

T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN PURE AND
APPLIED SCIENCES

DESIGN AND PRODUCTION OF A NEW RAPID
PROTOTYPING DEVICE

Aykut AKALIN
(Mechanical Engineering)

THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING PROGRAMME

SUPERVISOR
Assistant Professor Dr. Bülent EKİCİ

İSTANBUL 2006

ACKNOWLEDGMENT

First and foremost, I would like to thank my supervisor, Dr. Bülent EKİCİ, for his valuable academic advices and for his support and guidance throughout the preparation of this thesis.

I am deeply grateful to Öncü BENTÜRK who has contributed his time, knowledge and expertise in helping me to make this study. Without his help, this work would not be possible.

I wish also to express my sincere gratitude to Özgür POYRAZ, who helped whenever I was in need although he was far away.

Finally, I would like to express my deepest gratitude for the constant support, understanding and love that I received from my parents and my sister during the past years.

October, 2006

Aykut AKALIN

CONTENTS

ÖZET.....	iv
ABSTRACT.....	v
LIST OF FIGURES.....	vi
LIST OF TABLES.....	viii
1 INTRODUCTION	1
2 GENERAL BACKGROUND.....	2
2.1 RAPID PROTOTYPING	2
2.1.1 Rapid Prototyping Techniques.....	5
2.1.1.1 Stereolithography.....	5
2.1.1.2 Selective Laser Sintering.....	7
2.1.1.3 Laminated Object Manufacturing.....	9
2.1.1.4 Solid Ground Curing.....	11
2.1.1.5 Laser Engineered Net Shaping TM	13
2.1.1.6 Fused Deposition Modeling	14
2.1.1.7 Inkjets.....	17
2.1.1.8 Thermal Phase Change Inkjets	17
2.1.1.9 Photopolymer Phase Change Inkjets	19
2.1.1.10 Three Dimensional Printing	20
2.1.1.11 Miscellaneous Uncommercialized Technologies	21
2.1.1.12 Polymer Materials.....	21
Design Controlled Automatic Fabrication (DesCAF).....	21
Electro setting Materials	22
2.1.1.13 Metals.....	22
Weld Deposition.....	23
Masked Deposition.....	23
2.2 CONTROL SYSTEM.....	24
2.2.1 Numerical Control.....	24
2.2.1.1 Historical notes	25
2.2.1.2 Today	26
2.2.1.3 Motion Control	27
2.2.2 Stepper Motor Basics.....	28
2.2.2.1 Technical Description	28
2.2.2.2 Stepper Motor Types.....	30
2.2.2.2.1 Variable Reluctance (VR)	30
2.2.2.2.2 Permanent Magnet (PM)	31
2.2.2.2.3 Hybrid (HB).....	31
2.2.3 Coil Excitation Types.....	32
2.2.3.1 Unipolar Stepper Motors.....	32
2.2.3.2 Bipolar Stepper Motors.....	34

2.2.4	Stepper Motor Drive Sequences	35
2.2.5	Stepper Motor Control	36
2.2.5.1	Modes	36
2.2.5.1.1	Full-Step	36
2.2.5.1.2	Half-Step	37
2.2.5.1.3	Micro-Step	37
2.3	INFORMATION ABOUT MECHANICAL COMPONENTS	38
2.3.1	Ballscrews	38
2.3.1.1	High efficiency and reversibility	38
2.3.1.2	Backlash elimination and high stiffness	38
2.3.1.3	Predictable life expectancy	39
2.3.1.4	Applications for Ballscrews	39
2.3.2	Linear Guideways	40
3	DESIGN AND PRODUCTION OF THE RP SYSTEM	42
3.1	STEPPER MOTOR, DRIVERS AND PARALLEL PORT INTERFACE	45
3.1.1	Design of the Printed Circuit Boards	46
3.1.2	Making the PCBs	47
3.1.3	Soldering The Components	50
3.1.4	PIC Programming	50
3.2	POWER SUPPLY UNIT	50
3.3	SOFTWARE	51
3.4	MECHANICAL COMPONENTS AND ASSEMBLY	52
4	RESULTS	59
5	CONCLUSIONS AND RECOMMENDATIONS	63
	REFERENCES	64
	CURRICULUM VITAE	66

ÖZET

Bu projenin amacı hızlı prototipleme teknolojisini, avantajlarını, hızlı prototipleme (HP) makinelerinin teknolojisini, HP makinelerinin kontrolünü açıklamak ve FDM tipi bir hızlı prototipleme makinesin tasarımı ve üretimini yapmaktır.

HP teknolojisi hakkında genel bilgiler açık bir şekilde açıklandı, ve HP teknikleri detaylı bir şekilde şematik çizimler kullanılarak tanımlandı. Her tekniğin önemli noktaları listelendi ve avantaj-dezavantajlarından bahsedildi.

Tasarlanan makine nümerik olarak kontrol edilmeliydi. Kafanın X,Y ve Z yönlerinde hareket etmesi için 3 hareket kaynağına ihtiyaç vardır. Step motorlar uygun fiyatları ve isabet oranları münasebetiyle hareket kaynağı olarak seçildi. Nümerik kontrol temelleri ve step motorlarla ilgili temel bilgiler üretime başlamadan önce açık bir şekilde anlatıldı.

Step motorların hareket kaynağı olarak seçilmesinden sonra, bu motorların sürücü birimleri yapıldı. Bu sürücülerin aynı zamanda bilgisayar ile bağlantıya geçmesi gerekir. Bunu sağlayabilmek için, paralel port ara yüzü üretildi. Step motorlar direk akıma(DA) ihtiyaç duyarlar. Bu akımı sağlayabilmek için yüksek dereceli güç kaynağı ünitesi yapıldı. Kontrolör ünitenin ve güç kaynağının bir kasaya montajından sonra, TUBOCNC programı yön ve step miktarı için gerekli sinyalleri üretmekte kullanıldı.

Elektrik ve elektronik işlerinden sonra, FDM makinesinin şasesi çelik profiller ve sac metal kullanılarak üretildi. Çelik profiller ve sac metaller lineer kızaklara ve vidalı millere gerekli kaideyi oluşturmaları için birbirine kaynaklandılar. Şasenin imalatından sonra, lineer kızaklar ve vidalı miller gerekli yardımcı parçalar ile birlikte şaseye monte edildiler. 3 dairesel hareket vidalı mil ve lineer kızaklar kullanılarak lineer harekete dönüştürüldü. Aynı zamanda rezistanslar da sac metal gövdeye tutturuldu. Ve gövde özel bir seramik fiber izolasyon malzemesiyle kaplandı. Mekanik montajın tamamlanmasından sonra step motorlar ve sürücüler makineye eklendi.

Ekim, 2006

Aykut AKALIN

ABSTRACT

The aim of this project is to explain the rapid prototyping technology, advantages, technology of rapid prototyping (RP) machines, control of RP machines and design and produce a FDM type rapid prototyping machine.

General information about RP technology is explained clearly, and RP techniques are described in detail with figures. Highlights of each technique listed and advantages-disadvantages are mentioned.

The designed machine has to be numerically controlled. For the movement of head at X, Y and Z direction three motion sources are needed. Stepper motors are chosen as motion source because of their suitable cost and accuracy range. Numerical control principles and basic information about stepper motors are explained clearly before starting to produce the machine.

