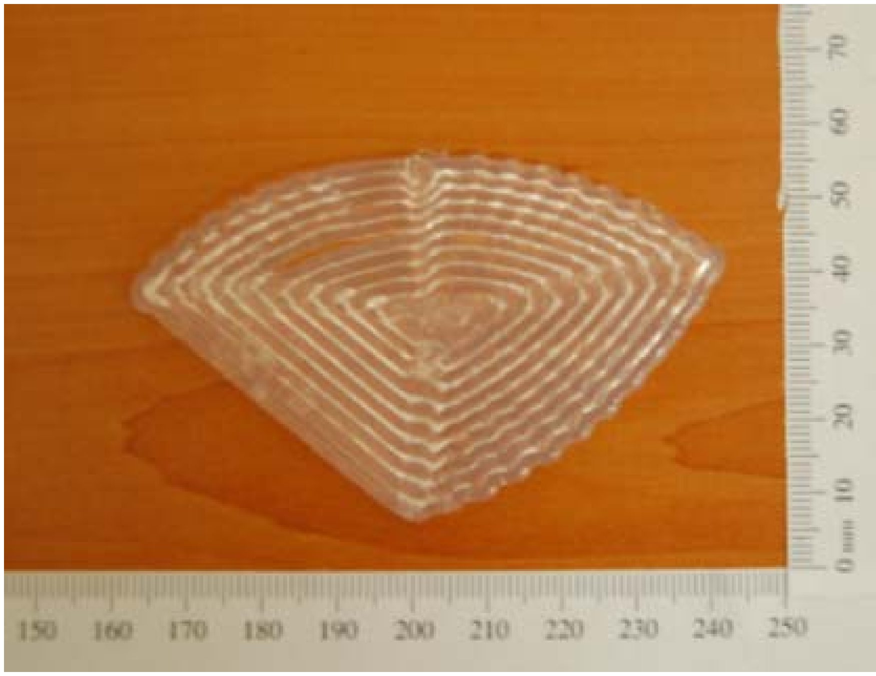


Figure 4. 19: One of the produced parts (1 layer)

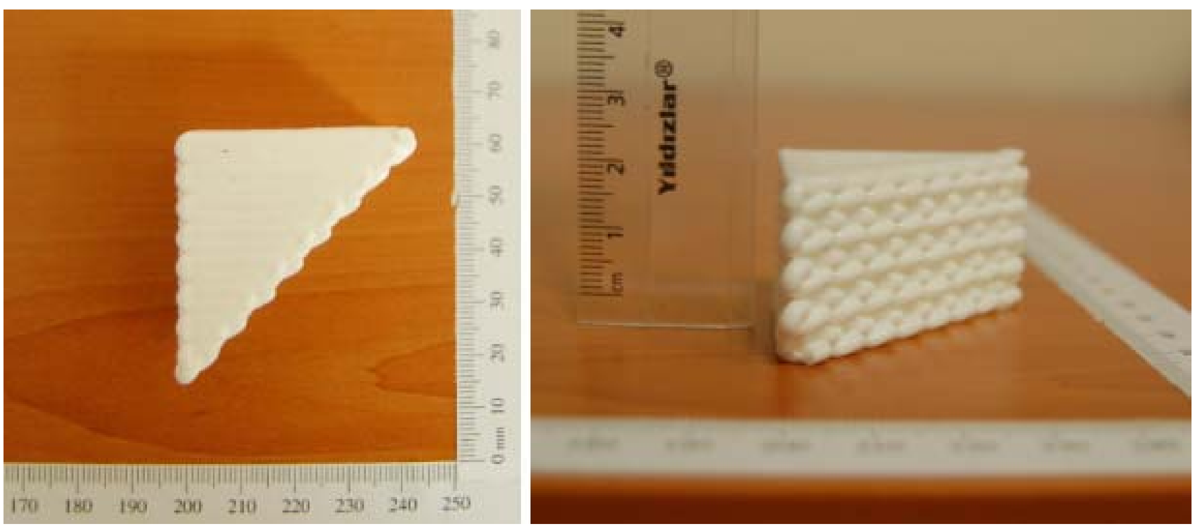


Figure 4. 20: One of the produced parts (10 layers)

Figure 4. 21: One of the produced parts (2 layers)

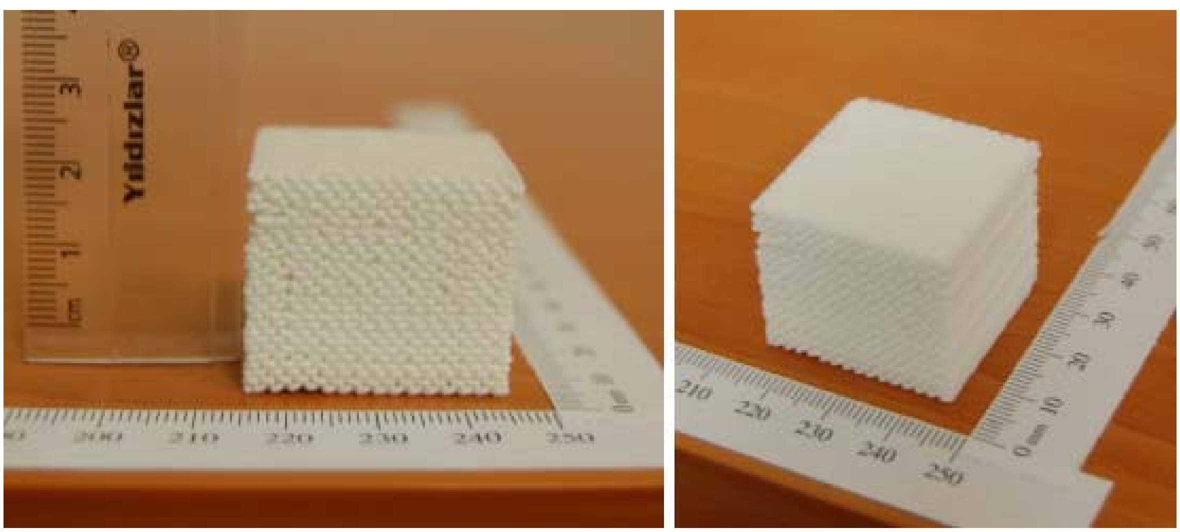


Figure 4. 22: One of the produced parts (27 layers)

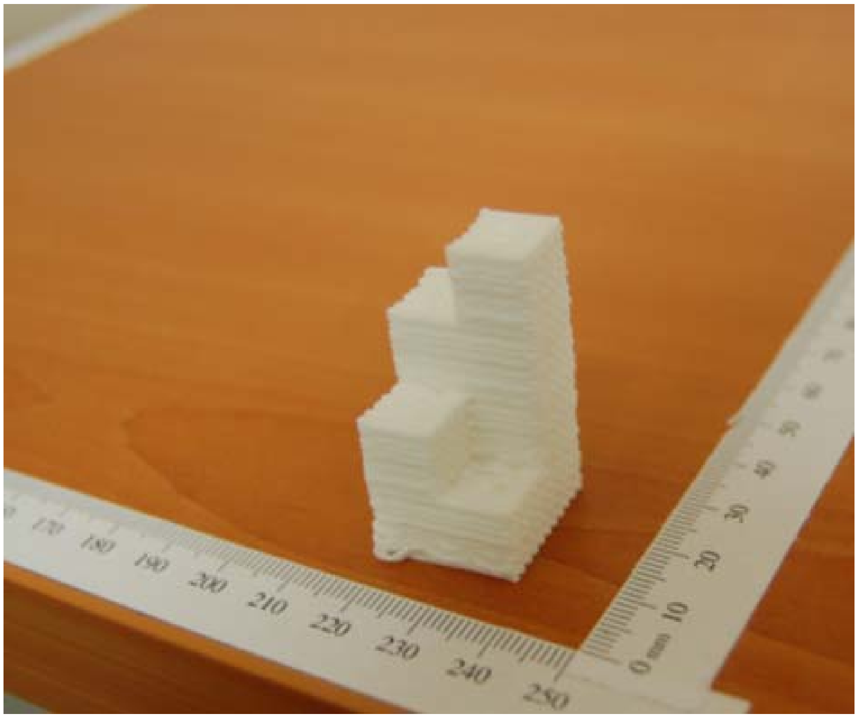


Figure 4. 23: One of the produced parts (40 layers)

Figure 4. 24: One of the produced parts (2 layers)

Figure 4. 25: One of the produced parts (1 layer)

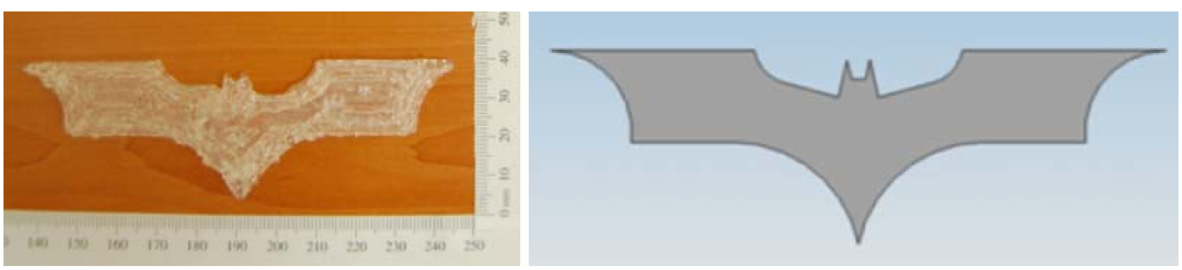


Figure 4. 26: One of the produced parts (2 layers)

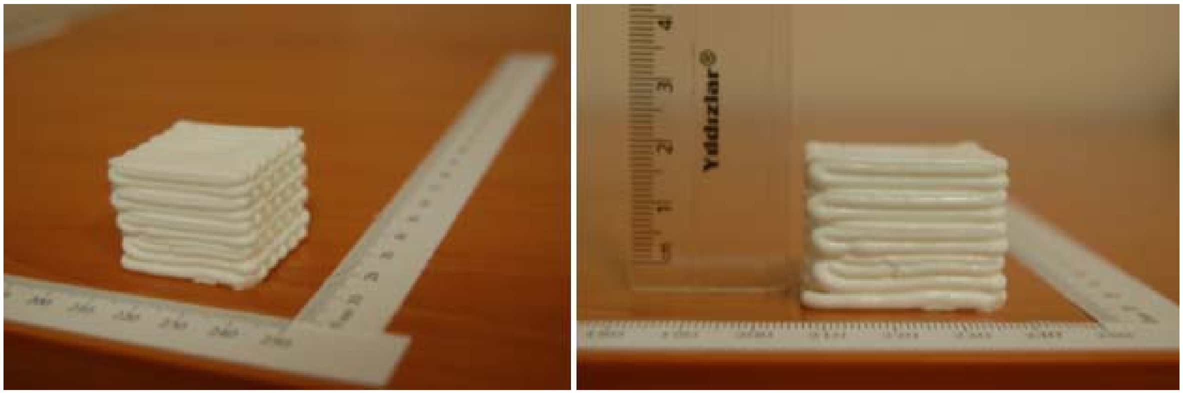


Figure 4. 27: One of the produced parts (13 layers)

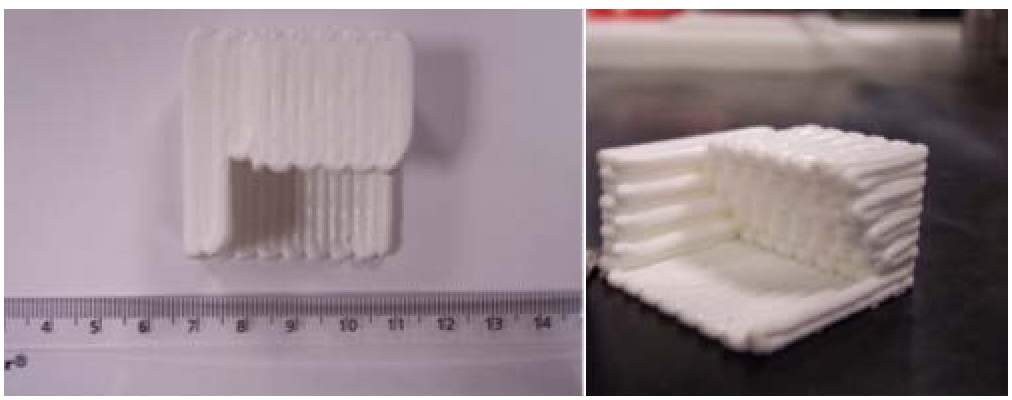


Figure 4. 28: One of the produced parts (12 layers)

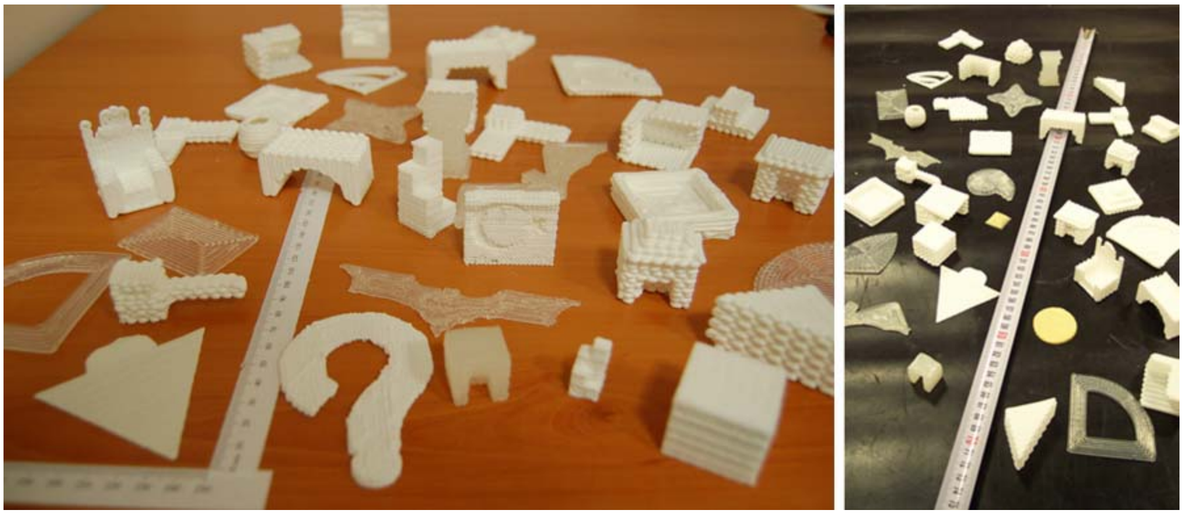


Figure 4. 29: General pictures of some of the produced parts

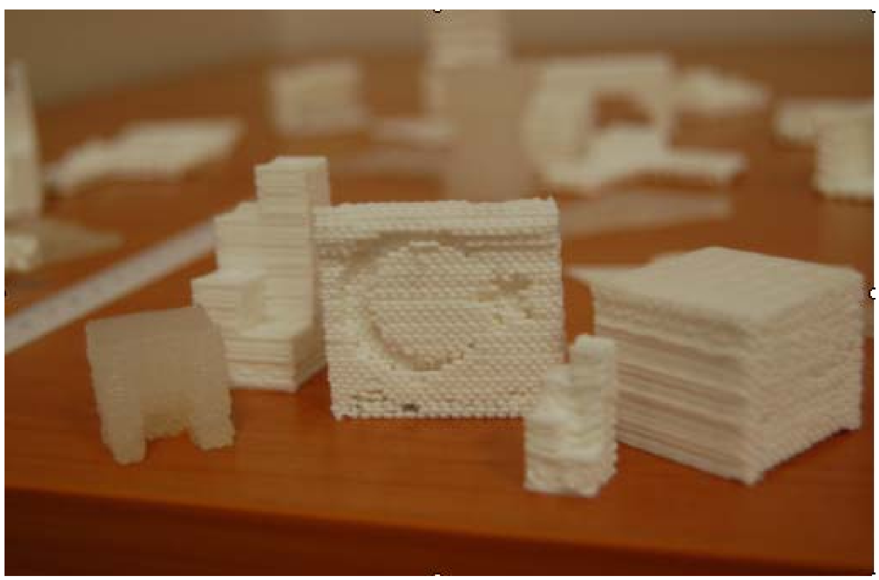


Figure 4. 30: A General picture from the produced parts

Chapter 5

CONCLUSIONS

A novel open architecture rapid prototyping system is designed and developed in this study. This developed system is the first domestic working RP system of Turkey.

A 3-axis carrying machine is built as the base of the RP machine. Motions in all directions are provided by servo motors. X and Y platforms of the machine are positioned horizontally and moves on guides by help of ball screw mechanisms. The motion in Z axis is again maintained with a guide and ball screw mechanism. But this time the mechanism is set on a vertical rod. An aluminum adaptor is mounted on the car of the ball screw mechanism and deposition system is attached at the tip of this aluminum adaptor. Four different deposition systems were designed and tested. Currently used deposition system is similar to the dispensing system known as rapid prototyping robot dispensing system in the literature. This deposition system basically consists of a syringe and a robust mechanical driving system. The dispensing system is driven by a stepper motor. A ball screw mechanism is attached to the shaft of the stepper motor. The set up is designed such that the rotational motion obtained from the stepper motor is converted to linear motion. Ball screw mechanism is placed in a special casing such that the nut that moves on the ball screw is located in a grove and this grove prevents the rotation of the nut. Consequently, the nut moves linearly on the ball screw. The piston of the syringe is in contact with the nut, and as the nut moves downward on the screw, the piston is pushed; and the material in the syringe is subjected to hydraulic pressure and it is deposited from the tip of the syringe.

The designed deposition system is very suitable for RP researches in medicine, because standard sterile medical syringes of 20 ml are used in this system as reservoir.