After the decision of stepper motors as motion source, driver units of these motors were built. Also these drivers need to communicate with the computer. In order to achieve this, parallel port interface card was produced. Stepper motors need direct current (DC) to supply the direct current high rating power supply unit (PSU) was built. After the installation of controller units and power unit to a case, TURBOCNC program was used to generate signals for direction and step amount from parallel port.

Afterwards electric and electronic works, the chassis of the FDM machine is built using steel profiles and sheet metal. Steel profiles are welded to each other in order to obtain the required base for the linear guideways and ballscrews. After production of the chassis, linear guideways and ballscrews are assembled to the chassis. Three rotary motions converted to linear motion by using ballscrews and linear guideways. Also resistances are mounted to the sheet metal body. And the body is covered with a special ceramic fiber isolation element. After completion of the mechanical assembly step motors and drivers are added to the machine.

October, 2006

Aykut AKALIN

LIST OF FIGURES

Figure 1 Product development system based on RP.....	2
Figure 2 Applications of RP.....	3
Figure 3 Stereolithography	6
Figure 4 Selective Laser Sintering.....	9
Figure 5 Laminated Object Manufacturing.....	10
Figure 6 Schematic diagram of solid ground curing.....	12
Figure 7 Laser Engineered Net Shaping TM	13
Figure 8 Fused Deposition Modeling	15
Figure 9 Solidscares implementation.	18
Figure 10 Three Dimensional Printing.....	20
Figure 11 A conventional machine's slide is moved by an operator turning the handwheel.....	27
Figure 12 A CNC machine takes the commanded position from the CNC program.....	28
Figure 13 Construction of a stepper motor.....	29
Figure 14 Variable Reluctance Motor.....	31
Figure 15 Permanent Magnet Motor.....	31
Figure 16 Hybrid Motor	32
Figure 17 6-wire Unipolar Stepper Motor.....	32
Figure 18 Reversal of Current in one coil of a Unipolar Stepper Motor	33
Figure 19 Unipolar Drive Sequence	33
Figure 20 4-wire Bipolar Stepper	34
Figure 21 Bipolar Drive Sequence.....	35
Figure 22 Consepctional H-Bridge Circuit.....	35
Figure 23 Typical step motor system.....	36
Figure 24 Basic configuration of ballscrews and contact thread lead screws.....	38
Figure 25 Typical contact types for ballscrews.....	39
Figure 26 The linear guideway used at the system, manufactured by HIWIN.	41
Figure 27 General view of the preliminary design made by computer aided design techniques.	43
Figure 28 Schematics of stepper driver and parallel port interface	47
Figure 29 PCB surface after rubbing with abrasive pad	49
Figure 30 PIC Programmer and PIC16F628A	50
Figure 31 Schematics of the power supply unit	51
Figure 32 Screen-shot of the TURBOCNC software.	52

Figure 33 CAD model of the preliminary design.	53
Figure 34 Picture taken during the test runs.	54
Figure 35 Top view of the system, showing the components of the Y axis.	54
Figure 36 Side view of the system showing the components of X and Z axes.	55
Figure 37 Section view of the system for better visualizing of Y axis components .	56
Figure 38 Section view of the system for better visualizing of X and Z axis components.	56
Figure 39 Simple explode view of the axis assemblies.	57
Figure 40 Picture of the X axis step motor and rim.	60
Figure 41 Picture of the Y axis step motor and rim.	60
Figure 42 Picture of the X axis ballscrew assembly.	61
Figure 43 Picture of the test run result, a triangle and a square was drawn by the help of a boardmarker.	61
Figure 44 Picture of the test run result, a triangle and a square was drawn by the help of a boardmarker.	62

LIST OF TABLES

Table 1 . Stepper Motor Drive Sequences.....	35
Table 2 . Stepper Motor parameters	45
Table 3 . Precise motion control components.....	57
Table 4 . Accuracy calculations.	58

1 INTRODUCTION

Rapid prototyping (RP) is a process in which a part is produced using layer-by-layer deposition of material. It is an important technology as it has potential to reduce the manufacturing lead time of the product up to 30–50% even the relative part complexity is very high [1]. Since the introduction of the first commercial rapid prototyping (RP) machine widely known as stereolithography in 1986, a wide range of RP machines have been commercialized, and many more newer systems continue to be developed in various parts of the world[2]. Fused deposition modeling (FDM) is one RP system that produces prototypes from plastic materials such as ABS by laying tracks of semi-molten plastic filament onto a platform in a layer wise manner from bottom to top [3]. In order to achieve high efficiency, accuracy and reliability of the manufacturing process, motion control is applied to move the head to a target position as fast as possible with micrometer precision[4]. An RP system has to be controlled by a numerical control system in order to achieve the complex movements of the machine. Numerical control is control of a process or machine by encoded commands that are commonly prepared by a computer. These commands are transferred to the electronic tools and the motors by certain instruments. And the desired movements of the machine tools are obtained. A RP machine using FDM method consists of a head unit-which supplies and melts the material-, a mechanical assembly which lets the desired motion to take place, a numerical control system, servo or stepper motors, motor drivers, temperature controllers, heat units and a chassis.

Today, Turkey industry is just an importer of the RP systems and machinery. This project's aim is to design and produce a new RP machine using Fused Deposition Modeling method in Turkey, with cooperating projects about the material properties and production methods of the material and the head unit design.

2 GENERAL BACKGROUND

2.1 RAPID PROTOTYPING

Rapid prototyping (RP) is the most common name given to a host of related technologies that are used to fabricate physical objects directly from CAD data sources. These methods are unique in that they add and bond materials in layers to form objects. Such systems are also known by the names additive fabrication, three dimensional printing, and solid freeform fabrication (SFF) and layered manufacturing. Today's additive technologies offer advantages in many applications compared to classical subtractive fabrication methods such as milling or turning:

- Objects can be formed with any geometric complexity or intricacy without the need for elaborate machine setup or final assembly;
- Rapid prototyping systems reduce the construction of complex objects to a manageable, straightforward, and relatively fast process.
- RP increase effective communication, decrease development time, decrease costly mistakes, minimize sustaining engineering changes.
- RP extend product lifetime by adding necessary features and eliminating redundant features early in the design.

This has resulted in their wide use by engineers as a way to reduce time to market in manufacturing, to better understand and communicate product designs, and to make rapid tooling to manufacture those products. Surgeons, architects, artists and individuals from many other disciplines also routinely use the technology.

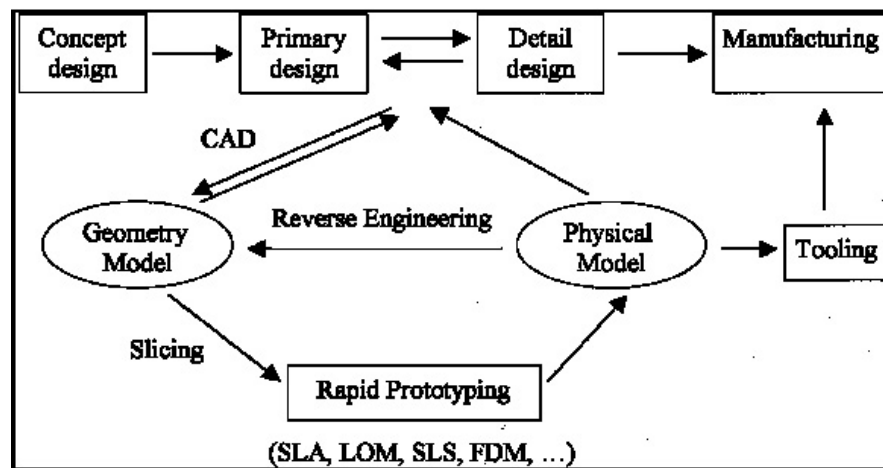


Figure 1 Product development system based on RP.

Rapid prototyping isn't a solution to every part fabrication problem. After all, CNC technology is economical, widely understood and available, offers wide material selection and excellent accuracy. However, if the requirement involves producing a part or object of even moderately complex geometry, and doing so quickly - RP has the advantage. It's very easy to look at extreme cases and make a determination of which technology route to pursue, CNC or RP. For many other less extreme cases the selection crossover line is hazy, moves all the time, and depends on a number of variably-weighted, case-dependent factors. While the accuracy of rapid prototyping isn't generally as good as CNC, it's adequate today for a wide range of exacting applications.

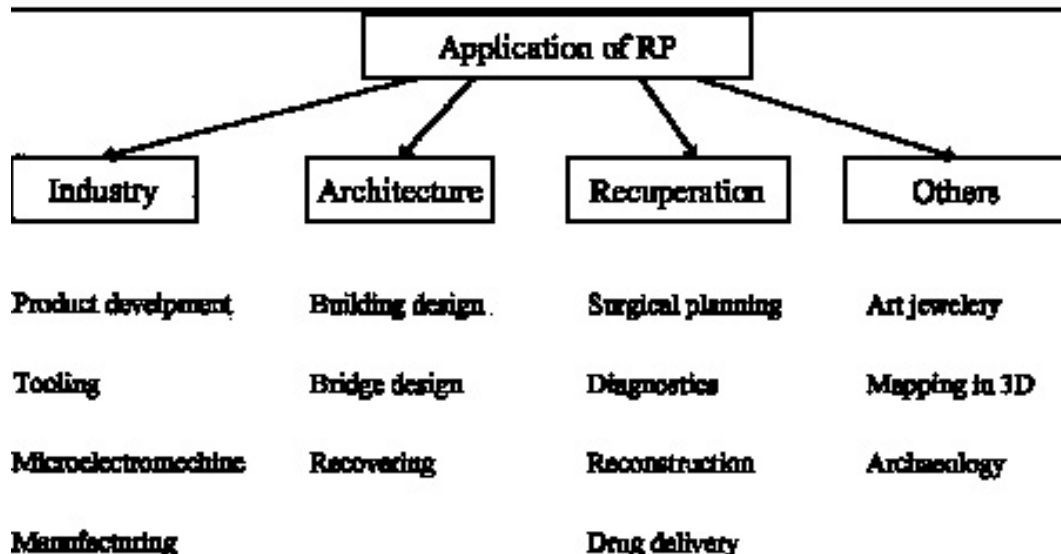


Figure 2 Applications of RP.

The materials used in rapid prototyping are limited and dependent on the method chosen. However, the range and properties available are growing quickly. Numerous plastics, ceramics, metals ranging from stainless steel to titanium, and wood-like paper are available. At any rate, numerous secondary processes are available to convert patterns made in a rapid prototyping process to final materials or tools.

The names of specific processes themselves are also often used as synonyms for the entire field. Among these are stereolithography (SLA for stereolithography apparatus), selective laser sintering (SLS), fused deposition modeling (FDM),

laminated object manufacturing (LOM), inkjet systems and three dimensional printing (3DP). Each of these technologies - and many others - has its singular strengths and weaknesses.

The basic methodology for all current rapid prototyping techniques can be summarized as follows:

1. Create a CAD model of the design
2. Convert the CAD model to STL format
3. Slice the STL file into thin cross-sectional layers
4. Construct the model one layer atop another
5. Clean and finish the model

CAD Model Creation: First, the object to be built is modeled using a Computer-Aided Design (CAD) software package. Solid modelers, such as Pro/ENGINEER, tend to represent 3-D objects more accurately than wire-frame modelers such as AutoCAD, and will therefore yield better results. The designer can use a pre-existing CAD file or may wish to create one expressly for prototyping purposes. This process is identical for all of the RP build techniques.

Conversion to STL Format: The various CAD packages use a number of different algorithms to represent solid objects. To establish consistency, the STL (stereolithography, the first RP technique) format has been adopted as the standard of the rapid prototyping industry. The second step, therefore, is to convert the CAD file into STL format. This format represents a three-dimensional surface as an assembly of planar triangles, "like the facets of a cut jewel." ⁶ The file contains the coordinates of the vertices and the direction of the outward normal of each triangle. Because STL files use planar elements, they cannot represent curved surfaces exactly. Increasing the number of triangles improves the approximation, but at the cost of bigger file size. Large, complicated files require more time to pre-process and build, so the designer must balance accuracy with manageability to produce a useful STL file. Since the .stl format is universal, this process is identical for all of the RP build techniques.

Slice the STL File: In the third step, a pre-processing program prepares the STL file to be built. Several programs are available, and most allow the user to adjust the size, location and orientation of the model. Build orientation is important for several

reasons. First, properties of rapid prototypes vary from one coordinate direction to another. For example, prototypes are usually weaker and less accurate in the z (vertical) direction than in the x-y plane. In addition, part orientation partially determines the amount of time required to build the model. Placing the shortest dimension in the z direction reduces the number of layers, thereby shortening build time. The pre-processing software slices the STL model into a number of layers from 0.01 mm to 0.7 mm thick, depending on the build technique. The program may also generate an auxiliary structure to support the model during the build. Supports are useful for delicate features such as overhangs, internal cavities, and thin-walled sections. Each PR machine manufacturer supplies their own proprietary pre-processing software.

Layer by Layer Construction: The fourth step is the actual construction of the part. Using one of several techniques (described in the next section) RP machines build one layer at a time from polymers, paper, or powdered metal. Most machines are fairly autonomous, needing little human intervention.

Clean and Finish: The final step is post-processing. This involves removing the prototype from the machine and detaching any supports. Some photosensitive materials need to be fully cured before use. Prototypes may also require minor cleaning and surface treatment. Sanding, sealing, and/or painting the model will improve its appearance and durability.

2.1.1 Rapid Prototyping Techniques

2.1.1.1 Stereolithography

The implementation shown in Fig. 1 is used by 3D Systems and some foreign manufacturers. A moveable table, or elevator (A), initially is placed at a position just below the surface of a vat (B) filled with liquid photopolymer resin (C). This material has the property that when light of the correct color strikes it, it turns from a liquid to a solid. The most common photopolymer materials used require an ultraviolet light, but resins that work with visible light are also utilized. The system is sealed to prevent the escape of fumes from the resin.

A laser beam is moved over the surface of the liquid photopolymer to trace the geometry of the cross-section of the object. This causes the liquid to harden in

areas where the laser strikes. The laser beam is moved in the X-Y directions by a scanner system (D). These are fast and highly controllable motors which drive mirrors and are guided by information from the CAD data.