Three different slicing and path generation algorithms are developed for this novel RP system. Two of these are STL based and CLSF based algorithms. The part that is desired to be produced is designed by using a solid based modeling program. Then this part is converted to an STL file or by using the manufacturing module of the CAD program, a CLSF is obtained. STL based algorithm is developed because this is one of the most common slicing and path generation methods of the RP industry. STL file defines the surface of the model with small triangles. Written program create virtual planes for entered layer thickness value and find the intersection of the surface of the model and virtual planes. Once the boundaries of the planes are determined, algorithm generates a zig-zag path for each layer.

For CLSF based algorithm, the model is designed as a vacancy in a block. Then a CLSF is prepared to create this vacancy with milling operation. This file contains coordinates of the nodes that the cutter visits during the milling operation. By reordering the data in this file, five columned data file is obtained. New file contains the data about the type of the motion that the tip of the deposition system follows, coordinates of the nodes that the tip visits on path, and the direction of the motion if it is circular. After this file is loaded into the written program, it generates the pulse data to drive the servo motors of the system. Manufacturing modules of the CAD programs provide different path options for milling operations such as peripherical path, circular path and zig-zag path. This is the main advantage of CLSF based algorithm.

Third algorithm is developed such that it allows the operator to create his own path by entering the coordinates of the nodes manually. This algorithm is very useful for producing grid like structures and it eliminates the need for initial preparations.

Since the aim of this study is to develop an RP system and to validate the success of the system, a special material development research was not performed during the study. Currently, liquid silicone which is technically known as polysiloxane is used as production material.

Know-how regarding to RP technology is obtained as a result of this study. The research on RP technology continues in MARC laboratory and currently, a new RP system which uses laser beam to cure the production material is being developed in MARC in the light of the experiences gained in this study

As a result, the objective of the study was achieved: An open architecture rapid prototyping system –both its hardware and software- was developed by using only domestic resources, and it is proved that this system is capable of producing basic 3D models and relatively complex shapes.

APPENDIX-1: Maintenance and Cleaning of the Machine

The importance of periodical maintenance and cleaning of the machine can be well understood when it is considered the fact that the kinematic resolution of the machine is 5μm. The cleaning of the guides and the ball screws that carry the X and Y platforms and of the ball screw mechanism that provides the motion in dispensing system is very crucial. Guides and ball screws must be cleaned with a clean piece of fabric and machine oil. During the production, surface of the X platform should be covered with stretch folio to prevent sticking of production material –silicone- on the machine. Another benefit of using stretch folio is that bottom surface of the produced part does not stick on the folio and can be removed easily. Moreover, the same folio piece can be used several times.

The degree of humidity must be low in the room where the machine is used, because oxidation is observed on the transmission parts when the humidity is high. Therefore, a condenser must be used if the environment is humid.

APPENDIX-2: Electrical Connection Diagram

The numbers seen in Figure-A1 correspond to pin numbers of CN cable of servo drivers which is given in Figure-A2. Outputs of the micro controller corresponds to X, Y and Z signals are transferred to BNC cables. Then, by making the connections as shown in Figure-A1 signals come from the micro controller are sent to the servo drivers.

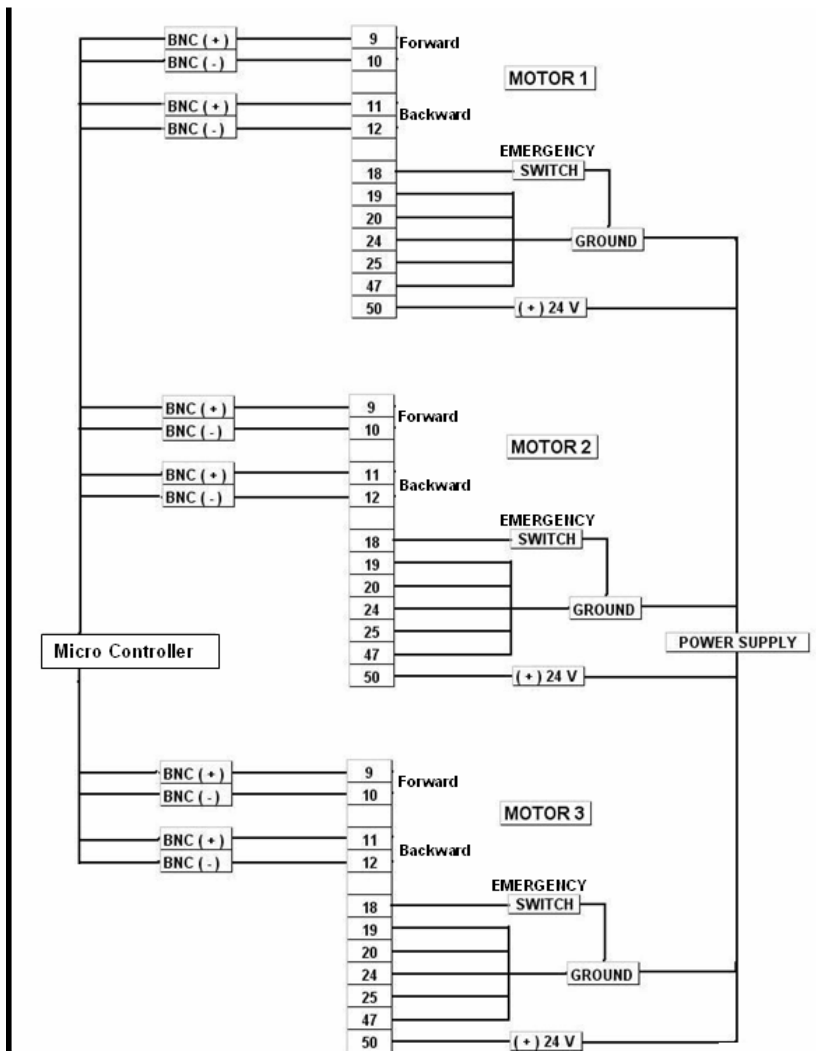


Figure A. 1: Connection diagram between servo drivers and micro controller

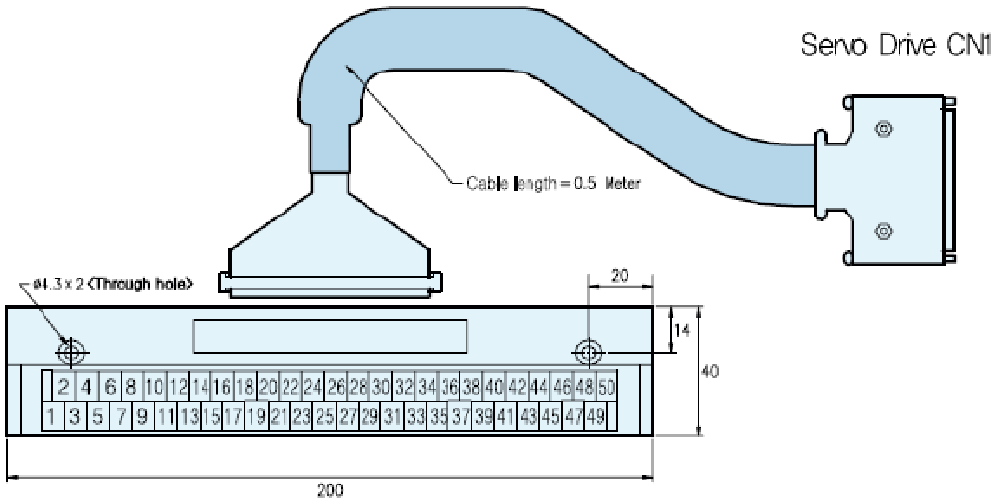


Figure A. 2: CN cable of the servo drivers and the pin numbers on it

APPENDIX-3: Manual for Conversion of the CAD Model and Generation of the Pulse Signals

A-3 A) Conversion to STL format and necessary adjustments

First thing to do is designing the CAD model of the part that is going to be produced (Figure-A3). In this study, Unigraphics NX CAD program is used.

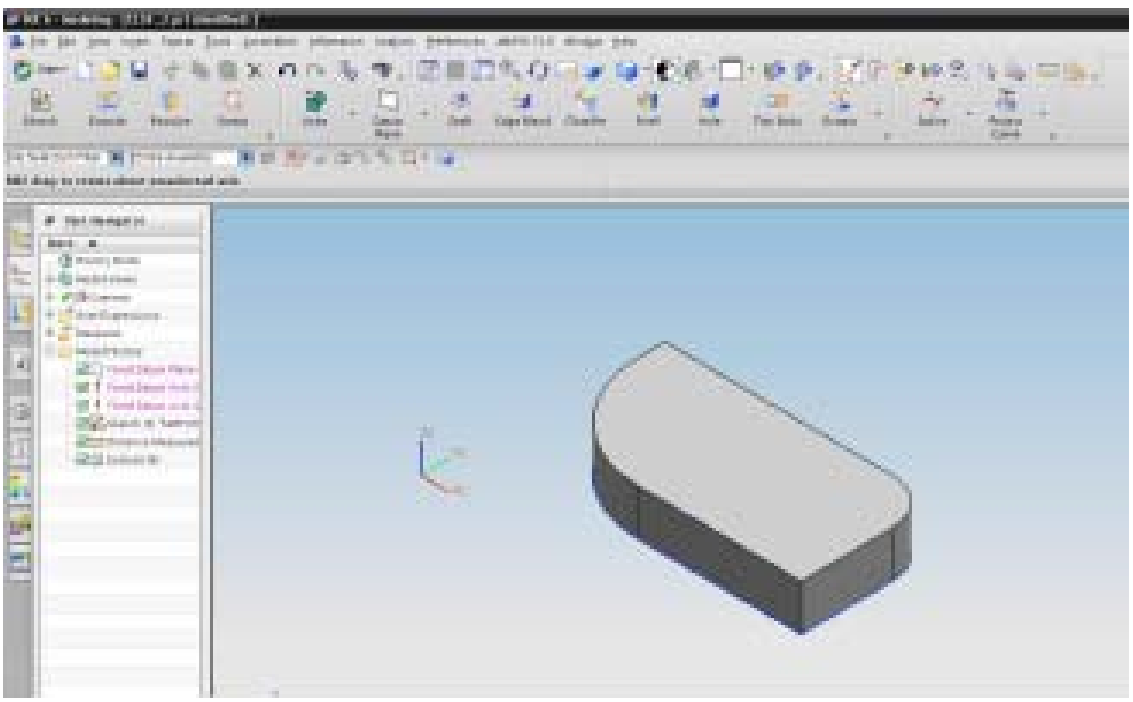


Figure A. 3: The part is designed in a CAD program

After the design is completed, the model is “Exported” as STL file format as shown in Figure-A4. For this process following path is used; File—Export—STL, and then a small pop-up window open as shown in Figure-A5.

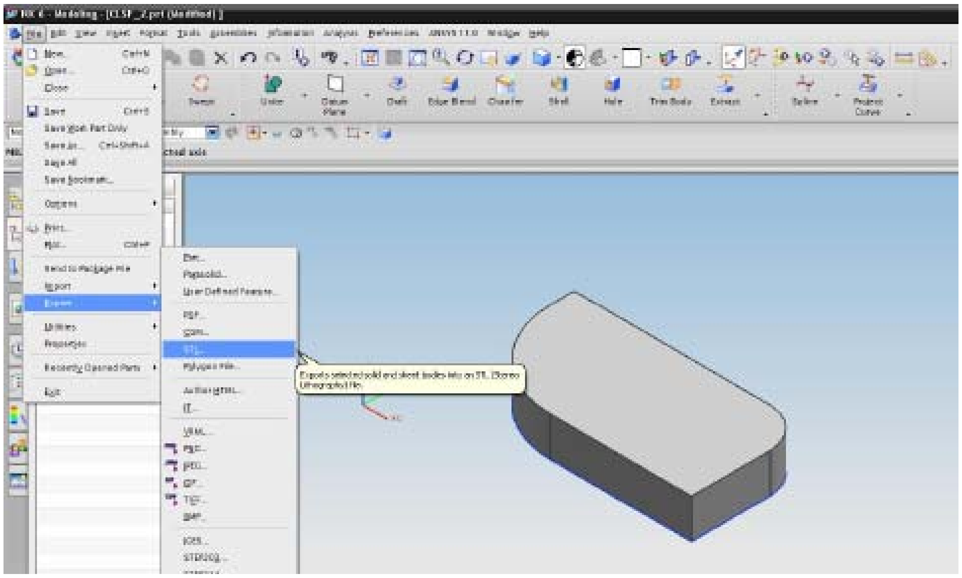


Figure A. 4: The model is converted to STL file format

Parameters of STL conversion is entered in this pop-up window. "Text" is chosen as output type. If the path will contain circular segments, it is recommended that "Triangle Tolerance" and "Adjacency Tolerance" values are entered as 0.025. After these steps are completed, the window is closed by pressing the "OK" icon.

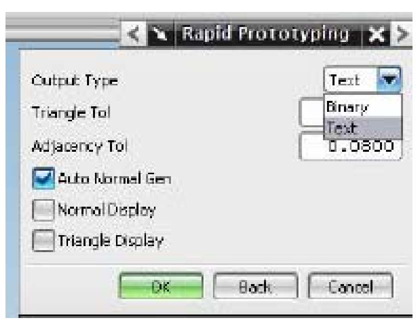


Figure A. 5: In the pop-up window, properties of the STL file is determined

A new window comes up and in this window the name of the STL file is entered. After this step is completed, "Class Selection" window opens (Figure-A6). Then, the model that is desired to be converted to STL file is selected. As a result, an STL file is created into the address which is determined in the previous step.

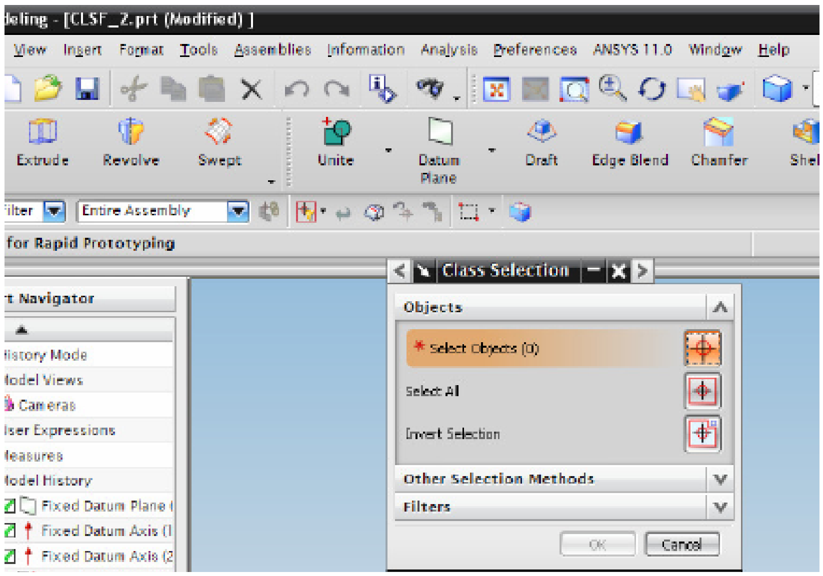
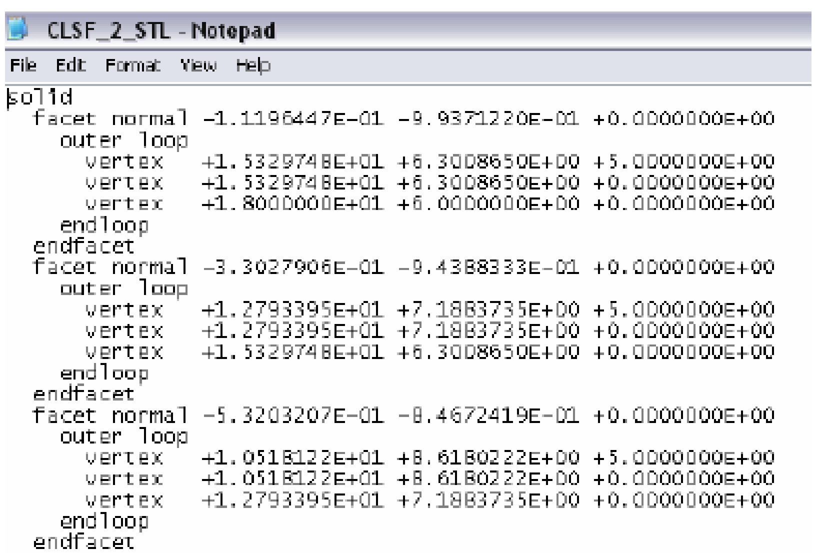


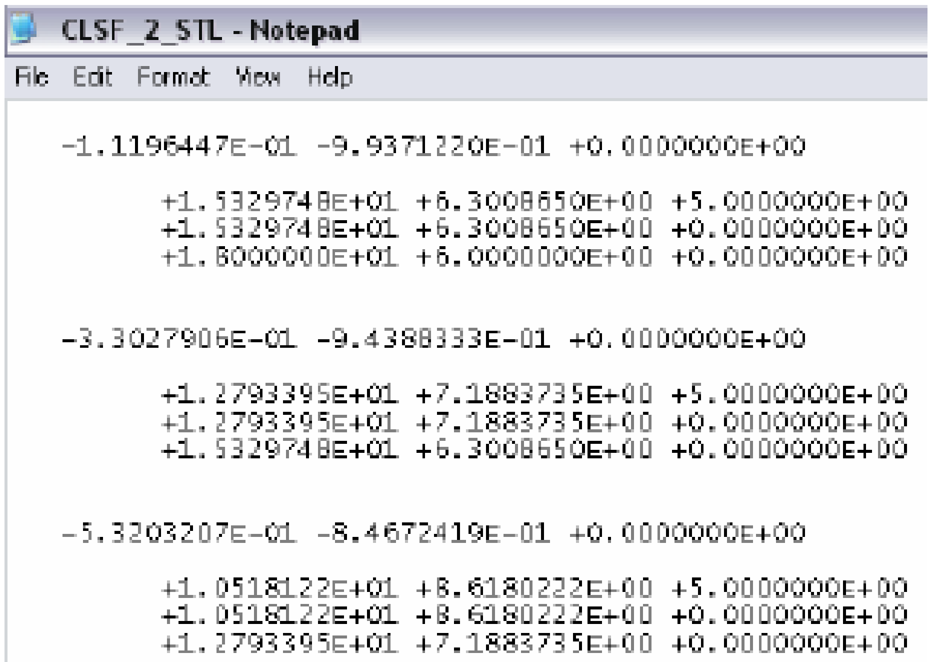
Figure A. 6: Class selection window




```
solid
  facet normal -1.1196447E-01 -9.9371220E-01 +0.0000000E+00
    outer loop
      vertex  +1.5329748E+01 +6.3008650E+00 +5.0000000E+00
      vertex  +1.5329748E+01 +6.3008650E+00 +0.0000000E+00
      vertex  +1.8000000E+01 +6.0000000E+00 +0.0000000E+00
    endloop
  endfacet
  facet normal -3.3027906E-01 -9.4388333E-01 +0.0000000E+00
    outer loop
      vertex  +1.2793395E+01 +7.1883735E+00 +5.0000000E+00
      vertex  +1.2793395E+01 +7.1883735E+00 +0.0000000E+00
      vertex  +1.5329748E+01 +6.3008650E+00 +0.0000000E+00
    endloop
  endfacet
  facet normal -5.3203207E-01 -8.4672419E-01 +0.0000000E+00
    outer loop
      vertex  +1.0518122E+01 +8.6180222E+00 +5.0000000E+00
      vertex  +1.0518122E+01 +8.6180222E+00 +0.0000000E+00
      vertex  +1.2793395E+01 +7.1883735E+00 +0.0000000E+00
    endloop
  endfacet
```

Figure A. 7: Appearance of an STL file

The STL file which is cleaned from words turns to a three columned file that is ready to be used in the MATLAB program (Figure-A8).