The exact pattern that the laser traces is a combination of the information contained in the CAD system that describes the geometry of the object, and information from the rapid prototyping application software that optimizes the faithfulness of the fabricated object. Of course, application software for every method of rapid prototyping modifies the CAD data in one way or another to provide for operation of the machinery and to compensate for shortcomings.

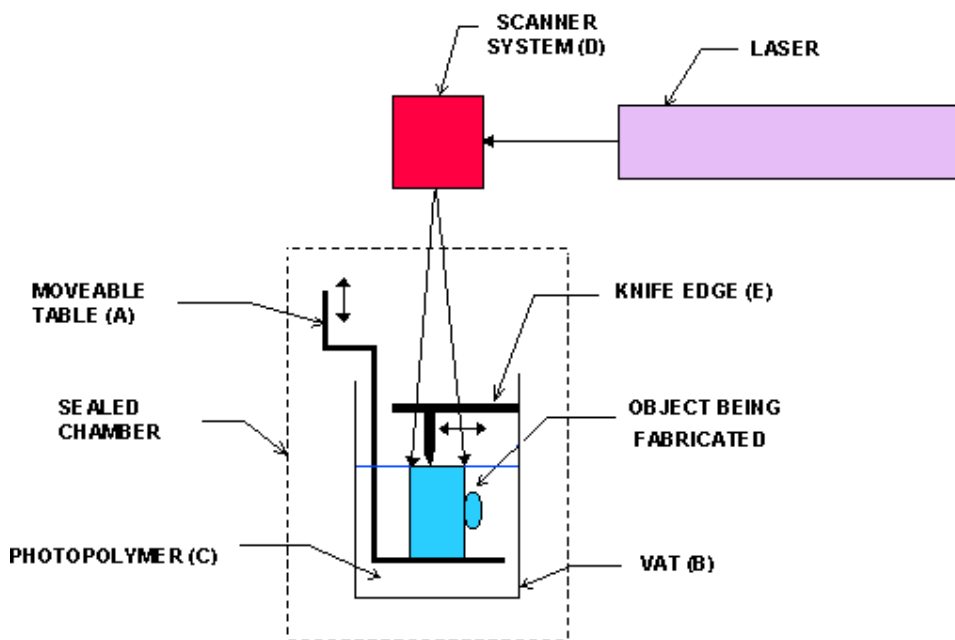


Figure 3 Stereolithography

After the layer is completely traced and for the most part hardened by the laser beam, the table is lowered into the vat a distance equal to the thickness of a layer. The resin is generally quite viscous, however. To speed this process of recoating, early stereolithography systems drew a knife edge (E) over the surface to smooth it. More recently pump-driven recoating systems have been utilized. The tracing and recoating steps are repeated until the object is completely fabricated and sits on the table within the vat.

Some geometry of objects has overhangs or undercuts. These must be supported during the fabrication process. The support structures are either manually or automatically designed.

Upon completion of the fabrication process, the object is elevated from the vat and allowed to drain. Excess resin is swabbed manually from the surfaces. The object is often given a final cure by bathing it in intense light in a box resembling an oven called a Post-Curing Apparatus (PCA). Some resins and types of stereolithography equipment don't require this operation, however.

After final cure, supports are cut off the object and surfaces are sanded or otherwise finished.

Stereolithography generally is considered to provide the greatest accuracy and best surface finish of any rapid prototyping technology. Work continues to provide materials that have wider and more directly useable mechanical properties. Recently, inkjet technology has been extended to operation with photopolymers resulting in systems that have both fast operation and good accuracy.

- The first Rapid Prototyping technique and still the most widely used.
- Inexpensive compared to other techniques.
- Uses a light-sensitive liquid polymer.
- Requires post-curing since laser is not of high enough power to completely cure.
- Long-term curing can lead to warping.
- Parts are quite brittle and have a tacky surface.
- No milling step so accuracy in z can suffer.
- Support structures are typically required.
- Process is simple: There are no milling or masking steps required.
- Uncured material can be toxic. Ventilation is a must.

2.1.1.2 Selective Laser Sintering

The process is somewhat similar to stereolithography in principle as can be seen from Fig. 2. In this case, however, a laser beam is traced over the surface of a tightly compacted powder made of thermoplastic material (A). The powder is spread by a roller (B) over the surface of a build cylinder (C). A piston (D) moves down one object layer thickness to accommodate the layer of powder.

The powder supply system (E) is similar in function to the build cylinder. It also comprises a cylinder and piston. In this case the piston moves upward incrementally to supply powder for the process.

Heat from the laser melts the powder where it strikes under guidance of the scanner system (F). The CO₂ laser used provides a concentrated infrared heating beam. The entire fabrication chamber is sealed and maintained at a temperature just below the melting point of the plastic powder. Thus, heat from the laser need only elevate the temperature slightly to cause sintering, greatly speeding the process. A nitrogen atmosphere is also maintained in the fabrication chamber which prevents the possibility of explosion in the handling of large quantities of powder.

After the object is fully formed, the piston is raised to elevate the object. Excess powder is simply brushed away and final manual finishing may be carried out. That's not the complete story, though. It may take a considerable time before the part cools down enough to be removed from the machine. Large parts with thin sections may require as much as two days of cooling time.

No supports are required with this method since overhangs and undercuts are supported by the solid powder bed. This saves some finishing time compared to stereolithography. However, surface finishes are not as good and this may increase the time. No final curing is required as in stereolithography, but since the objects are sintered they are porous. Depending on the application, it may be necessary to infiltrate the object with another material to improve mechanical characteristics. Much progress has been made over the years in improving surface finish and porosity. The method has also been extended to provide direct fabrication of metal and ceramic objects and tools.