CLSF_2_STL - Notepad

File Edit Format View Help

```
-1.1196447E-01 -9.9371220E-01 +0.0000000E+00

      +1.5329748E+01 +6.3008650E+00 +5.0000000E+00
      +1.5329748E+01 +6.3008650E+00 +0.0000000E+00
      +1.8000000E+01 +6.0000000E+00 +0.0000000E+00


-3.3027906E-01 -9.4388333E-01 +0.0000000E+00

      +1.2793395E+01 +7.1883735E+00 +5.0000000E+00
      +1.2793395E+01 +7.1883735E+00 +0.0000000E+00
      +1.5329748E+01 +6.3008650E+00 +0.0000000E+00


-5.3203207E-01 -8.4672419E-01 +0.0000000E+00

      +1.0518122E+01 +8.6180222E+00 +5.0000000E+00
      +1.0518122E+01 +8.6180222E+00 +0.0000000E+00
      +1.2793395E+01 +7.1883735E+00 +0.0000000E+00
```

Figure A. 8: Final format of the STL file

The name of the prepared STL file is entered as input to the algorithm as shown in Figure-A9. The increment value must also be entered. As the last step, the program is run and X(+), X(-), Y(+), Y(-) and Z(+) signal arrays are generated by the program.

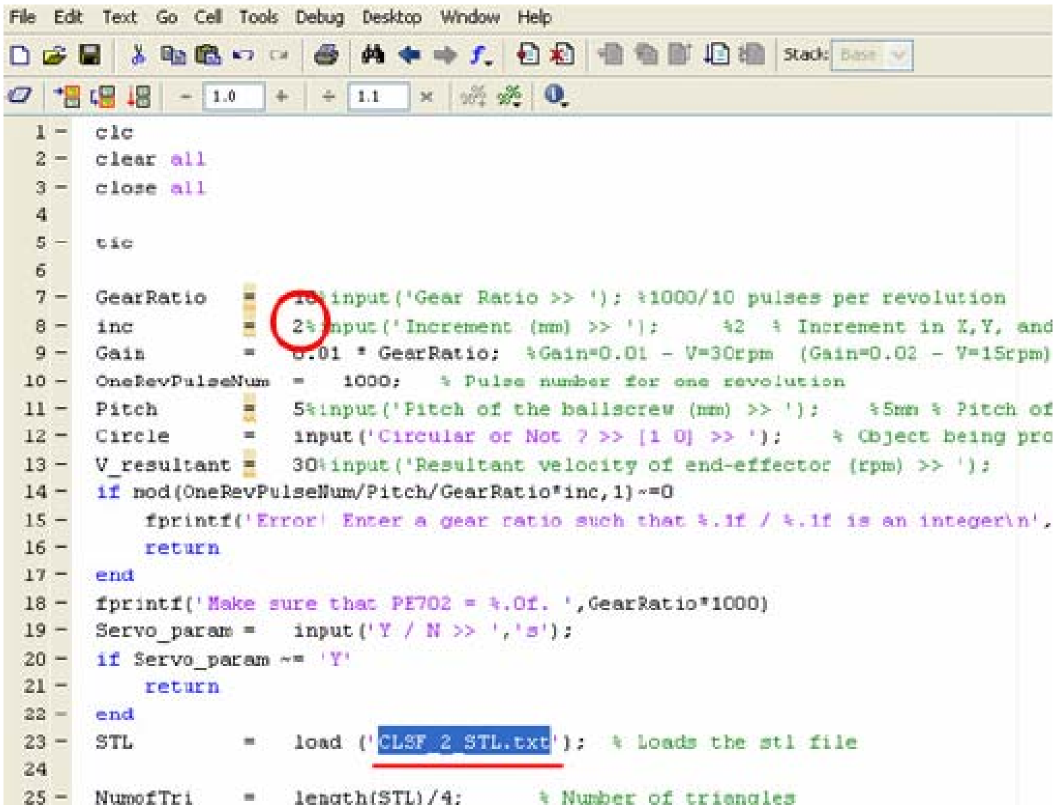
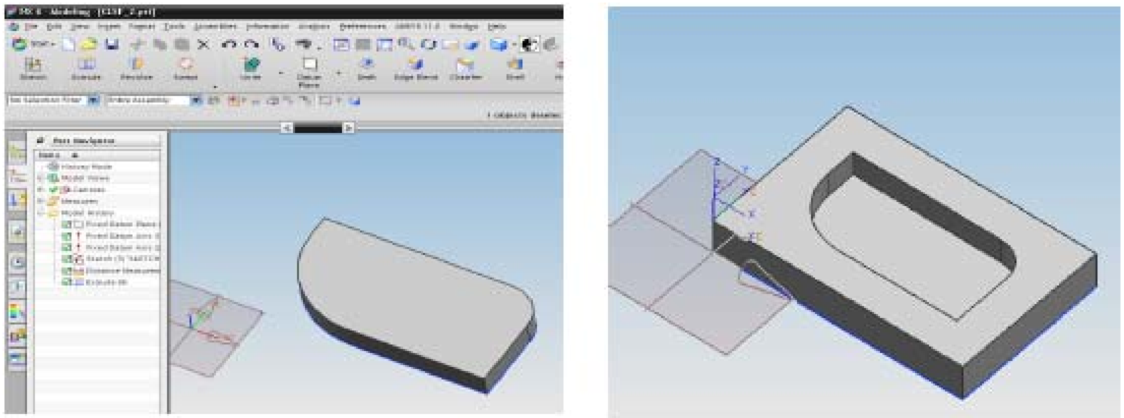


Figure A. 9: Loading of the STL file into the program

A-3 B) Conversion to CLSF format and necessary adjustments

While using an STL file in the procedure, the model itself that is desired to be produced is used. However, for the case where CLSF is used, the model geometry must be designed as a vacancy in a solid block. Because the CLSF file is obtained in the manufacturing module of the Cad program as if this vacancy is milled layer by layer. For example, if the model shown in Figure-A10-a is going to be produced, it has to be designed as the model shown in Figure-A10-b.



a) b)

Figure A. 10: a) The model that is going to be produced, b) corresponding model that has to be designed

After the model shown in Figure-A10-b is designed, in the manufacturing module of the Unigraphics the steps are followed which are used to generate G-codes (Figure-A11).

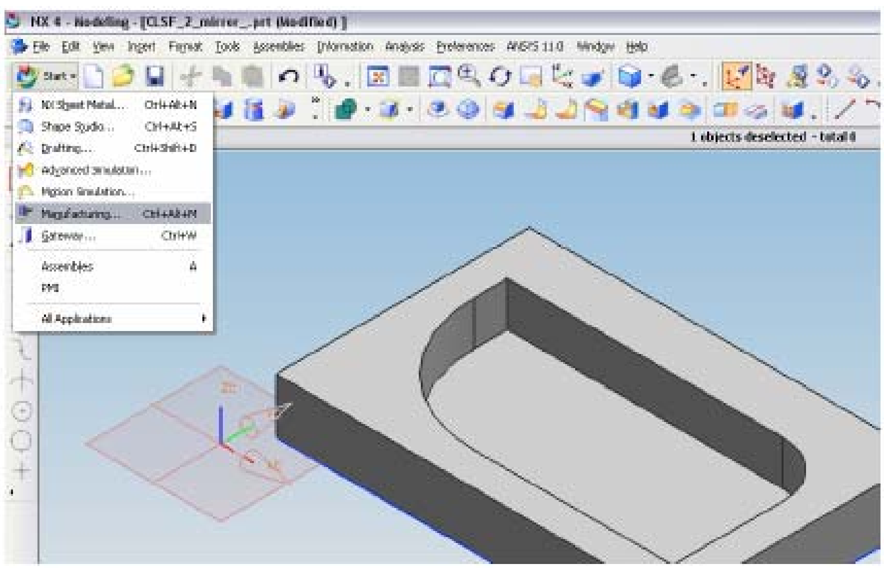


Figure A. 11: After the model is designed, manufacturing module of the CAD program is used to create the CLSF

The main advantage of the CLSF is that it provides different types of path options (Figure-A12). Any of he path options such as “zig-zag”, “zig”, “zig with contour”, “periphery”, “follow part”, “trochoidal” and “profile” which are used in milling operations can be chosen according to properties of the structure that is decided to be produced.

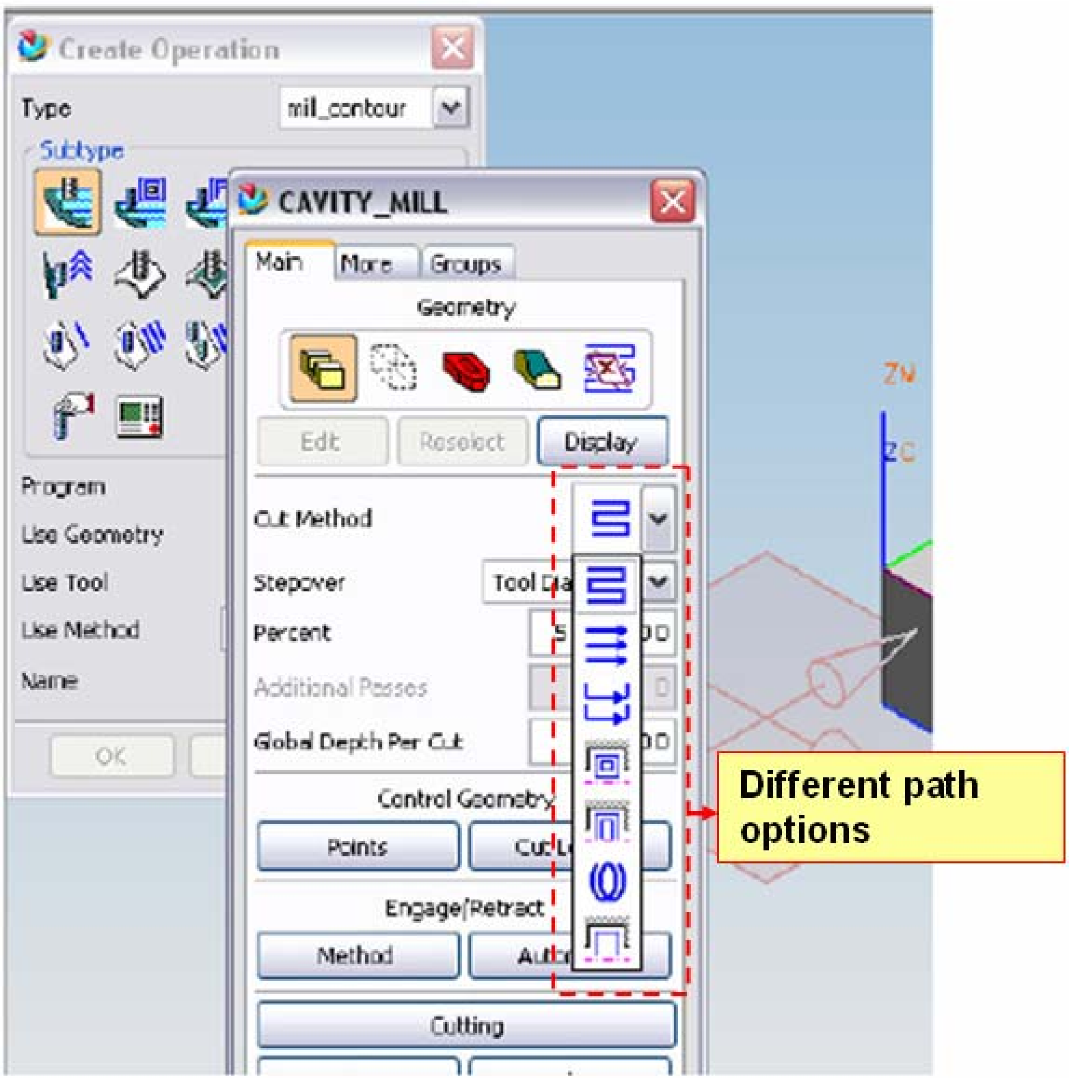


Figure A. 12: A wide range of path options are available with CLSF

The next step after the path is chosen is to set the hatch distance and layer thickness parameters. “Stepover” parameter is set as constant (Figure-A13). “Distance” and “Global depth of cut” parameters define the hatch distance and the layer thickness respectively. Although it is recommended that these parameters are set equal to the tip diameter of the nozzle, different numbers can be set for these parameters according to application. For example, to produce a scaffold for tissue engineering stepover parameter can be set much greater than the tip diameter of the nozzle resulting structures with hollow sections. This is another advantage of CLSF algorithm, because in STL algorithm, both hatch distance and the layer thickness values are same; they can not be set as different numbers.

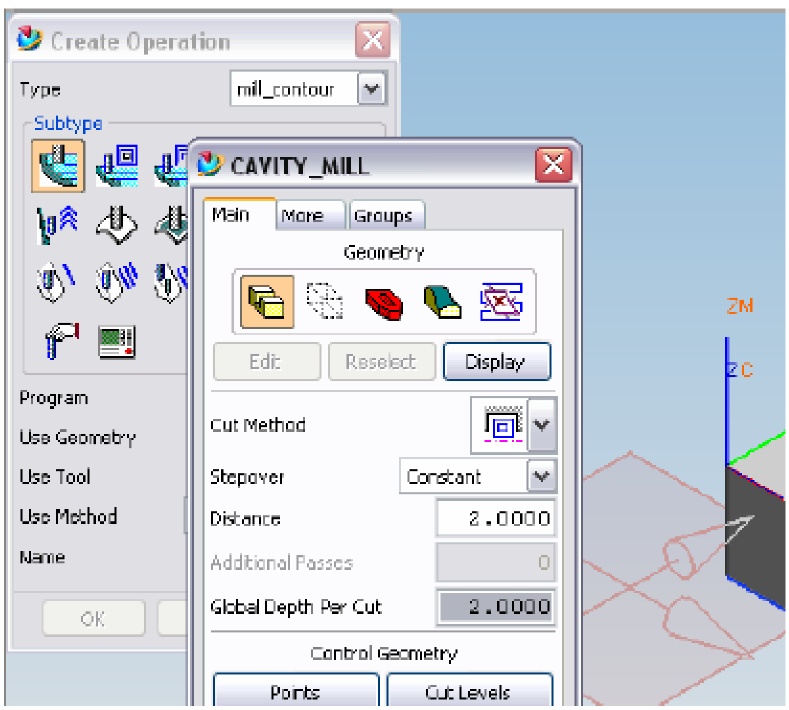


Figure A. 13: Parameters determine the hatch distance and layer thickness

After the foregoing steps are completed, path for milling operation is generated and the CLSF is obtained. At first, the CLSF is looks as in Figure-A14. Some of the unnecessary data is deleted from the file and the file arranged such that it can be processed in the MATLAB code.

```
CLSF_2 - Notepad
File  Edit  Format  View  Help
==============================================================
Information listing created by :  marc
Date                           :  26.08.2008 21:57:12
Current work part              :  C:\Documents and Settings\marc\Desktop\STUDENT FILES\Erdem\CLSF_2_mirror
Node name                      :  manf-lab-asus3
==============================================================
TOOL PATH/CAVITY_MILL,TOOL,MILL_1
TLDATA/MILL,2.1000,0.0000,75.0000,0.0000,0.0000
MSYS/0.0000,0.0000,6.0000,1.0000000,0.0000000,0.0000000,0.0000000,1.0000000,0.0000000
$$ centerline data
PAINT/PATH
PAINT/SPEED,10
PAINT/COLOR,186
RAPID
GOTO/18.2867,19.5948,3.0000,0.0000000,0.0000000,1.0000000
PAINT/COLOR,6
FEDRAT/MMPM,250.0000
CIRCLE/19.0250,19.0050,-2.0000,0.0000000,0.0000000,1.0000000,0.9450,0.0600,0.5000,2.1000,0.0000,TIMES,4
GOTO/19.0250,19.9500,-2.0000
PAINT/COLOR,31
GOTO/31.0000,19.9500,-2.0000
CIRCLE/31.0000,16.0000,-2.0000,0.0000000,0.0000000,1.0000000,3.9500,0.0600,0.5000,2.1000,0.0000
GOTO/34.9500,16.0000,-2.0000
GOTO/34.9500,7.0500,-2.0000
GOTO/16.0000,7.0500,-2.0000
CIRCLE/16.0000,16.0000,-2.0000,0.0000000,0.0000000,1.0000000,8.9500,0.0600,0.5000,2.1000,0.0000
GOTO/7.0618,15.5403,-2.0000
CIRCLE/16.0000,16.0000,-2.0000,0.0000000,0.0000000,1.0000000,8.9500,0.0600,0.5000,2.1000,0.0000
GOTO/7.0500,16.0000,-2.0000
GOTO/7.0500,19.9500,-2.0000
GOTO/19.0250,19.9500,-2.0000
PAINT/COLOR,36
GOTO/19.0250,17.9500,-2.0000
PAINT/COLOR,31
GOTO/31.0000,17.9500,-2.0000
CIRCLE/31.0000,16.0000,-2.0000,0.0000000,0.0000000,1.0000000,1.9500,0.0600,0.5000,2.1000,0.0000
GOTO/32.9500,16.0000,-2.0000
GOTO/32.9500,9.0500,-2.0000
GOTO/33.7526,8.2474,-2.0000
GOTO/32.9500,9.0500,-2.0000
GOTO/16.0000,9.0500,-2.0000
CIRCLE/16.0000,16.0000,-2.0000,0.0000000,0.0000000,1.0000000,6.9500,0.0600,0.5000,2.1000,0.0000
```

Figure A. 14: Appearance of a CLSF

Some expressions are changed in the CLSF. The "GOTO/" and "CIRCLE/" expressions are replaced with "1" and "2" respectively. The commas between the numbers are replaced with blanks. First three numbers and the sixth numbers in the expressions begins with "CIRCLE/" are kept but the other numbers in these expressions are deleted. The sixth numbers in these expressions are either "1" or "-1". If it is "1", the direction of the circular motion is CW; and if they are "-1", the direction of the circular motion is CCW. To fill the blanks in the fifth column, "0"s are placed after the expressions begins with "GOTO/". Appearance of the resultant file is shown in Figure-A15.