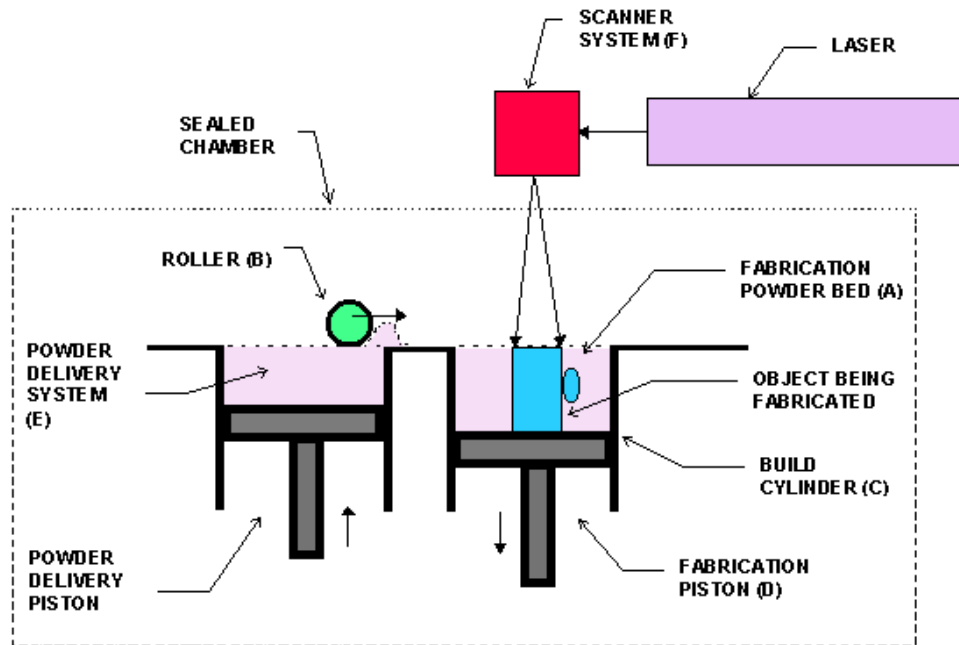


Figure 4 Selective Laser Sintering

- Patented in 1989.
- Considerably stronger than Stereolithography; sometimes structurally functional parts are possible.
- Laser beam selectively fuses powder materials: nylon, elastomer, and soon metal;
- Advantage over SLA: Variety of materials and ability to approximate common engineering plastic materials.
- No milling step so accuracy in z can suffer.
- Process is simple: There is no milling or masking steps required.
- Living hinges are possible with the thermoplastic-like materials.
- Powdery, porous surface unless sealant is used. Sealant also strengthens part.
- Uncured material is easily removed after a build by brushing or blowing it off.

2.1.1.3 Laminated Object Manufacturing

Profiles of object cross sections are cut from paper using a CO₂ laser as shown in Fig. 3. The paper is unwound from a feed roll (A) onto the stack and bonded to the previous layer using a heated roller (B). The roller melts a plastic

coating on the bottom side of the paper to create the bond. The profiles are traced by an optics system that is mounted to an X-Y stage (C). The process generates considerable smoke. Either a chimney or a charcoal filtration system is required (E) and the build chamber must be sealed.

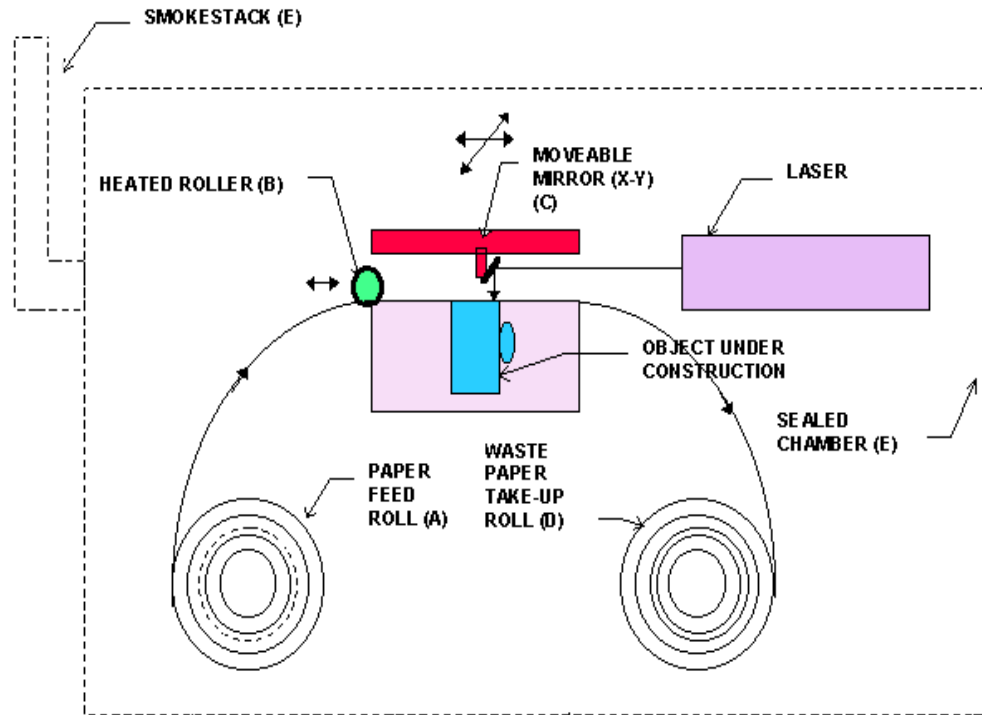


Figure 5 Laminated Object Manufacturing

After cutting the geometric features of a layer is completed, the excess paper is cut away to separate the layer from the web. The extra paper of the web is wound on a take-up roll (D). The method is self-supporting for overhangs and undercuts. Areas of cross sections which are to be removed in the final object are heavily cross-hatched with the laser to facilitate removal. It can be time consuming to remove extra material for some geometries.

The finish and accuracy are not as good as with some methods, however objects have the look and feel of wood and can be worked and finished in the same manner.

Several companies provide variations of LOM technologies: For example, Kira's Paper Lamination Technology (PLT) uses a knife to cut each layer instead of a laser and applies adhesive to bond layers using the xerographic process. Solidimension of Israel also uses a knife, but instead bonds layers of plastic film with

a solvent. This technology is sold in the US by 3D Systems as the InVision™ LD. Other variations include Thick Layer Lamination from Stratoconception of France, Precision Stratiform Machining from Ford Research, and Adaptive-Layer Lamination developed by Landfoam Topographics. These are hybrids of additive and subtractive CNC technologies which seek to increase speed and material versatility by cutting the edges of thick layers to avoid stair stepping.

The principal US commercial provider of laser-based LOM systems, Helisys, ceased operation in 2000. However the company's products are still sold and serviced by a successor organization, Cubic Technologies.

- Layers of glue-backed paper form the model.
- Low cost: Raw material is readily available.
- Large parts: Because there is no chemical reaction involved, parts can be made quite large.
- Accuracy in z is less than that for SLA and SLS®. No milling step.
- Outside of model, cross-hatching removes material
- Models should be sealed in order to prohibit moisture.
- Before sealing, models have a wood-like texture.
- Not as prevalent as SLA and SLS®.

2.1.1.4 Solid Ground Curing

Developed by Cubital, solid ground curing (SGC) is somewhat similar to stereolithography (SLA) in that both use ultraviolet light to selectively harden photosensitive polymers. Unlike SLA, SGC cures an entire layer at a time. Figure 5 depicts solid ground curing, which is also known as the solider process. First, photosensitive resin is sprayed on the build platform. Next, the machine develops a photomask (like a stencil) of the layer to be built. This photomask is printed on a glass plate above the build platform using an electrostatic process similar to that found in photocopiers. The mask is then exposed to UV light, which only passes through the transparent portions of the mask to selectively harden the shape of the current layer.

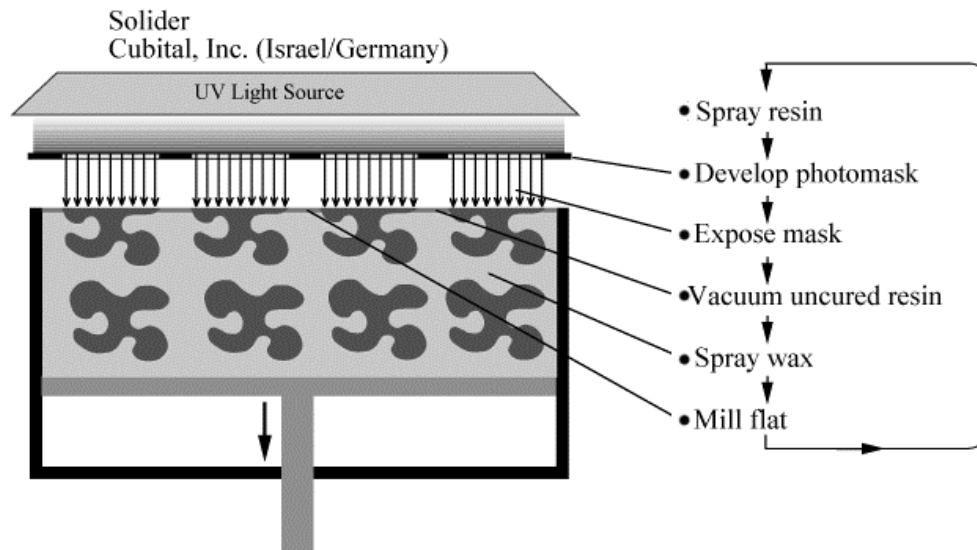


Figure 6 Schematic diagram of solid ground curing.

After the layer is cured, the machine vacuums up the excess liquid resin and sprays wax in its place to support the model during the build. The top surface is milled flat, and then the process repeats to build the next layer. When the part is complete, it must be de-waxed by immersing it in a solvent bath. SGC machines are distributed in the U.S. by Cubital America Inc. of Troy, MI. The machines are quite big and can produce large models.

- Large parts, $500 \times 500 \times 350$ mm ($20 \times 20 \times 14$ in), can be fabricated quickly.
- High speed allows production-like fabrication of many parts or large parts.
- Masks are created w/ laser printing-like process, then full layer exposed at once.
- No post-cure required.
- Milling step ensures flatness for subsequent layer
- Wax supports model: no extra supports needed.
- Creates a lot of waste.
- Not as prevalent as SLA and SLS, but gaining ground because of the high throughput and large parts.

2.1.1.5 Laser Engineered Net Shaping™

Laser Engineered Net Shaping™ [LENS®]* and other laser powder forming technologies are gaining in importance and in early stages of commercialization. The strength of these technologies lie in the ability to fabricate fully-dense metal parts with good metallurgical properties at reasonable speeds. The work was initiated at several government and university laboratories, both in the US and in Europe, and several variations on the technique have been explored. The approaches are also sometimes referred to by the general term, *laser fusing*. Fig. 8 shows the approach adopted by Sandia National Labs and being commercialized by Optomec Design Corp. Several other companies are commercializing similar processes.

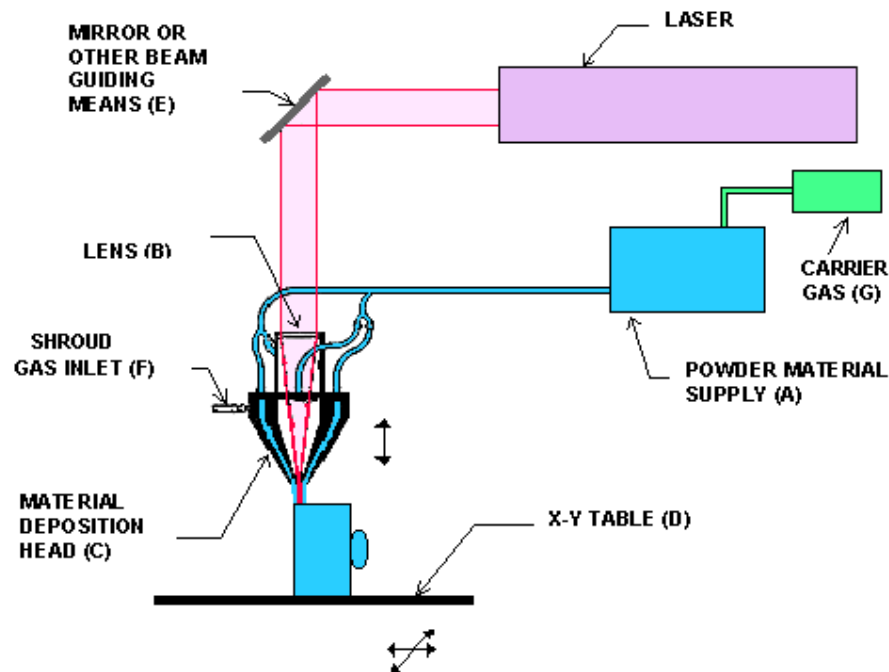


Figure 7 Laser Engineered Net Shaping™

A high power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head (C). The laser beam typically travels through the center of the head and is focused to a small spot by one or more lenses (B). The X-Y table (D) is moved in raster fashion to fabricate each layer of the object. Typically the head is moved up vertically as each layer is completed. The laser beam may be delivered to the work by any convenient means. A simple right angle mirror (E) is shown, but fiber optics could also be used. Metal powders (A) are delivered and distributed around the circumference of the head either by gravity, or

by using an inert, pressurized carrier gas (G). Even in cases where it's not required for feeding, an inert shroud gas (F) is typically used to shield the melt pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface wetting.

A variety of materials can be used such as stainless steel, Inconel, copper, aluminum etc. Of particular interest are reactive materials such as titanium. Most systems use powder feedstock, but there has also been work done with material provided as fine wires. In this case the material is fed off-axis to the beam. Materials composition can be changed dynamically and continuously, leading to objects with properties that might be mutually exclusive using classical fabrication methods.

The building area is usually contained within a chamber both to isolate the process from the ambient surroundings and to shield the operators from possible exposure to fine powders and the laser beam. The laser power used varies greatly, from a few hundred watts to 20KW or more, depending on the particular material, feed-rate and other parameters.

Objects fabricated are near net shape, but generally will require finish machining. They are fully-dense with good grain structure, and have properties similar to, or even better than the intrinsic materials. LENS has fewer material limitations than SLS, doesn't require secondary firing operations as some of those processes do, and can also be used to repair parts as well as fabricate them.

Initial applications are concentrated on the fabrication and repair of injection molding tools and the fabrication of large titanium and other exotic metal parts for aerospace applications. This emphasis is partly due to the fact that support structures for overhanging sections generated by the technology are fully dense and hard to remove. These applications don't need to address that problem. Work is ongoing to find a more convenient means of generating supports.

2.1.1.6 Fused Deposition Modeling

FDM is the second most widely used rapid prototyping technology, after stereolithography. A plastic filament, approximately 1/16 inch in diameter, is unwound from a coil (A) and supplies material to an extrusion nozzle (B). Some configurations of the machinery have used plastic pellets fed from a hopper rather than a filament. The nozzle is heated to melt the plastic and has a mechanism which

allows the flow of the melted plastic to be controlled. The nozzle is mounted to a mechanical stage (C) which can be moved in horizontal and vertical directions. As the nozzle is moved over the table (D) in the required geometry, it deposits a thin bead of extruded plastic to form each layer. The plastic hardens immediately after being squirted from the nozzle and bonds to the layer below. The entire system is contained within an oven chamber which is held at a temperature just below the melting point of the plastic. Thus, only a small amount of additional thermal energy needs to be supplied by the extrusion nozzle to cause the plastic to melt. This provides much better control of the process.