CLSF_2_clean - Notepad

File Edit Format View Help

1	19.0250	19.9500	-2.0000	0
1	31.0000	19.9500	-2.0000	0
2	31.0000	16.0000	-2.0000	1
1	34.9500	16.0000	-2.0000	0
1	34.9500	7.0500	-2.0000	0
1	16.0000	7.0500	-2.0000	0
2	16.0000	16.0000	-2.0000	1
1	7.0618	15.5403	-2.0000	0
2	16.0000	16.0000	-2.0000	1
1	7.0500	16.0000	-2.0000	0
1	7.0500	19.9500	-2.0000	0
1	19.0250	19.9500	-2.0000	0
1	19.0250	17.9500	-2.0000	0
1	31.0000	17.9500	-2.0000	0
2	31.0000	16.0000	-2.0000	1
1	32.9500	16.0000	-2.0000	0
1	32.9500	9.0500	-2.0000	0
1	33.7526	8.2474	-2.0000	0
1	32.9500	9.0500	-2.0000	0
1	16.0000	9.0500	-2.0000	0
2	16.0000	16.0000	-2.0000	1

Figure A. 15: Cleaned and arranged version of the CLSF

The algorithm is written such that the numbers in each column has a different meaning during the processing of CLSF. The numbers in first column defines whether the interpolation is linear or circular. The next three numbers are X, Y and Z coordinates of the nodes on the path. And the numbers in the last column, as mentioned before, define the direction of the circular interpolation. When the last version of the CLSF is loaded into the algorithm, the algorithm generates the array of pulses that run the RP system.

A3-C) Transmission of the generated signals

So far the processes for both methods are different, but when the signals are generated, transmission processes of them are same for both of them. Signals are sent from the RS232 serial port of PC by using a third program written in MATLAB program. This program is given in Appendix-6 D & E. Before this program is started to send the signals to the system, some of the steps that are given in Appendix-4 must be completed.

APPENDIX-4: Manual of the System

- Before the production begins, the X platform must be covered with a piece of stretch folio to prevent sticking of the production material on to the platform. Also, removing the produced part is easier when it is used. Cleaning of the machine is another reason of using a piece of stretch folio.

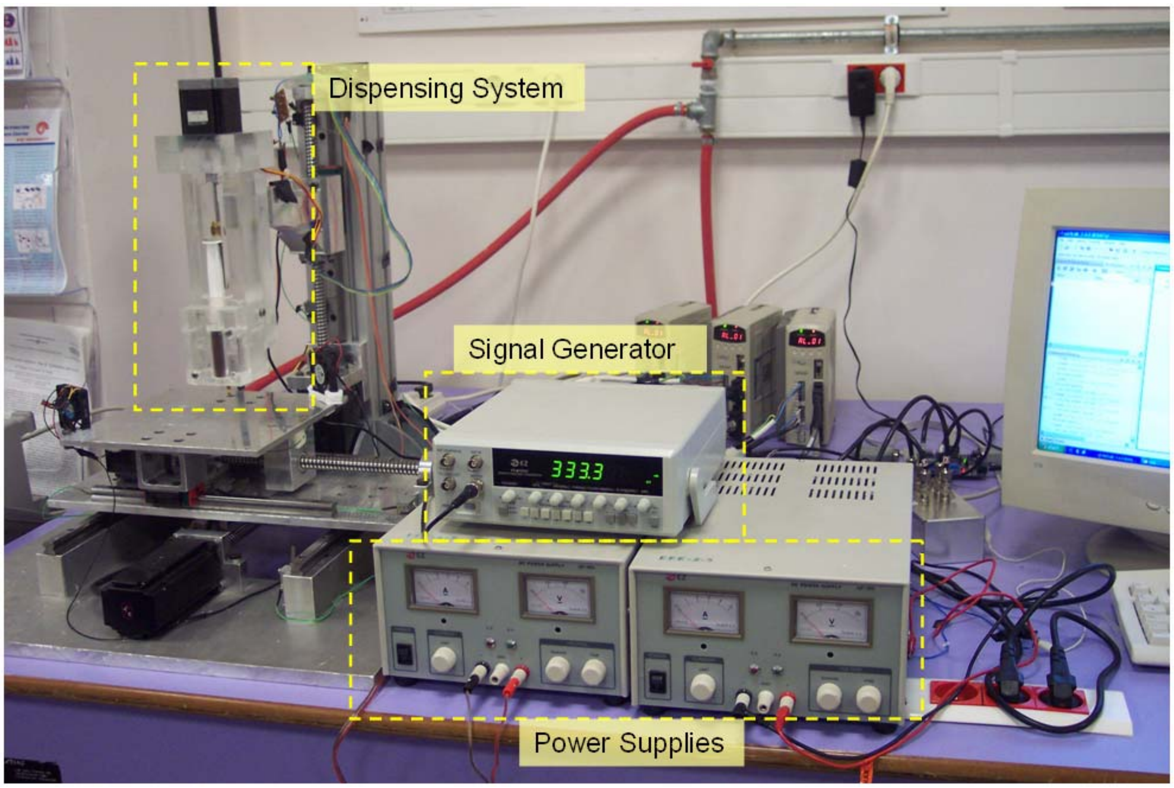


Figure A. 16: A general view from the developed RP system

- The dispensing system, seen in Figure-A16, must be brought closer to the X platform manually. The distance between the tip of the nozzle and the platform varies depending on the diameter of the nozzle going to be used. For example, if a nozzle diameter of 2mm is chosen, it is recommended that the distance between the nozzle and platform is adjusted between 2 to 3mm. Otherwise, if the distance is smaller than 2mm, the form of the disposed material is deformed and it spreads on a wider area (Figure-A17). And if the distance is much larger than 2mm, such as 5mm or higher, buckling occurs before the material reaches onto the platform. Resulting form is an S shaped line instead of a straight line (Figure-A17).

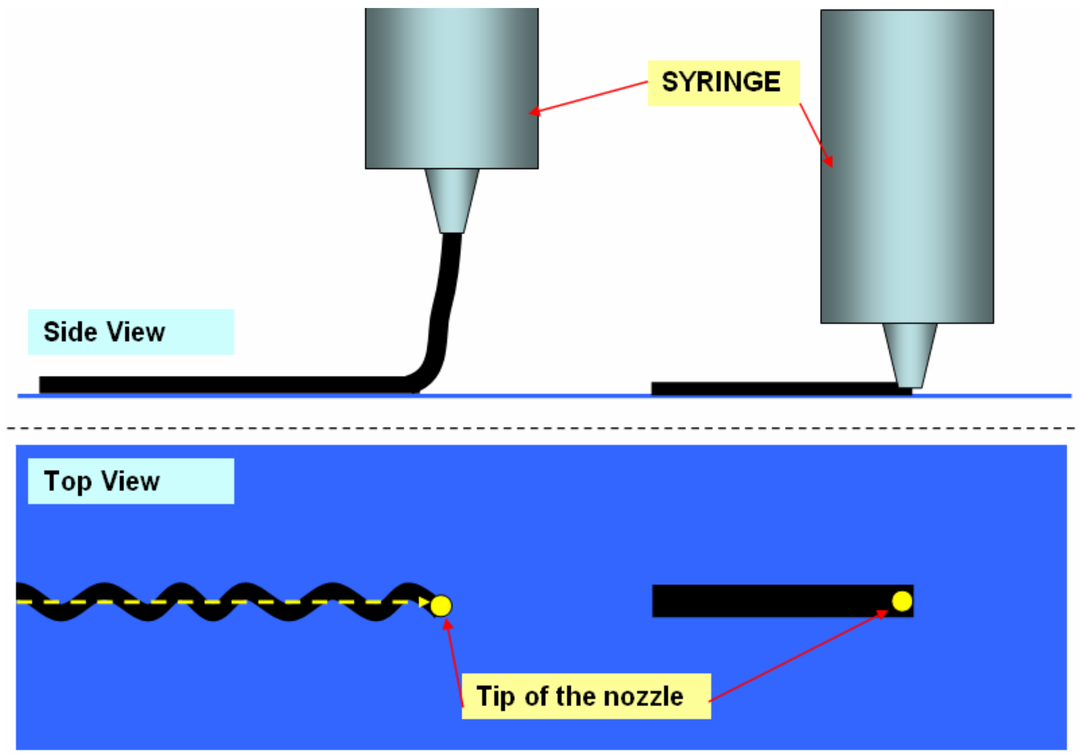


Figure A. 17: The distance between the nozzle and the platform is crucial. If the position of the tip is higher or lower than ideal level, deformations in the lines occur

- Before the system is started and signals are sent over the RS232 port of the PC, two power supplies shown in Figure-A16 must be turned on. One these power supplies feed the stepper motor of the dispensing system, and the other one supplies power to servo drivers and motors. Both power supplies must be adjusted to 24V.

According to the type of the stepper motor used in dispensing system, supplied voltage value and ampere value of the current may differ.

- The next step is turning on the signal generator from which square signals of magnitude 5V is sent to the driver of the stepper motor. The frequency of the signal varies according to chosen tip diameter and used material. For example; if the diameter is 2mm, the ideal working frequency is between 2.5 and 3.5Hz. If the diameter is 0.9mm, depending on the production material, the ideal working frequency is between 350 and 550mHz. Instead of using signal generator, the signals to drive the stepper motor of the dispensing system can be sent from the PC as done for servo drivers. But the development process of the system is still in progress and new material still have being tested. The frequency is tuned again if a new material is tested or a new nozzle diameter is chosen. Trial and error method is used for tuning of the frequency. Therefore, instead of sending signals from PC, it is preferred to use a signal generator.
- The MATLAB program that sends the generated pulse signals over RS232 port to the servo drivers is started.
- When the production is completed, the system stops since the signal flow is finished. At this step, first thing to do is to turn off the power supply and the signal generator that feed the stepper motor. Then, the other power supply is turned off, and dispensing system is risen manually. The waste material between the upper level of the part and the nozzle is removed with a long object.
- Since the current production material is silicone, it is waited for at least about 25 minutes of solidification time to remove the produced part from the platform.

APPENDIX-5: Technical Specifications of the Servo Motors

In developed system, three servo motors and their drivers are used as main driving system. The servo motor that maintains the motion of X platform has power of 100W and the other two are of 400W. Metronix Company's, currently known as Mecapion, servo motors are used. The codes of the motors of 100W and 400W are APM-SB01ADK and APM-SB04ADK respectively.

A technical drawing of the motor containing the exterior dimensions is given in Figure-A18. Variable dimensions are given in Table-A1.

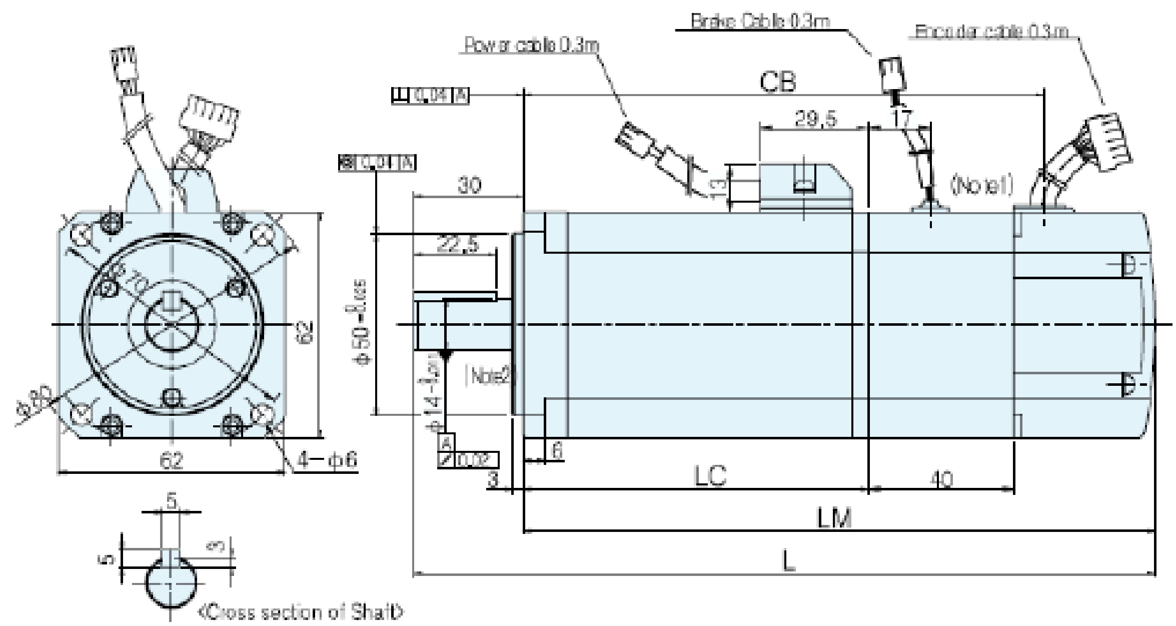


Figure A. 18: Technical drawing of servo motors and their exterior dimensions

Table A. 1: Variable dimensions of the servo motors –Complementary to Figure-A18

Model	Dimensions (mm)				Weight (kg)
	L	LM	LC	CB	
SB01A	122	92	52	59.5	0.82
SB04A	164	134	94	101.5	1.58

Torque and RPM data of the motors are given in Table-A2. This table also contains the code of the used servo drivers.

Table A. 2: Torque and RPM data of the servo motors

Servo Motor Model (APM-)		SB01A	SB04A
Servo Driver Model (APD-)		VS01	VS04
Rated Torque	[N.m]	0.318	1.274
Max. instantaneous Torque	[N.m]	0.955	3.822
Rated RPM	[r/min]	3000	
Max. RPM	[r/min]	5000	

APPENDIX-6: Developed Software and Used Programs

Three different slicing and path generator algorithm have been developed. The first algorithm which is STL based has been developed by Onur Demir who was initially responsible from this project. Except these three algorithms, two different programs are written to send generated signal data over RS232 port to the system. As mentioned in Section-3.3.1, generated signal data is composed of six different arrays of data and these arrays are compacted into one single array before sending through RS232 port. These compacted data must be decomposed later to be able to transfer the corresponding data to right destination. Therefore a program is written and loaded into a microchip which is connected directly to the RS232 serial port of the PC. Sixth program which is used in the system is loaded into the driver of the stepper motor that drives the dispensing subsystem. This is an ordinary program which drives the stepper motor in CW or CCW directions when signal is reached. These foregoing programs are given in this section.

A6-A) Algorithm-1: STL based program

```
clc
clear all
close all

tic

GearRatio   =   10%input('Gear Ratio >> '); %1000/10 pulses per
revolution
inc         =   2.5%input('Increment (mm) >> ');     %2  % Increment in
X,Y, and Z directions
Gain        =   0.01 * GearRatio;  %Gain=0.01 - V=30rpm  (Gain=0.02 -
V=15rpm)
OneRevPulseNum  =   1000;   % Pulse number for one revolution
Pitch       =   5%input('Pitch of the ballscrew (mm) >> ');    %5mm %
Pitch of the ballscrew
Circle      =   input('Circular or Not ? >> [1 0] >> ');    % Object
being processed is circular or not
V_resultant =   30%input('Resultant velocity of end-effector (rpm) >> ');
if mod(OneRevPulseNum/Pitch/GearRatio*inc,1)~=0
```

```
    fprintf('Error! Enter a gear ratio such that %.1f / %.1f is an
integer\n',OneRevPulseNum*inc/Pitch,GearRatio)
    return
end
fprintf('Make sure that PE702 = %.0f. ',GearRatio*1000)
Servo_param =   input('Y / N >> ','s');
if Servo_param ~= 'Y'
    return
end
STL         =   load ('mine.txt');  % Loads the stl file

NumofTri    =   length(STL)/4;      % Number of triangles
%arbitrary values for min & max of workspace to be used in determining
%actual values of workspace boundaries
MAXX = -200;
MINX = 200;
MAXY = -200;
MINY = 200;
MAXZ = -200;
MINZ = 200;

%determining the boundaries of workspace in X,Y, and Z directions
for i = 1:NumofTri
    MaxX = max([(STL(i*4-2,1));(STL(i*4-1,1));(STL(i*4,1))]);
    MaxY = max([(STL(i*4-2,2));(STL(i*4-1,2));(STL(i*4,2))]);
    MaxZ = max([(STL(i*4-2,3));(STL(i*4-1,3));(STL(i*4,3))]);
    MinX = min([(STL(i*4-2,1));(STL(i*4-1,1));(STL(i*4,1))]);
    MinY = min([(STL(i*4-2,2));(STL(i*4-1,2));(STL(i*4,2))]);
    MinZ = min([(STL(i*4-2,3));(STL(i*4-1,3));(STL(i*4,3))]);
    if MaxX>MAXX
        MAXX = MaxX;
    end
    if MaxY>MAXY
        MAXY = MaxY;
    end
    if MaxZ>MAXZ
        MAXZ = MaxZ;
    end
    if MinX<MINX
        MINX = MinX;
    end
    if MinY<MINY
        MINY = MinY;
    end
    if MinZ<MINZ
        MINZ = MinZ;
    end
end
```

```
clear MinX MinY MinZ MaxX MaxY MaxZ

%rounds up the min values to the nearest incremental value in the
positive direction
%rounds up the max values to the nearest incremental value in the
negative direction
if mod(MAXX,inc)~=0
    MAXX = MAXX-mod(MAXX,inc);
end
if mod(MAXY,inc)~=0
    MAXY = MAXY-mod(MAXY,inc);
end
if mod(MAXZ,inc)~=0
    MAXZ = MAXZ-mod(MAXZ,inc);
end
if mod(MINX,inc)~=0
    MINX = MINX+inc-mod(MINX,inc);
end
if mod(MINY,inc)~=0
    MINY = MINY+inc-mod(MINY,inc);
end
if mod(MINZ,inc)~=0
    MINZ = MINZ+inc-mod(MINZ,inc);
end

%arrays define 3D grid
MX = MINX:inc:MAXX;
MY = MINY:inc:MAXY;
MZ = MINZ:inc:MAXZ;

% clear MINX MINY MINZ MAXX MAXY MAXZ

%initial values for reference points to be used in creating pulse matrix
refx = 0;
refy = 0;
refz = 0;

pp = 0;     %initial index value for the pulse matrix

fid = fopen('izo.txt','w');     % Open file izo.dat

%main loop
for z = 1:length(MZ)    %z represents each cross section (layer)

    clear XY izo

    %creating X lines for current layer
    for xloop=1:length(MX)
```

```
    izo(xloop,1)=MX(xloop);
end

line_segment=0;
j=1;

%determines the points where z crosses each triangle and stores the X
%values, Y values, and the number of triangle
for i = 1:NumofTri
    V  = [(STL(i*4-3,1));(STL(i*4-3,2));(STL(i*4-3,3))];
    P1 = [(STL(i*4-2,1));(STL(i*4-2,2));(STL(i*4-2,3))];
    P2 = [(STL(i*4-1,1));(STL(i*4-1,2));(STL(i*4-1,3))];
    P3 = [(STL(i*4,1));(STL(i*4,2));(STL(i*4,3))];
    if (V(3)~=1.000 & V(3)~=-1.000)
        if P1(3)==MZ(z)
            XY(j,1) = P1(1);
            XY(j,2) = P1(2);
            XY(j,3) = i;
            j=j+1;
        end
        if P2(3)==MZ(z)
            XY(j,1) = P2(1);
            XY(j,2) = P2(2);
            XY(j,3) = i;
            j=j+1;
        end
        if P3(3)==MZ(z)
            XY(j,1) = P3(1);
            XY(j,2) = P3(2);
            XY(j,3) = i;
            j=j+1;
        end
    end
    %MaxZ = max([P1(3);P2(3);P3(3)]);
    %MinZ = min([P1(3);P2(3);P3(3)]);
    MaxZ12 = max([P1(3);P2(3)]);
    MinZ12 = min([P1(3);P2(3)]);
    MaxZ13 = max([P1(3);P3(3)]);
    MinZ13 = min([P1(3);P3(3)]);
    MaxZ23 = max([P2(3);P3(3)]);
    MinZ23 = min([P2(3);P3(3)]);
    if MZ(z)>MinZ12 & MZ(z)<MaxZ12
        X1 = ((MZ(z)-P1(3))*(P2(1)-P1(1))/(P2(3)-P1(3)))+P1(1);
        Y1 = ((MZ(z)-P1(3))*(P2(2)-P1(2))/(P2(3)-P1(3)))+P1(2);
        XY(j,1) = X1;
        XY(j,2) = Y1;
        XY(j,3) = i;
        j=j+1;
```

```
        end
        if MZ(z)>MinZ13 & MZ(z)<MaxZ13
            X2 = ((MZ(z)-P1(3))*(P3(1)-P1(1))/(P3(3)-P1(3)))+P1(1);
            Y2 = ((MZ(z)-P1(3))*(P3(2)-P1(2))/(P3(3)-P1(3)))+P1(2);
            XY(j,1) = X2;
            XY(j,2) = Y2;
            XY(j,3) = i;
            j=j+1;
        end
        if MZ(z)>MinZ23 & MZ(z)<MaxZ23
            X3 = ((MZ(z)-P2(3))*(P3(1)-P2(1))/(P3(3)-P2(3)))+P2(1);
            Y3 = ((MZ(z)-P2(3))*(P3(2)-P2(2))/(P3(3)-P2(3)))+P2(2);
            XY(j,1) = X3;
            XY(j,2) = Y3;
            XY(j,3) = i;
            j=j+1;
        end
    end

    clear MaxZ MaxZ12 MaxZ13 MaxZ23 MinZ MinZ12 MinZ13 MinZ23

    %creates line segments between the points where z crosses each
triangle
    % & stores the points in izo matrix where each X line crosses line
    % segments
    for line_x = 1:length(XY(:,3))-1
        if XY(line_x,3) == XY(line_x+1,3)
            X1 = XY(line_x,1);
            Y1 = XY(line_x,2);
            X2 = XY(line_x+1,1);
            Y2 = XY(line_x+1,2);
            maxx = min(find((MX<max(X1,X2)+inc)&(MX>max(X1,X2)-inc)));
            minx = max(find((MX<min(X1,X2)+inc)&(MX>min(X1,X2)-inc)));
            if (X1-X2)~=0
                line_segment=line_segment+1;
                izo(:,line_segment+1) = 10000;  %10000 is used in order
to prevent
                %the confusion of zeros,cross points and automatically
assigned ones
                for ixx = minx:maxx
                    izo(ixx,line_segment+1) = (Y1-Y2)*(MX(ixx)-X1)/(X1-
X2)+Y1;
                end
            end
        end
    end
```

```
    izo(:,2:line_segment+1)=sort(izo(:,2:line_segment+1),2);    %sorts
the crossing points

    %%%%%%%%%% Write izo matrix to file %%%%%%%%%%
    %     size_izo=size(izo);
    %     if size_izo(2)~=1
    %         for iw=1:length(izo(:,1))
    %             for jw=1:length(izo(1,:))
    %                 fprintf(fid,'%5.4f\t\t',izo(iw,jw));
    %             end
    %             fprintf(fid,'\n');
    %         end
    %     end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    if Circle == 1
        pulsez = (MZ(z)-refz);
    else
        pulsez = (MZ(z)-refz)/inc;  %generates the pulse to be operated
in Z direction
    end
    pulsez = abs(pulsez);   %magnitude of Z-pulse
    refz = MZ(z);   %new location of the injector in Z direction

    if Circle == 1

        for xx=1:length(izo(:,1))
            pp = pp+1;
            pulsex = (izo(xx,1)-refx);
            pulsey = -((izo(xx,2)-refy));
            dir =   sign([pulsex pulsey pulsez]);
            pulse(pp,:) = [abs(pulsex) abs(pulsey) abs(pulsez) dir ];
            refx = izo(xx,1);
            refy = izo(xx,2);
            pulsez = 0;
        end

        for xx=length(izo(:,1))-1:-1:1
            pp = pp+1;
            pulsex = (izo(xx,1)-refx);
            pulsey = (izo(xx,2)-refy);
            dir =   sign([pulsex pulsey pulsez]);
            pulse(pp,:) = [abs(pulsex) abs(pulsey) abs(pulsez) dir ];
            refx = izo(xx,1);
            refy = izo(xx,2);
            pulsez = 0;
        end
```

```
    else

        if mod(z,2) ~= 0
            %loop generating pulse matrix
            for xx=1:length(izo(:,1))
                clear repeat find_y
                find_y =
izo(xx,find(izo(xx,2:length(izo(1,:)))~=10000)+1); %takes the points X
lines crossed

                %if there is no crossing, jump next xx for the next
iteration
                if length(find_y)==0
                    continue
                end

                length_find = 1;
                k_repeat = 1;
                %cancels repeating X-line-crossed points
                while length_find <= length(find_y)
                    t_repeat = find(find_y==find_y(length_find));
                    repeat(k_repeat) = find_y(t_repeat(end));
                    length_find = t_repeat(end)+1;
                    k_repeat = k_repeat+1;
                end

                pulsex = (izo(xx,1)-refx)/inc;  %generates the pulse to
be operated in X direction
                mat = 1;
                pp = pp+1;

                if mod(xx,2) ~= 0
                    pulsey = (MY(min(find(MY>=repeat(1))))-refy)/inc;
                    dir = sign([pulsex pulsey pulsez]);
                    pulsex = abs(pulsex);
                    pulsey = abs(pulsey);
                    pulse(pp,:) = [pulsex pulsey pulsez dir mat];
                    refy = MY(max(find(MY<=repeat(end))));
                else
                    pulsey = (MY(max(find(MY<=repeat(end))))-refy)/inc;
                    dir = sign([pulsex pulsey pulsez]);
                    pulsex = abs(pulsex);
                    pulsey = abs(pulsey);
                    pulse(pp,:) = [pulsex pulsey pulsez dir mat];
                    refy = MY(min(find(MY>=repeat(1))));
                end
```

```
                if length(repeat) == 1
                    pp = pp+1;
                    pulse(pp,:) = [0 0 0 0 0 0 1];
                else
                    if mod(xx,2) ~= 0
                        dir = [0 1 0];
                    else
                        dir = [0 -1 0];
                    end
                    if mod(xx,2)~=0
                        for k=1:length(repeat)-1
                            pp = pp+1;
                            pulsex = 0;
                            kk1 = MY(max(find(MY<=repeat(k+1))));
                            kk2 = MY(min(find(MY>=repeat(k))));
                            pulsez = 0;
                            MY_repmax = length(find(MY==repeat(k+1)));
                            MY_repmin = length(find(MY==repeat(k)));
                            if mod(k,2)==0
                                if (MY_repmax==1 & MY_repmin==1)
                                    pulsey = (kk1-kk2)/inc;
                                elseif (MY_repmax==0 & MY_repmin==1) |
(MY_repmax==1 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+1;
                                elseif (MY_repmax==0 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+2;
                                end
                                mat = 1;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            else
                                pulsey = (kk1-kk2)/inc;
                                mat = 0;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            end
                        end
                    else
                        for k=length(repeat):-1:2
                            pp = pp+1;
                            pulsex = 0;
                            kk1 = MY(max(find(MY<=repeat(k))));
                            kk2 = MY(min(find(MY>=repeat(k-1))));
                            pulsez = 0;
                            MY_repmax = length(find(MY==repeat(k)));
                            MY_repmin = length(find(MY==repeat(k-1)));
                            if mod(k,2)==0
                                pulsey = (kk1-kk2)/inc;
```

```
                                mat = 0;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            else
                                if (MY_repmax==1 & MY_repmin==1)
                                    pulsey = (kk1-kk2)/inc;
                                elseif (MY_repmax==0 & MY_repmin==1) |
(MY_repmax==1 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+1;
                                elseif (MY_repmax==0 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+2;
                                end
                                mat = 1;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            end
                        end
                    end
                end
                refx = izo(xx,1);
                pulsez = 0;
            end
        end

        if mod(z,2) == 0
            %loop generating pulse matrix
            for xx=length(izo(:,1)):-1:1
                clear repeat find_y
                find_y =
izo(xx,find(izo(xx,2:length(izo(1,:)))~=10000)+1); %takes the points X
lines crossed

                %if there is no crossing, jump next xx for the next
iteration
                if length(find_y)==0
                    continue
                end

                length_find = 1;
                k_repeat = 1;
                %cancels repeating X-line-crossed points
                while length_find <= length(find_y)
                    t_repeat = find(find_y==find_y(length_find));
                    repeat(k_repeat) = find_y(t_repeat(end));
                    length_find = t_repeat(end)+1;
                    k_repeat = k_repeat+1;
                end
```

```
                pulsex = (izo(xx,1)-refx)/inc;  %generates the pulse to
be operated in X direction
                mat = 1;
                pp = pp+1;

                if mod(xx,2) ~= 0
                    pulsey = (MY(min(find(MY>=repeat(1))))-refy)/inc;
                    dir = sign([pulsex pulsey pulsez]);
                    pulsex = abs(pulsex);
                    pulsey = abs(pulsey);
                    pulse(pp,:) = [pulsex pulsey pulsez dir mat];
                    refy = MY(max(find(MY<=repeat(end))));
                else
                    pulsey = (MY(max(find(MY<=repeat(end))))-refy)/inc;
                    dir = sign([pulsex pulsey pulsez]);
                    pulsex = abs(pulsex);
                    pulsey = abs(pulsey);
                    pulse(pp,:) = [pulsex pulsey pulsez dir mat];
                    refy = MY(min(find(MY>=repeat(1))));
                end


                if length(repeat) == 1
                    pp = pp+1;
                    pulse(pp,:) = [0 0 0 0 0 0 1];
                else
                    if mod(xx,2) ~= 0
                        dir = [0 1 0];
                    else
                        dir = [0 -1 0];
                    end
                    if mod(xx,2)~=0
                        for k=1:length(repeat)-1
                            pp = pp+1;
                            pulsex = 0;
                            kk1 = MY(max(find(MY<=repeat(k+1))));
                            kk2 = MY(min(find(MY>=repeat(k))));
                            pulsez = 0;
                            MY_repmax = length(find(MY==repeat(k+1)));
                            MY_repmin = length(find(MY==repeat(k)));
                            if mod(k,2)==0
                                if (MY_repmax==1 & MY_repmin==1)
                                    pulsey = (kk1-kk2)/inc;
                                elseif (MY_repmax==0 & MY_repmin==1) |
(MY_repmax==1 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+1;
                                elseif (MY_repmax==0 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+2;
```

```
                                end
                                mat = 1;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            else
                                pulsey = (kk1-kk2)/inc;
                                mat = 0;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            end
                        end
                    else
                        for k=length(repeat):-1:2
                            pp = pp+1;
                            pulsex = 0;
                            kk1 = MY(max(find(MY<=repeat(k))));
                            kk2 = MY(min(find(MY>=repeat(k-1))));
                            pulsez = 0;
                            MY_repmax = length(find(MY==repeat(k)));
                            MY_repmin = length(find(MY==repeat(k-1)));
                            if mod(k,2)==0
                                pulsey = (kk1-kk2)/inc;
                                mat = 0;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            else
                                if (MY_repmax==1 & MY_repmin==1)
                                    pulsey = (kk1-kk2)/inc;
                                elseif (MY_repmax==0 & MY_repmin==1) |
(MY_repmax==1 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+1;
                                elseif (MY_repmax==0 & MY_repmin==0)
                                    pulsey = (kk1-kk2)/inc+2;
                                end
                                mat = 1;
                                pulse(pp,:) = [pulsex pulsey pulsez dir
mat];
                            end
                        end
                    end
                end
                refx = izo(xx,1);
                pulsez = 0;
            end
        end
    end
end
fclose(fid);
```

```
toc

if Circle == 1
    pulse_n =   [OneRevPulseNum/Pitch/GearRatio*pulse(:,1:3)
pulse(:,4:6)];
    pulse_n(:,2)    =   round(pulse_n(:,2));
else
    pulse_n =   pulse;
end
yg=pulse_n(:,2);
xg=pulse_n(:,1);
zg=pulse_n(:,3);
xr=pulse_n(:,4);
yr=pulse_n(:,5);
zr=pulse_n(:,6);
mg=pulse_n(:,7);

f0=[0 0];   f1=[1 0];   px=0;   py=0;   pz=0;   pm=0;

for i=1:length(xg)
    mm=max(max(xg(i),yg(i)),zg(i));
    zz1=abs(xg(i)-yg(i));
    zz2=abs(zg(i)-yg(i));
    zz3=abs(zg(i)-xg(i));

    if Circle == 1
        PulseRepeat = 1;
    else
        PulseRepeat = OneRevPulseNum/Pitch/GearRatio*inc;
    end
    pxa=repmat(f1,1,round(PulseRepeat*xg(i)));
    pya=repmat(f1,1,round(PulseRepeat*yg(i)));
    pza=repmat(f1,1,round(PulseRepeat*zg(i)));

    if mg(i)==1
        pma=repmat(f0,1,round(PulseRepeat*mm));
    elseif mg(i)==0
        pma=repmat(f1,1,round(PulseRepeat*mm));
    end

    if xr(i)<0
        pxa=-pxa;
    end

    if yr(i)<0
        pya=-pya;
    end
```

```
    if zr(i)<0
        pza=-pza;
    end

    px=[px pxa];
    py=[py pya];
    pz=[pz pza];
    pm=[pm pma];

    if mm==xg(i)
        pyb=repmat(f0,1,round(PulseRepeat*zz1));
        py=[py pyb];
        pzb=repmat(f0,1,round(PulseRepeat*zz3));
        pz=[pz pzb];
    elseif mm==yg(i)
        pxb=repmat(f0,1,round(PulseRepeat*zz1));
        px=[px pxb];
        pzb=repmat(f0,1,round(PulseRepeat*zz2));
        pz=[pz pzb];
    else
        pxb=repmat(f0,1,round(PulseRepeat*zz3));
        px=[px pxb];
        pyb=repmat(f0,1,round(PulseRepeat*zz2));
        py=[py pyb];
    end
end

pm_bool   = boolean(abs(pm));
px_f_bool = boolean(abs(px));
px_r_bool = boolean(sign((px+[px(2:end) px(end-1)])+1));
py_f_bool = boolean(abs(py));
py_r_bool = boolean(sign((py+[py(2:end) py(end-1)])+1));
pz_f_bool = boolean(abs(pz));


toc

PosX=0;
PosY=0;
PosZ=0;

PosIncX=0;
PosIncY=0;
PosIncZ=0;

figure(1)
axis([MINX MAXX MINY MAXY MINZ MAXZ])
plot3(PosX,PosY,PosZ,'b*'),hold on
```

```
axis([MINX MAXX MINY MAXY MINZ MAXZ])
color='b*g*m*r*k*b*g*m*r*k*b*g*m*r*k*b*g*m*r*k*b*g*m*r*k*b*g*m*r*k*';
color_count=1;
%
for pulse_counter = 1:length(px)

    mmm =   0;
    nnn =   0;
    lll =   0;

    if px(pulse_counter)==1
        PosIncX  =   PosIncX + 1;
    end

    if py(pulse_counter)==1
        PosIncY  =   PosIncY + 1;
    end

    if pz(pulse_counter)==1
        PosIncZ  =   PosIncZ + 1;
    end

    if px(pulse_counter)==-1
        PosIncX  =   PosIncX - 1;
    end

    if py(pulse_counter)==-1
        PosIncY  =   PosIncY - 1;
    end

    if pz(pulse_counter)==-1
        PosIncZ  =   PosIncZ - 1;
    end

    if (mod(PosIncX,OneRevPulseNum/Pitch/GearRatio*inc)==0) &
(px(pulse_counter)~=0)
        PosX  =   PosIncX * Pitch * GearRatio/OneRevPulseNum;
        mmm    =   1;
    end

    if (mod(PosIncY,OneRevPulseNum/Pitch/GearRatio*inc)==0) &
(py(pulse_counter)~=0)
        PosY  =   PosIncY * Pitch * GearRatio/OneRevPulseNum;
        nnn    =   1;
    end

    if (mod(PosIncZ,OneRevPulseNum/Pitch/GearRatio*inc)==0) &
(pz(pulse_counter)~=0)
```

```
        PosZ  =   PosIncZ * Pitch * GearRatio/OneRevPulseNum;
        lll    =   1;
        color_count=color_count+2;
    end

    if (mmm==1) | (nnn==1) | (lll==1)
        plot3(PosX,PosY,PosZ,color(color_count:color_count+1)),hold on
        axis([MINX MAXX MINY MAXY MINZ MAXZ])
        pause(0.001)
    end
end

xlabel('X'),ylabel('Y'),zlabel('Z')

%%%%%%%%%%%%%%%%%%%%%%%%% PLOT PULSES IN THREE AXES %%%%%%%%%%%%%%%

% x_activation    =   0.5*sign((px+[px(2:end) px(end-1)])+1);
% y_activation    =   0.5*sign((py+[py(2:end) py(end-1)])+1);
% z_activation    =   0*sign((pz+[pz(2:end) pz(end-1)])+1);
%
% figure(2)
% plot(px,'r'), hold on
% plot(x_activation,'b')
% xlabel('Number of pulses in x-direction')
% ylabel('Pulse Amplitude')
% title('Pulses in x-direction')
%
% figure(3)
% plot(py,'r'), hold on
% plot(y_activation,'b')
% xlabel('Number of pulses in y-direction')
% ylabel('Pulse Amplitude')
% title('Pulses in y-direction')
%
% figure(4)
% plot(pz,'r'), hold on
% plot(z_activation,'b')
% xlabel('Number of pulses in z-direction')
% ylabel('Pulse Amplitude')
% title('Pulses in z-direction')
%
% figure(5)
% plot(px,'r'), hold on
% plot(x_activation,'b'), hold on
% plot(py,'y'), hold on
% plot(y_activation,'m'), hold on
% plot(pz,'g'), hold on
% plot(z_activation,'k')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%% SPEED CONTROL %%%%%%%%%%%%%%%%%%%%%%%%%%%%

% warning off
% pulse_s = pulse;
% for i_s = 1:length(pulse(:,1))
%     row_sum =   sum((pulse(i_s,1:3)).^2);
%     if row_sum == 0
%         continue
%     end
%     vel =   (pulse(i_s,1:3) / (sqrt(row_sum) / V_resultant)) .*
pulse(i_s,4:6);
%     voltage(i_s,1:3)  =   vel * 0.1 / 21;
%     voltage(i_s,4)  =   max(pulse(i_s,1:3) * inc ./ (abs(vel) * pitch /
60),[],2);
% end
% warning on
% for kkk=1:length(voltage(:,1))
%     voltage(kkk,5)=sum(voltage(1:kkk,4));
% end
% voltage_x=[voltage(find(voltage(:,1)~=0),1)
voltage(find(voltage(:,1)~=0)-1,5) voltage(find(voltage(:,1)~=0),5)];
% voltage_y=[voltage(find(voltage(:,2)~=0),1)
voltage(find(voltage(:,2)~=0)-1,5) voltage(find(voltage(:,2)~=0),5)];
% voltage_z=[voltage(find(voltage(:,3)~=0),1)
voltage(find(voltage(:,3)~=0)-1,5) voltage(find(voltage(:,3)~=0),5)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%

toc

%rtwbuild('dson4_erdem_gecici')
```