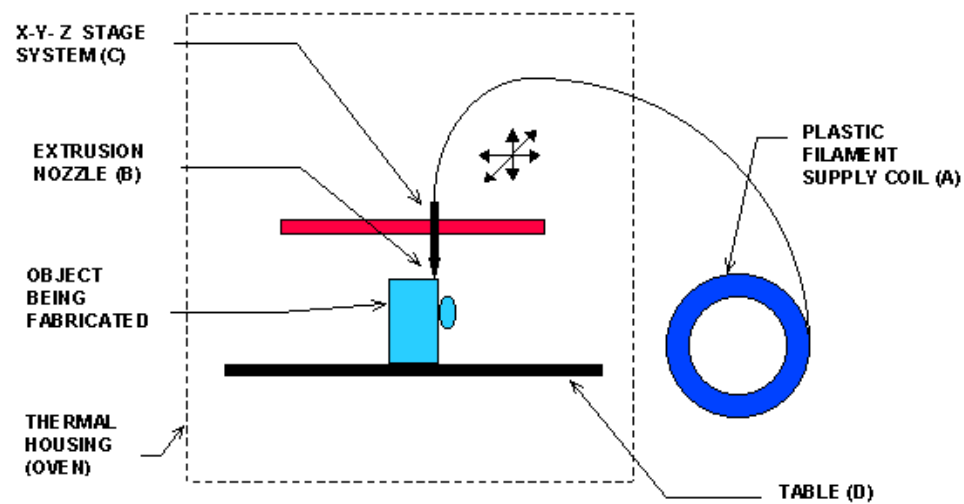


Figure 8 Fused Deposition Modeling

The FDM machine consists of a movable head which deposits a thread of molten material onto a substrate [5]. The build material is heated to 0.5°C above its melting point so that it solidifies about 0.1 s after extrusion and cold welds to the previous layers. Factors to be taken into consideration are the necessity for a steady nozzle speed and material extrusion rate, the addition of a support structure for overhanging parts, and the speed of the head which affects the overall layer thickness [6,7]. The latest FDM system includes two nozzles, one for the part material and one for the support material. The latter is cheaper and breaks away from the prototype without impairing its surface. It is also possible to create horizontal supports to minimize material usage and build time [7,8].

An advantage of this system is that it may be viewed as a desktop prototyping facility in a design office since the materials it uses are cheap, non-

toxic, non-smelly and environmentally safe. There is also a large range of colors and materials available, such as investment casting wax, ABS plastic, medical grade ABS (MABS) and elastomer. Parts made by this method have a high stability since they are not hygroscopic [6].

A disadvantage is that the surface finish of the parts is inferior to that produced using SL due to the resolution of the process which is dictated by the filament thickness [9]. It has not yet been demonstrated whether the material extrusion may be stopped quickly enough to produce small holes in vertical sections [10].

A typical commercially available machine is a stand alone system measuring 660 x 914 x 1067 mm which weighs 160 kg and operates at about 80°C. The build chamber in such a system measures 254 x 254 x 254 mm. The system costs around £100 000, deposits approximately 380 mm of material a second, produces layer thicknesses of 50-762 μ m and has an accuracy of $\pm 127 \mu$ m [11].

Support structures must be designed and fabricated for any overhanging geometries and are later removed in secondary operations. Several materials are available for the process including a nylon-like polymer and both machinable and investment casting waxes. The introduction of ABS plastic material led to much greater commercial acceptance of the method. It provided better layer to layer bonding than previous materials and consequently much more robust fabricated objects. Also a companion support material was introduced at that time which was easily removable by simply breaking it away from the object. Water-soluble support materials have also become available which can be removed simply by washing them away. The recent introduction of polycarbonate and poly(phenyl)sulfone modeling materials have further extended the capabilities of the method in terms of strength and temperature range. Several other polymer systems as well as ceramic and metallic materials are under development.

The method is office-friendly and quiet. FDM is fairly fast for small parts on the order of a few cubic inches, or those that have tall, thin form-factors. It can be very slow for parts with wide cross sections, however. The finish of parts produced with the method have been greatly improved over the years, but aren't quite on a par with stereolithography. The closest competitor to the FDM process is probably three dimensional printing. However, FDM offers greater strength and a wider range of

materials than at least the implementations of 3DP from Z Corp. which are most closely comparable.

Stratasys is the only western supplier. Similar technology has also been under development in China.

- Standard engineering thermoplastics, such as ABS, can be used to produce structurally functional models.
- Two build materials can be used, and latticework interiors are an option.
- Parts up to $600 \times 600 \times 500$ mm ($24 \times 24 \times 20$ inches) can be produced.
- Filament of heated thermoplastic polymer is squeezed out like toothpaste from a tube.
- Thermoplastic is cooled rapidly since the platform is maintained at a lower temperature.
- Milling step not included and layer deposition is sometimes non-uniform so "plane" can become skewed.
- Not as prevalent as SLA and SLS, but gaining ground because of the desirable material properties.

2.1.1.7 Inkjets

2.1.1.8 Thermal Phase Change Inkjets

This technology has also in the past been called ballistic particle manufacturing (BPM). Fig. 6 shows Solidscape, Inc.'s implementation. It uses a single jet each for build and support materials. All phase change inkjet technologies rely on squirting a build material in a liquid or melted state which cools or otherwise hardens to form a solid on impact. 3D Systems also produces an inkjet machine, called the ThermoJet ModelerTM which utilizes several hundred nozzles. 3D's name for their inkjet technology is MultiJet ModelingTM.

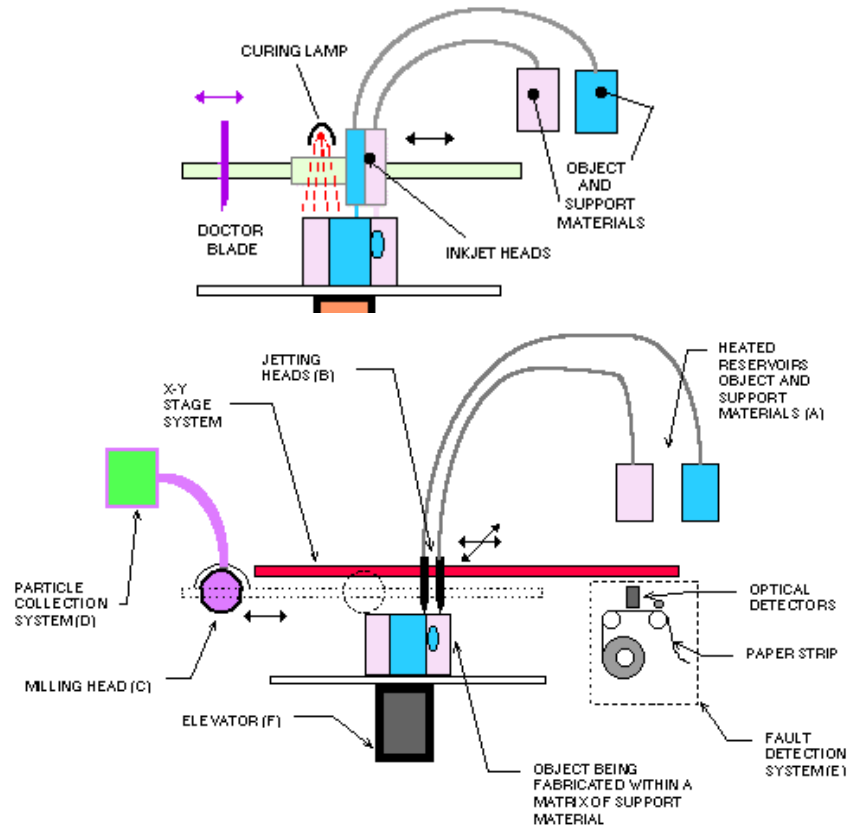


Figure 9 Solidscape implementation.