A6-B) Algorithm-2: CLSF based program

```
% Bu program NX ten alýnmýþ CLSF dosyasýnýn iþlenip RPM da kullanýlacak
% path in hazýrlanmasýný için yazýlmýþtýr
clear all
close all
clc

%% Dsoya alýmý ve dosyada ki ilk düzenleme
% iþlenecek dosyanýn yüklenmesi
A = load('upper_part_1_22_zigzag.txt');

% incrementin belirlenmesi
inc = input('Enter the increment value=');

% 4. kolonda ki Z koordinatlarýnýn yönlerinin -Z den + Z de çevrilmesi
for i=1:length(A(:,:));
    for j=1:4;
        A(i,j) = A(i,j);
        if j==4
            A(i,j) = A(i,j) .* -1;
        end
    end
end

% Maximum row ve column deðerlerinin belirlenmesi
MaxRow = length(A(:,1));
MaxColumn = length(A(1,:));

%% Ýstenmeyen Z koordinatlarýnýn silinmesi ve yeni bir matx.
oluþturulmasý
% A matrixinden Z coordinatlarýnýn alt katmana geçmesini engellemek için
% oluþturulan yeni B matrixinin loopundan kullanlacak icrement deðiþkeni
k = 1;

% Referans aldýðýmýz ilk koordinat dizisinin Z koordinatý
Ref1 = A(1,4);

% Pre-allocation for preB matrix
Bpre = zeros(MaxRow,MaxColumn);

% Bir alt levele inen koordinatlarýn temizlenerek yeni preB matx. nin
oluþturulmasý
for i=1:length(A(:,:));

    if (Ref1 <= A(i,4))
  Bpre(k,1) = A(i,1);
  Bpre(k,2) = A(i,2);
```

```
  Bpre(k,3) = A(i,3);
  Bpre(k,4) = A(i,4);
  Bpre(k,5) = A(i,5);

  k = k + 1;
  Ref1 = A(i,4);
    end
end

%% GOTO ve CIRCLE komutlarýnýn tanýmlanmasý ve koor. farklarýnýn hesabý

% % Referans aldýðýmýz ikinci satýrýn ilk elemaný; 1 yada 2 olabilir,
% % 1: GOTO 2: CIRCLE
% Ref2 = B(2,1);

% Dosyada kaç GOTO ve kaç CIRCLE olduðunu bulmak için aþaðýda yazýlan for
% döngüsünde kullanýlacak deðiþkenlerin tanýmlanmasý
Zero = 0; % Bpre matrixinde bos kalan sat?rlar? tutacak
One = 0; % for döngüsü sonunda dosyada kaç GOTO olduðunu bu deðiþken
tutacak
Two = 0; % for döngüsü sonunda dosyada kaç CIRCLE olduðunu bu deðiþken
tutacak

% Dosyada kaç tane GOTO ve CIRCLE olduðunu hesaplayan döngü
for i=1:length(Bpre(:,:))
    if Bpre(i,1) == 1
        One = One + 1;
    end

    if Bpre(i,1) == 2
        Two = Two + 1;
    end

    if Bpre(i,1) == 0
        Zero = Zero + 1;
    end
end

% Level atlamalar? ortadan kald?rmak icin yukar?da yazd?g?m?z döngülerden
% sonra Bpre matrixinde bos kalan sat?rlar?n problem yaratmamas? icin B
% ad?nda yeni bir matrixe aktar?l?yor data
B = zeros(MaxRow-Zero,MaxColumn);

for i=1:(MaxRow-Zero)
    for j=1:MaxColumn
        B(i,j) = Bpre(i,j);
    end
end
```

```
% Eðer path de CIRCLE komutu varsa program eðriyi oluþturabilmesi için
% aralýklarýn girilmesi
if Two >= 1;
    Gap = input('The path contains curves. Please enter the number of
gaps for circular interpolation =');

    % CIRCLE komutunda verilen daire merkezi koordinatýnýn çýkarýlýp
yerine
    % bizim belirlediðimiz sayýda gap oluþturabilmek için aralara yeni
rowlarýn
    % eklenmesi
    MaxRow2 = One + Two * (Gap-1);
else
    MaxRow2 = One;
end



C = zeros(MaxRow2,MaxColumn); %Koordinatlar arasýnda ki farklarý
yazdýracaðýmýz matx.
k = 1; %Dif matrixinin elelmanlarýný tutmak icin yapýlmýs bir counter

for i=1:length(B(:,:))
    Ref2 = B(i,1);

    if Ref2 == 1
        C(k,2) = B(i,2);
        C(k,3) = B(i,3);
        C(k,4) = B(i,4);
        C(k,5) = B(i,5);

        k = k + 1;

    else
        temp_coord_1(1) = B((i-1),2);
        temp_coord_1(2) = B((i-1),3);
%         temp_coord_1(3) = B((i-1),4);

        temp_coord_2(1) = B((i+1),2);
        temp_coord_2(2) = B((i+1),3);
%         temp_coord_2(3) = B((i+1),4);

        temp_coord_3(1) = B(i,2);
        temp_coord_3(2) = B(i,3);
%         temp_coord_3(3) = B(i,4);
```

```
        lengthc = sqrt(((temp_coord_1(1) - temp_coord_2(1))^2) +
((temp_coord_1(2) - temp_coord_2(2))^2));
        lengtha = sqrt((temp_coord_1(1) - temp_coord_3(1))^2 +
(temp_coord_1(2) - temp_coord_3(2))^2);
        lengthb = sqrt((temp_coord_2(1) - temp_coord_3(1))^2 +
(temp_coord_2(2) - temp_coord_3(2))^2);

        alfa = acos((((lengtha^2) + (lengthb^2) - (lengthc^2)) / (2 *
lengtha * lengthb)));

        alfa_sub = (alfa / Gap) ;
%         alfa_sub_degree = (alfa / Gap)*(180/pi) ;

%         Rmtrx = [cos(alfa_sub) -sin(alfa_sub); sin(alfa_sub)
cos(alfa_sub)];
        Distance = sqrt(lengtha^2 + lengthb^2 -
2*lengtha*lengthb*cos(alfa_sub));

        temp_coord_1(1) = temp_coord_1(1) - temp_coord_3(1);
        temp_coord_1(2) = temp_coord_1(2) - temp_coord_3(2);

        for j=1:Gap-1
            if B(i,5) == 1
                Rmtrx = [cos(-alfa_sub*j) -sin(-alfa_sub*j); sin(-
alfa_sub*j) cos(-alfa_sub*j)];
            elseif B(i,5) == -1
                    Rmtrx = [cos(alfa_sub*j) -sin(alfa_sub*j);
sin(alfa_sub*j) cos(alfa_sub*j)];
            end

            New = Rmtrx * temp_coord_1';
            New(1) = New(1) + temp_coord_3(1);
            New(2) = New(2) + temp_coord_3(2);

            C(k,2) = New(1);
            C(k,3) = New(2);
            C(k,4) = B(i,4);
            C(k,5) = B(i,5);

        k = k + 1;
%         temp_coord_1 = New';
        end

    end

end

figure(1)
```

```
plotcx = C(:,2);
plotcy = C(:,3);
plotcz = C(:,4);
plotbx = B(:,2);
plotby = B(:,3);
plotbz = B(:,4);

plot3(plotcx,plotcy,plotcz)
hold on
plot(plotbx,plotby,'r')
grid

Dif = zeros(MaxRow2-1,MaxColumn);

for i=2:length(C(:,:));
     Dif((i-1),2) = (C(i,2) - C((i-1),2));
     Dif((i-1),3) = (C(i,3) - C((i-1),3));
     Dif((i-1),4) = (C(i,4) - C((i-1),4));
end

Dif_pulse = zeros(MaxRow2-1,MaxColumn);

for i=1:length(Dif(:,:));
     Dif_pulse(i,2) = round((Dif(i,2) / (5e-2)));
     Dif_pulse(i,3) = round((Dif(i,3) / (5e-2)));
     Dif_pulse(i,4) = round((Dif(i,4) / (5e-2)));
end

Test = 0;
Max_total = 0;
Max_total1 = 0;
Dif_pulse_double = Dif_pulse.*2;%

Max = zeros(1,length(Dif_pulse(:,:)));%
Max1 = zeros(1,length(Dif_pulse(:,:)));%
Start = zeros(1,length(Dif_pulse(:,:)));
Finish = zeros(1,length(Dif_pulse(:,:)));

Max_abs = zeros(1,4);%
Max_abs1 = zeros(1,4);%
Division = zeros(1,4);%
Mod = zeros(1,3);%


for i=1:length(Dif_pulse(:,:));%
    for j=2:4
        Max_abs1(j) = abs(Dif_pulse(i,j));
    end
```

```
    Max1(i) = max(Max_abs1);
    Max_total1 = Max_total1 + Max1(i);
end%

x_f = zeros(1,2*Max_total1);%
x_r = zeros(1,2*Max_total1);%
y_f = zeros(1,2*Max_total1);%
y_r = zeros(1,2*Max_total1);%
z_f = zeros(1,2*Max_total1);%
z_r = zeros(1,2*Max_total1);%


for i=1:length(Dif_pulse(:,:));
    for j=1:4
        Max_abs(j) = abs(Dif_pulse(i,j));
    end
    Max(i) = max(Max_abs);
    Max_total = Max_total + Max(i);

    Start(i) = (Max_total*2-Max(i)*2)+1;
    Finish(i) = Max_total*2;
    Kosul = Max_total*2-Max(i)*2;

        if (sign(Dif_pulse(i,2)) == 1)
            for k=Start(i):Finish(i)
                x_r(k) = 0;
                if (k <= ((abs(Dif_pulse(i,2)*2)) + Kosul))

                    if (mod(k,2) == 1)
                        x_f(k) = 0;
                    else
                        x_f(k) = 1;
                    end
                else
                    x_f(k) = 0;
                end
            end
        end

        if (sign(Dif_pulse(i,2)) == 0)
            for k=Start(i):Finish(i)
                x_f(k) = 0;
                x_r(k) = 0;

            end
        end

        if (sign(Dif_pulse(i,2)) == -1)
```

```
        for k=Start(i):Finish(i)
            x_r(k) = 1;
            if (k <= ((abs(Dif_pulse(i,2)*2)) + Kosul))

                if (mod(k,2) == 1)
                    x_f(k) = 0;

                else
                    x_f(k) = 1;
                end
            else
                x_f(k) = 0;
            end
        end
    end



    if (sign(Dif_pulse(i,3)) == 1)
        for k=Start(i):Finish(i)
            y_r(k) = 0;
            if (k <= ((abs(Dif_pulse(i,3)*2)) + Kosul))

                if (mod(k,2) == 1)
                    y_f(k) = 0;
                else
                    y_f(k) = 1;
                end
            else
                y_f(k) = 0;
            end
        end
    end

    if (sign(Dif_pulse(i,3)) == 0)
        for k=Start(i):Finish(i)
            y_f(k) = 0;
            y_r(k) = 0;

        end
    end

    if (sign(Dif_pulse(i,3)) == -1)
        for k=Start(i):Finish(i)
            y_r(k) = 1;

            if (k <= ((abs(Dif_pulse(i,3)*2)) + Kosul))
```

```
                if (mod(k,2) == 1)
                    y_f(k) = 0;
                else
                    y_f(k) = 1;
                end
            else
                y_f(k) = 0;
            end
        end
    end
    if (sign(Dif_pulse(i,4)) == 1)
        for k=Start(i):Finish(i)
            z_r(k) = 0;
            if (k <= ((abs(Dif_pulse(i,4)*2)) + Kosul))

                if (mod(k,2) == 1)
                    z_f(k) = 0;
                else
                    z_f(k) = 1;
                end
            else
                z_f(k) = 0;
            end
        end
    end

    if (sign(Dif_pulse(i,4)) == 0)
        for k=Start(i):Finish(i)
            z_f(k) = 0;
            z_r(k) = 0;

        end
    end

    if (sign(Dif_pulse(i,4)) == -1)
        for k=Start(i):Finish(i)
            z_r(k) = 1;

            if (k <= ((abs(Dif_pulse(i,4)*2)) + Kosul))

                if (mod(k,2) == 1)
                    z_f(k) = 0;
                else
                    z_f(k) = 1;
                end
            else
                z_f(k) = 0;
            end
```

```
            end
        end

        Test = Test + 1
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pre allocation of plot arrays
x_f_plot = zeros(1,length(x_f));
x_r_plot = zeros(1,length(x_f));
y_f_plot = zeros(1,length(x_f));
y_r_plot = zeros(1,length(x_f));
z_f_plot = zeros(1,length(x_f));
z_r_plot = zeros(1,length(x_f));

% Creation of plot arrays
for i=1:length(x_f)
    if x_r(i) == 0
        x_f_plot(i) = x_f(i);
    else
        x_f_plot(i) = 0;
    end

    if x_r(i) ==1
        x_r_plot(i) = x_f(i)*-1;
    else
        x_r_plot(i) = 0;
    end
end

figure(3)
plot(x_f_plot,'b')
hold on
plot(x_r_plot,'r')
hold on
xlabel('Number of Pulses')
ylabel('X forward and X reverse pulses')


for i=1:length(x_f)
    if y_r(i) == 0
        y_f_plot(i) = y_f(i);
    else
        y_f_plot(i) = 0;
    end

    if y_r(i) ==1
```

```
        y_r_plot(i) = y_f(i)*-1;
    else
        y_r_plot(i) = 0;
    end
end

% figure(3)
% plot(y_f_plot,'b')
% hold on
% plot(y_r_plot,'r')
% hold on
% xlabel('Number of Pulses')
% ylabel('Y forward and Y reverse pulses')


for i=1:length(x_f)
    if z_r(i) == 0
        z_f_plot(i) = z_f(i);
    else
        z_f_plot(i) = 0;
    end

    if z_r(i) ==1
        z_r_plot(i) = z_f(i)*-1;
    else
        z_r_plot(i) = 0;
    end
end

% figure(4)
% plot(z_f_plot,'b')
% hold on
% plot(z_r_plot,'r')
% hold on
% xlabel('Number of Pulses')
% ylabel('Z forward and Z reverse pulses')

x_f_inc = 0;
x_r_inc = 0;
y_f_inc = 0;
y_r_inc = 0;
z_f_inc = 0;
z_r_inc = 0;

x = C(1,2);
y = C(1,3);
z = C(1,4);
```

A6-C) Algorithm-3:

This algorithm is designed such that the operator can create his own path by entering the coordinates of the nodes that are on the path.

```
clear all
close all
clc

inc = input('Enter the increment value=');

stop = 0;
i = 1;

x_current = 0;
y_current = 0;
z_current = 0;

X(1) = 0;
Y(1) = 0;
Z(1) = 0;

while stop == 0
    x = input('Enter the increment in X direction=');
    y = input('Enter the increment in Y direction=');
    z = input('Enter the increment in Z direction=');

    x_current = x_current + x;
    y_current = y_current + y;
    z_current = z_current + z;

    X(i+1) = x_current;
    Y(i+1) = y_current;
    Z(i+1) = z_current;

    plot3(X,Y,Z),grid
    xlabel('X')
    ylabel('Y')
    zlabel('Z')


    stop = input('If you want to end the process press 1 otherwise press
0!! ');

    Dif_pulse(i,1) = round((x) / (5e-2));
    Dif_pulse(i,2) = round((y) / (5e-2));
```

```
    Dif_pulse(i,3) = round((z) / (5e-2));

    i= i + 1;
end

Test = 0;
Max_total = 0;

for i=1:length(Dif_pulse(:,3));
    for j=1:3
        Max_abs(j) = abs(Dif_pulse(i,j));
    end

    Max(i) = max(Max_abs);
    Max_total = Max_total + Max(i);

    Start(i) = (Max_total*2-Max(i)*2)+1;
    Finish(i) = Max_total*2;
    Kosul = Max_total*2-Max(i)*2;

        if (sign(Dif_pulse(i,1)) == 1)
            for k=Start(i):Finish(i)
                x_r(k) = 0;
                if (k <= ((abs(Dif_pulse(i,1)*2)) + Kosul))

                    if (mod(k,2) == 1)
                        x_f(k) = 0;
                    else
                        x_f(k) = 1;
                    end
                else
                    x_f(k) = 0;
                end
            end
        end

        if (sign(Dif_pulse(i,1)) == 0)
            for k=Start(i):Finish(i)
                x_f(k) = 0;
                x_r(k) = 0;

            end
        end

        if (sign(Dif_pulse(i,1)) == -1)
            for k=Start(i):Finish(i)
                x_r(k) = 1;
                if (k <= ((abs(Dif_pulse(i,1)*2)) + Kosul))
```

```
                if (mod(k,2) == 1)
                    x_f(k) = 0;

                else
                    x_f(k) = 1;
                end
            else
                x_f(k) = 0;
            end
        end
    end



    if (sign(Dif_pulse(i,2)) == 1)
        for k=Start(i):Finish(i)
            y_r(k) = 0;
            if (k <= ((abs(Dif_pulse(i,2)*2)) + Kosul))

                if (mod(k,2) == 1)
                    y_f(k) = 0;
                else
                    y_f(k) = 1;
                end
            else
                y_f(k) = 0;
            end
        end
    end

    if (sign(Dif_pulse(i,2)) == 0)
        for k=Start(i):Finish(i)
            y_f(k) = 0;
            y_r(k) = 0;

        end
    end

    if (sign(Dif_pulse(i,2)) == -1)
        for k=Start(i):Finish(i)
            y_r(k) = 1;

            if (k <= ((abs(Dif_pulse(i,2)*2)) + Kosul))

                if (mod(k,2) == 1)
                    y_f(k) = 0;
                else
```

```
                y_f(k) = 1;
            end
        else
            y_f(k) = 0;
        end
    end
end



if (sign(Dif_pulse(i,3)) == 1)
    for k=Start(i):Finish(i)
        z_r(k) = 0;
        if (k <= ((abs(Dif_pulse(i,3)*2)) + Kosul))

            if (mod(k,2) == 1)
                z_f(k) = 0;
            else
                z_f(k) = 1;
            end
        else
            z_f(k) = 0;
        end
    end
end

if (sign(Dif_pulse(i,3)) == 0)
    for k=Start(i):Finish(i)
        z_f(k) = 0;
        z_r(k) = 0;

    end
end

if (sign(Dif_pulse(i,3)) == -1)
    for k=Start(i):Finish(i)
        z_r(k) = 1;

        if (k <= ((abs(Dif_pulse(i,3)*2)) + Kosul))

            if (mod(k,2) == 1)
                z_f(k) = 0;
            else
                z_f(k) = 1;
            end
        else
            z_f(k) = 0;
        end
```

```
            end
        end

        Test = Test + 1
end
```

A6-D) Serial port program for Algortihm-1

This algorithm compact the signal data generated by algorithm-2, and sends this data over RSR232 port to the system.

```
T = px_f_bool*32 + px_r_bool*16 + py_f_bool*8 + py_r_bool*4 +
pz_f_bool*2 + pm_bool;

port = serial('COM1','BaudRate', 115200,'Timeout', 100000000);
fopen(port);

for i=1:length(px_f_bool)
      fwrite(port, 85);
      fwrite(port,T(i));
end

dbloop close

fclose(port);
```

A6-E) Serial port program for Algorithm-2

```
T = x_f*32 + x_r*16 + y_f*8 + y_r*4 + z_f*2 + z_r;

port = serial('COM1','BaudRate', 115200,'Timeout', 100000000);
fopen(port);

for i=1:length(x_f)
        fwrite(port, 85);
        fwrite(port,T(i));
end

dbloop close

fclose(port);
```

A6-F) Program loaded into microcontroller

```
/************************************************************
/* RapidPrototypingMachine elektronik kontrol yazýlýmý.
/* Seri Porttan gelen datayý direk olarak bir portuna aktarýr.
/************************************************************/

#include "init.c"
#include <stdio.h>

sbit  LED = P1^6;                  // green LED: '1' = ON; '0' = OFF
sfr16 ADC0     = 0xbe;             // ADC0 data


void UART0_ISR (void);
void waitms(int );
unsigned int BirMsSayac[5];
void TMR0_ISR (void);


void TMR0_ISR (void) interrupt 1
{
char a;
      SFRPAGE   = TIMER01_PAGE;
      //TL0       = 0xA0;
    //TH0       = 0xF4;
      TL0       = 0x4c;
    TH0       = 0xa0;
      TF0=0;
      SFRPAGE = CONFIG_PAGE;
   //LED = !LED;
      for(a=0;a<5;a++)
      {
            if (BirMsSayac[a]!=0) BirMsSayac[a]--;
      }
}

unsigned char StateMachine=0;
void UART0_ISR (void) interrupt 4
{
unsigned char GelenByte;
      SFRPAGE   = UART0_PAGE;
      if (RI0)
      {
            RI0=0;
            GelenByte=SBUF0;
            LED = !LED;
            switch (StateMachine)
```

```
            {
                  case 0:
                        if (GelenByte==0x55)
                              StateMachine=1;
                        break;
                  case 1:
                        P3=GelenByte;
                        StateMachine=0;
                        break;
                  default:
                        StateMachine=0;
            }
      }
      if(TI0)
      {
            TI0=0;
      }
}

void waitms(int ms)
{
      BirMsSayac[0]=ms;
      while(BirMsSayac[0]);
}

char s[]=   {     0x00, 0x00, 0x3C, 0x0C, 0x7E, 0x1C, 0xE7, 0x38, 0xC3,
0x30, 0xC3, 0x30, 0xC3, 0x30, 0xC3, 0x30, 0xC7, 0x39, 0x8E, 0x1F, 0x0C,
0x0F, 0x00, 0x00};

main()
{
      Init_Device();

while(1){}
}
```

A6-G) Program loaded into the driver of the stepper motor

MPP-16 driver is used for stepper motor of the dispensing system. Following is the program written and loaded in to the driver to control the stepper motor with signals sent from function generator.

```
#include <pic.h>
//giriþ pinlerinin isimlendirilmesi...
#define PulseInput RB0
#define YonInput RB1

__CONFIG (UNPROTECT & LVPDIS & BORDIS & PWRTDIS & WDTDIS & INTIO & MCLREN
); //pic'in çalýþmasý için gerekli konfigrasyon ayarlarý
char stepdata[4]={8,4,2,1};
char stepdata1[4]={1,2,4,8};

main()
{
      char sayac;
      di();
      TRISA=0;
      PORTA=0;
      TRISB=0xff;
      OPTION=0;
      PORTA=1;
      while(1)
      {
            if(PulseInput)
            {
                  if (YonInput)
                  {
                        PORTA=stepdata[sayac++];
```

```
                        if (sayac==4) sayac=0;
                        while(PulseInput);
                  }
                  else
                  {
                              PORTA=stepdata1[sayac++];
                              if (sayac==4) sayac=0;
                              while(PulseInput);
                  }
            }
      }
}
```

APPENDIX-7: Kinematic Accuracy Measurement Data

Table A. 3: Accuracy measurement data in X-axis for a translation of 100 mm

+X Direction				-X Direction			
Initial measurement	Final measurement	Error	Average Kinematic Accuracy	Initial measurement	Final measurement	Error	Average Kinematic Accuracy
189.18	89.22	-0.04	-0.04	89.22	189.18	-0.04	-0.04
189.18	89.21	-0.03		89.21	189.16	-0.05	
189.16	89.23	-0.07		89.23	189.18	-0.05	
189.18	89.2	-0.02		89.2	189.14	-0.06	
189.14	89.18	-0.04		89.18	189.13	-0.05	
189.13	89.21	-0.08		89.21	189.2	-0.01	
189.2	89.2	0.0		89.2	189.18	-0.02	
189.18	89.18	0.0		89.18	189.17	-0.01	
189.17	89.2	-0.03		89.2	189.15	-0.05	
189.15	89.21	-0.06		89.21	189.17	-0.04	

Table A. 4: Accuracy measurement data in Y-axis for a translation of 100 mm

+Y Direction				-Y Direction			
Initial measurement	Final measurement	Error	Average Kinematic Accuracy	Initial measurement	Final measurement	Error	Average Kinematic Accuracy
51.41	151.16	-0.25	-0.12	151.16	51.31	-0.15	-0.11
51.31	151.22	-0.09		151.22	51.3	-0.08	
51.3	151.18	-0.12		151.18	51.29	-0.11	
51.29	151.17	-0.12		151.17	51.28	-0.11	
51.28	151.13	-0.15		151.13	51.27	-0.14	
51.27	151.16	-0.11		151.16	51.26	-0.1	
51.26	151.17	-0.09		151.17	51.29	-0.12	
51.29	151.17	-0.12		151.17	51.26	-0.09	
51.26	151.15	-0.11		151.15	51.25	-0.1	
51.25	151.17	-0.08		151.17	51.26	-0.09	

Table A. 5: Accuracy measurement data in +Z direction for a translation of 60 mm

+Z Direction			
Initial measurement	Final measurement	Error	Average Kinematic Accuracy
121.54	61.53	-0.01	+0.03 -0.06
118.28	58.38	0.1	
116.75	56.81	0.06	
116.53	56.57	0.04	
115.47	55.47	0	
112.62	52.7	0.08	
115.39	55.31	-0.08	
115.36	55.34	-0.02	
121.43	61.48	0.05	
120.84	60.87	0.03	

APPENDIX-8: CAD Pictures and Technical Drawings

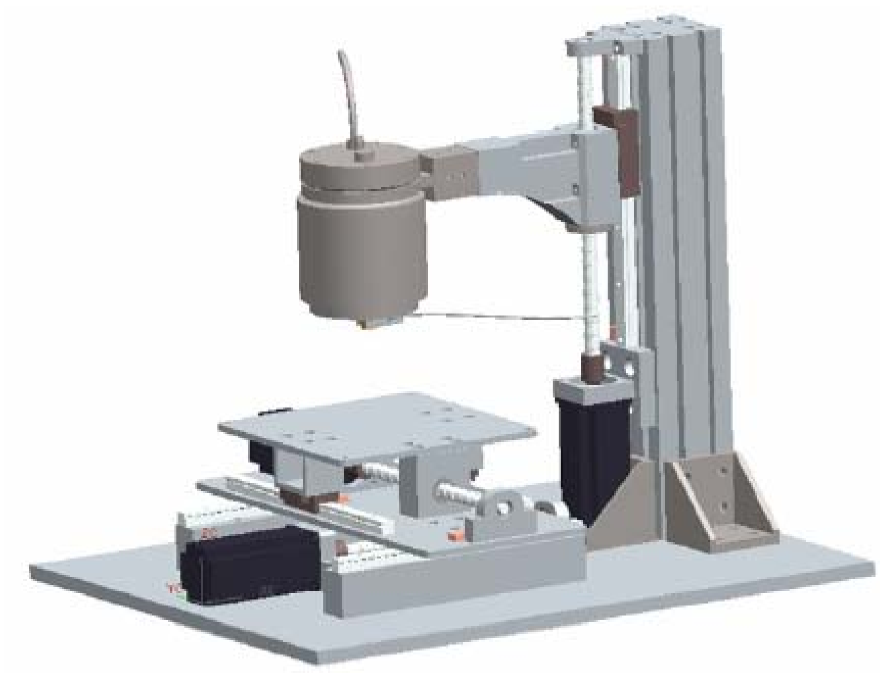


Figure A. 19: A picture of the CAD assembly from the first version of the System

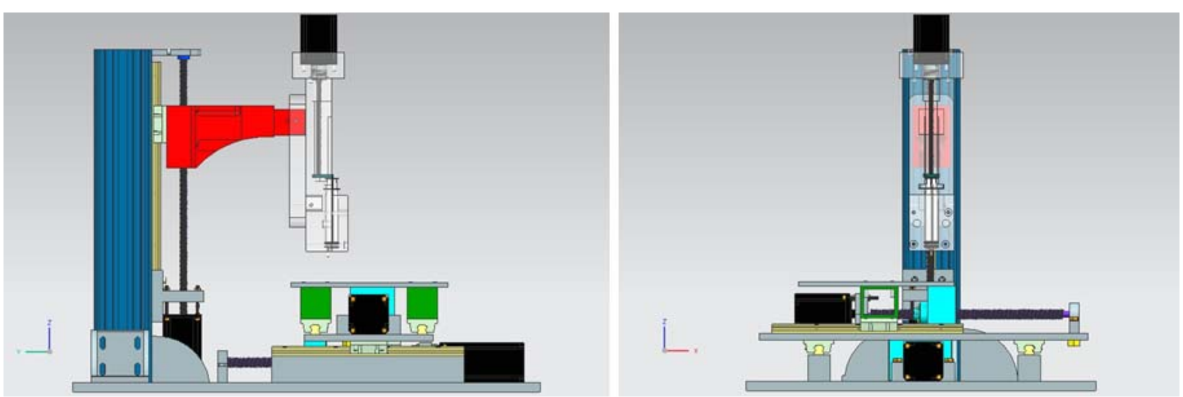


Figure A. 20: Left and front view from the CAD assembly of the current system

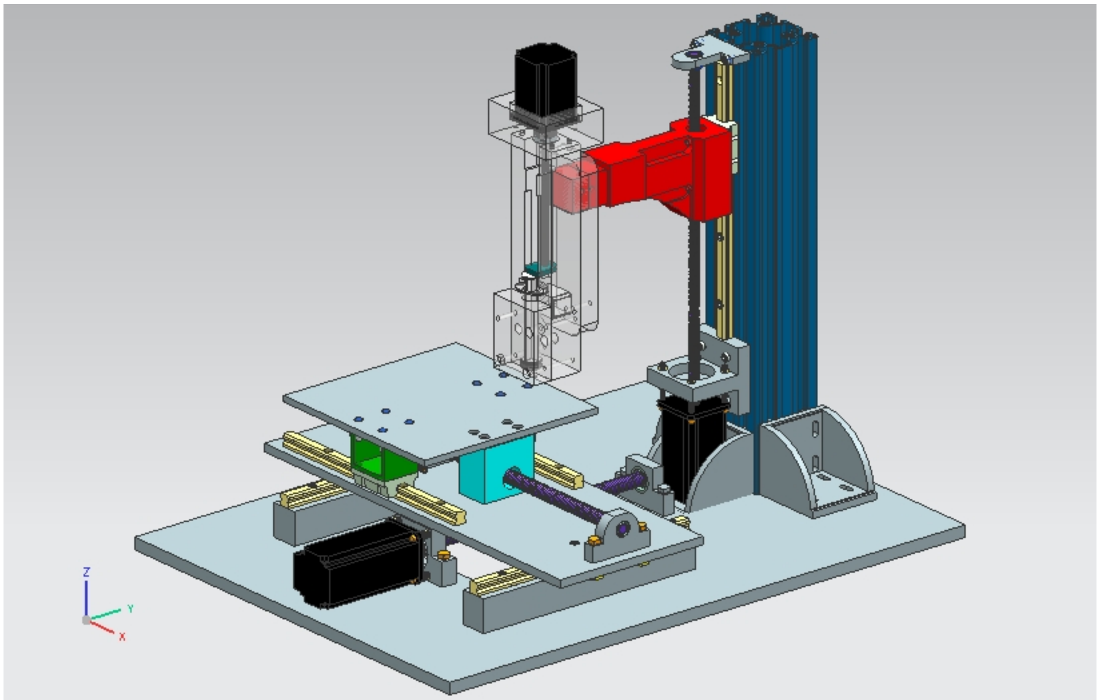


Figure A. 21: A trimetric view from the CAD model of the current system

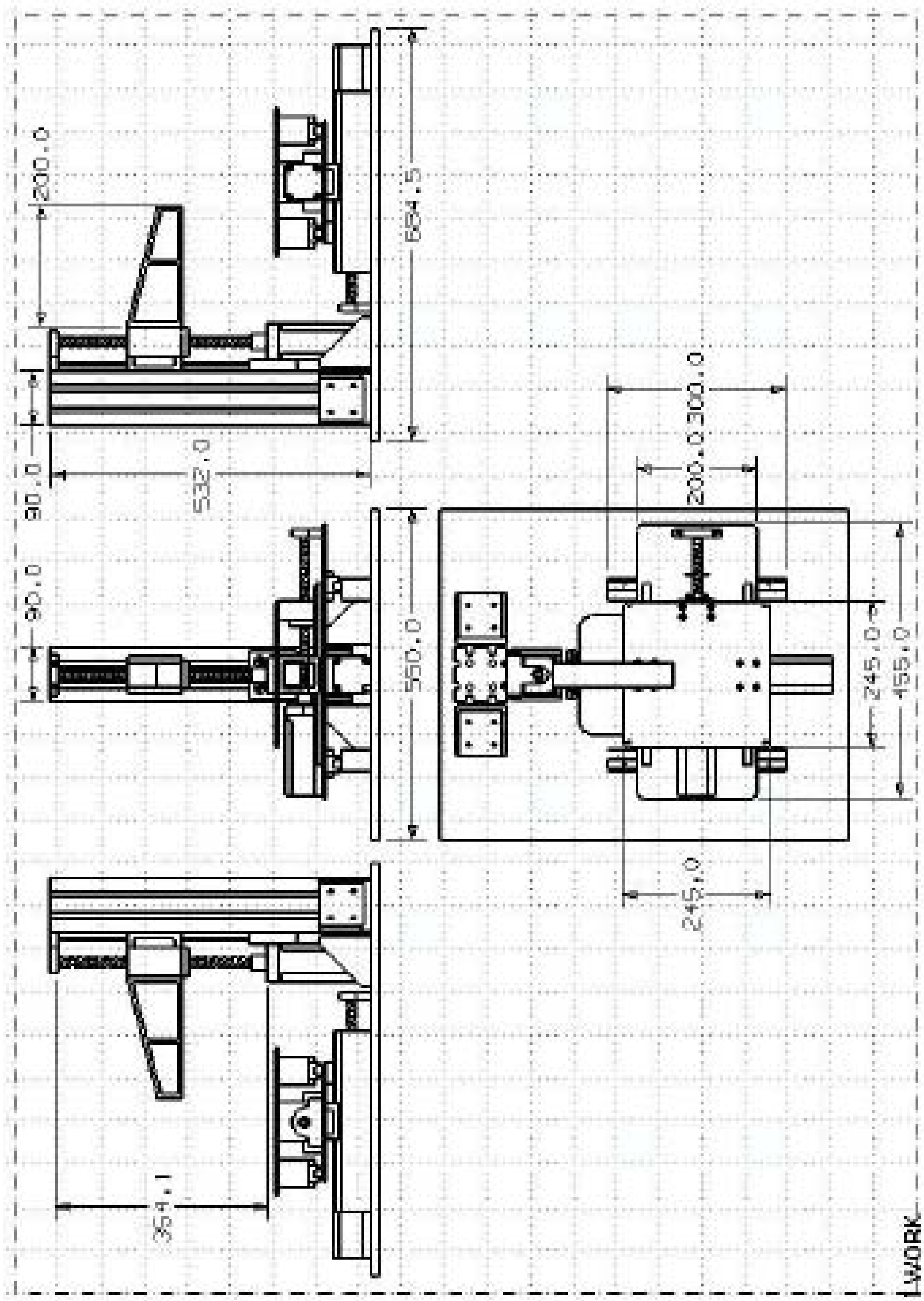


Figure A. 22: Technical drawing of the carriage system of RP machine

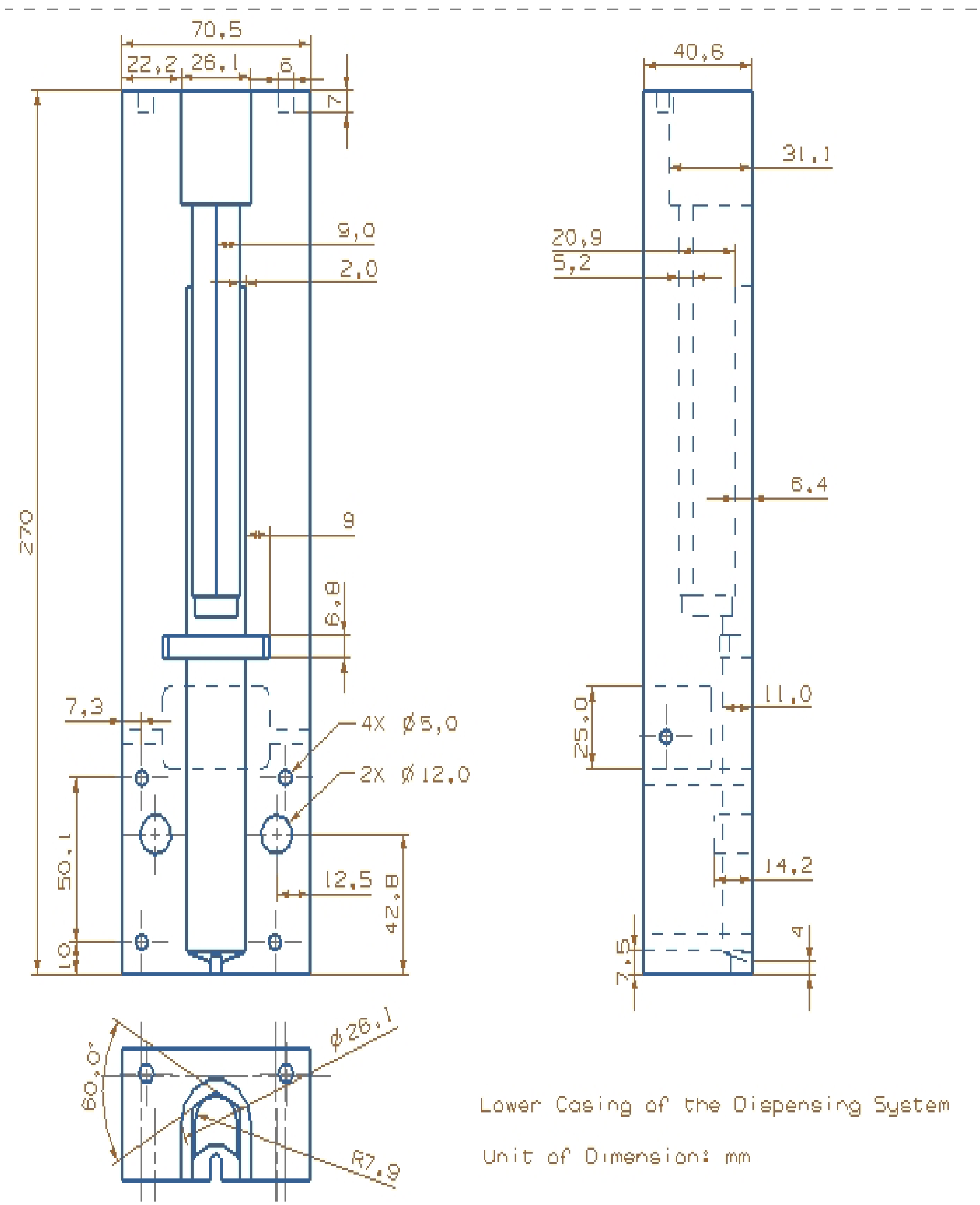


Figure A. 23: Technical drawing -lower casing of dispensing system

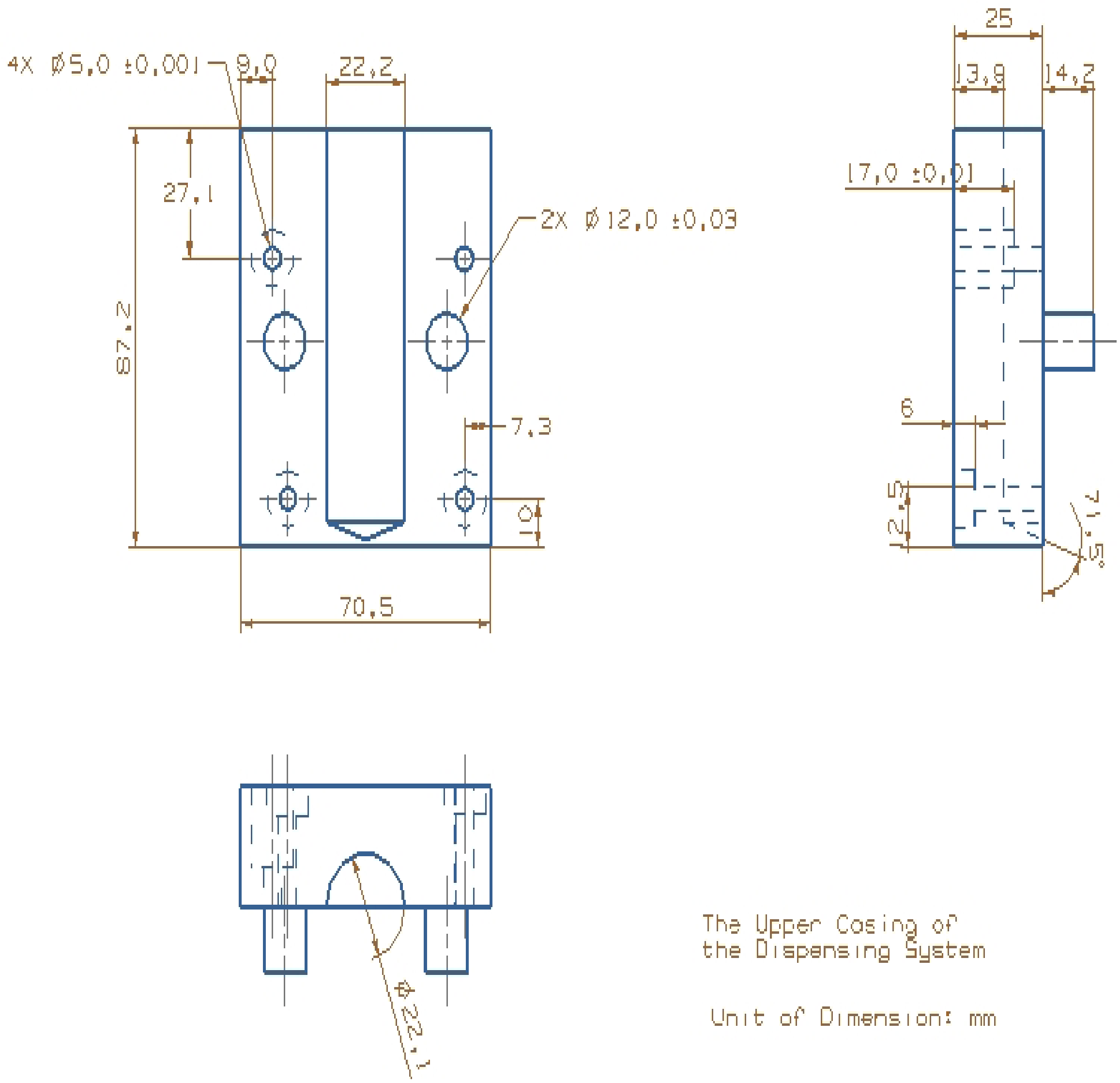


Figure A. 24: Technical drawing -upper casing of dispensing system

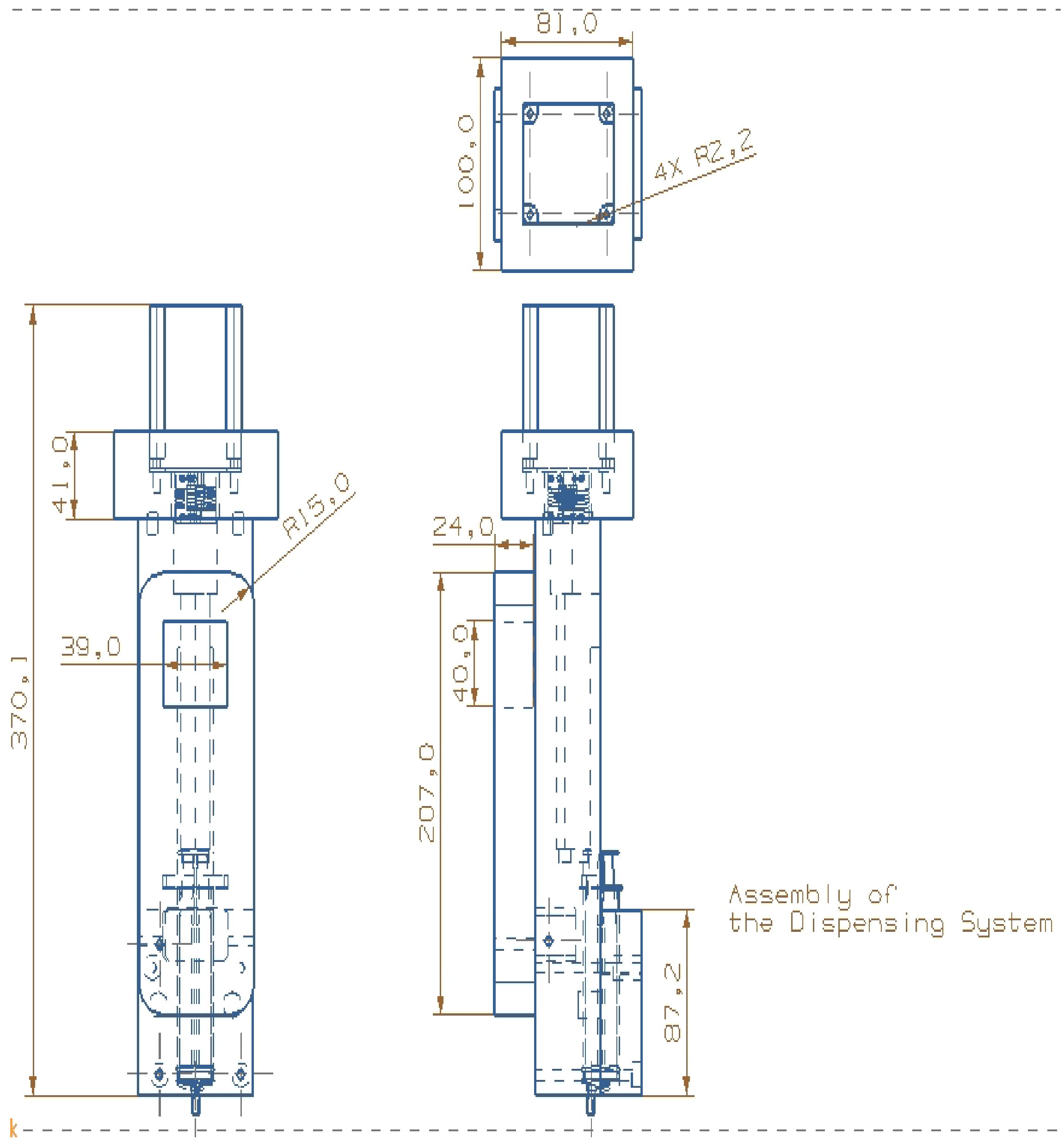


Figure A. 25: Technical drawing –Assembly of the dispensing system

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