The Solidscape machine uses plastic object and wax and support materials which are held in a melted liquid state at elevated temperature in reservoirs (A). The liquids are fed to individual jetting heads (B) through thermally insulated tubing. The jetting heads squirt tiny droplets of the materials as they are moved side to side in the required geometry to form the layer of the object. The heads are controlled and only place droplets where they are required to. The materials harden by rapidly dropping in temperature as they are deposited.

After an entire layer of the object is formed by jetting, a milling head (C) is passed over the layer to make it a uniform thickness. Particles are vacuumed away as the milling head cuts and are captured in a filter (D).

The operation of the nozzles is checked after a layer has been fabricated by depositing a line of each material on a narrow strip of paper and reading the result optically (E). If all is well, the elevator table (F) is moved down a layer thickness and the next layer is begun. If a clog is detected, a jetting head cleaning cycle is carried out. If the clog is cleared, the problem layers are milled off and then repeated.

After the object is completed, the wax support material is either melted or dissolved away. The Solidscape system is capable of producing fine finishes, but to do so results in slow operation. Thus, there is a tradeoff between fabrication time and the amount of hand finishing required.

The 3D Systems ThermoJet is much faster since it simultaneously deposits materials from hundreds of jets, but it's also somewhat less accurate. This machine uses fine, hair-like structures made of the modeling material itself to support overhangs and undercuts. To remove the supports, these structures are simply brushed away manually after the part is fabricated.

2.1.1.9 Photopolymer Phase Change Inkjets

Objet Geometries Ltd., an Israeli company, introduced its first machine based on *PolyJetTM* technology in early 2000. The process is based on photopolymers, but uses a wide area inkjet head to layer wise deposit both build and support materials. It subsequently completely cures each layer after it is deposited with a UV flood lamp mounted on the print head. The support material, which is also a photopolymer, is removed by washing it away with pressurized water in a secondary operation.

With specifications that are similar to laser-based stereolithography systems costing several times as much, and operational conveniences much like lower-cost 3D printers, this an important technology to watch. In 2004, Stratasys started selling Objet's products in the US market. Objet's Eden series machines are considered office-friendly and provide uniquely thin layers of approximately 16 microns (0.0006 in). This is said to greatly reduce post-processing and finishing operations, frequently making them unnecessary.

In July, 2002, 3D Systems announced a similar photopolymer-based system called the *InVisionTM*. It uses the technology originally developed for the *ThermoJet ModelerTM* and deliveries began in late 2003. The company has priced the system at \$40K to better compete with 3D printers from Stratasys and Z Corp. One major difference from the Objet technology is that the support material is a wax that is melted away from the part, rather than washed away with water. A high-resolution version of the system is also available. Users praise the quality of the parts and the convenience and size of the machine, although they feel the output isn't quite on a par with stereolithography in terms of feature size and material properties. However,

such jetted photopolymer technologies are still relatively new and will not achieve a similar level of maturity as stereolithography's for a few years.

2.1.1.10 Three Dimensional Printing

The system was developed at MIT and is shown schematically in Fig. 7. The method is very reminiscent of selective laser sintering, except that the laser is replaced by an inkjet head. The multi-channel jetting head (A) deposits a liquid adhesive compound onto the top layer of a bed of powder object material (B). The particles of the powder become bonded in the areas where the adhesive is deposited.

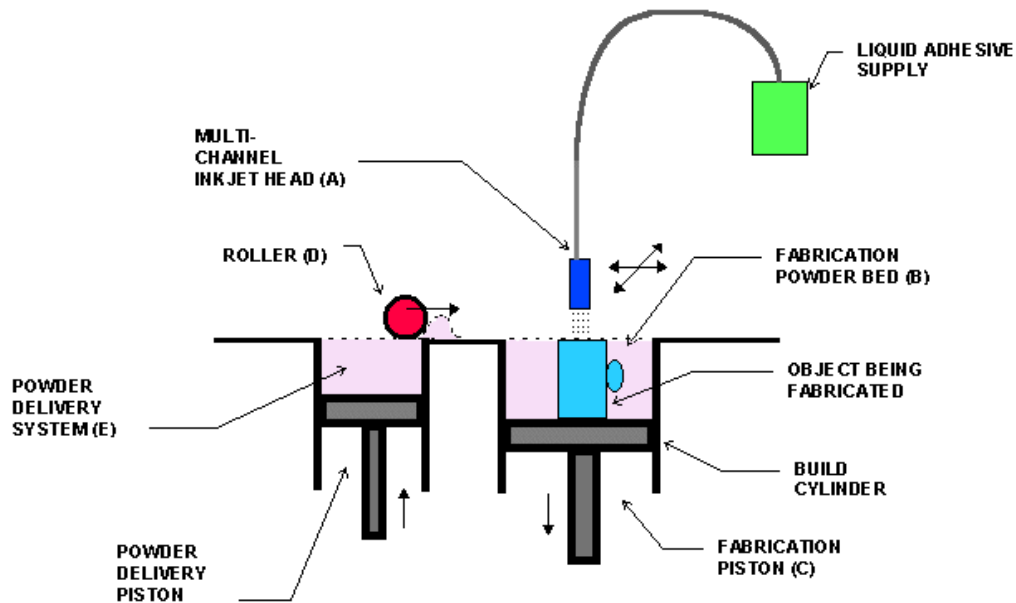


Figure 10 Three Dimensional Printing

Once a layer is completed the piston (C) moves down by the thickness of a layer. As in selective laser sintering, the powder supply system (E) is similar in function to the build cylinder. In this case the piston moves upward incrementally to supply powder for the process and the roller (D) spreads and compresses the powder on the top of the build cylinder. The process is repeated until the entire object is completed within the powder bed.

After completion the object is elevated and the extra powder brushed away leaving a "green" object. Parts must usually be infiltrated with a hardener before they can be handled without much risk of damage.

The three dimensional printing process has been licensed to several companies: Soligen is using it to make investment castings from ceramic powders;

Therics for manufacture of controlled-dosage pharmaceuticals and in tissue engineering applications; ProMetal for direct metal tooling, etc. Several additional companies have either optioned or licensed the technology for applications ranging from filtration to figurines. Z Corp. is the only licensee that addresses the RP market directly, however. They use the process to create conceptual models out of starch, plaster and other types of powders. The company introduced a color-capable system in 2000, and greatly improved that technology in 2004 with the introduction of a 24-bit color system.

2.1.1.11 Miscellaneous Uncommercialized Technologies

Numerous techniques have been - and are being - investigated as solutions to one or more facets of the rapid prototyping problem. A sampler of a few interesting projects follow. Keep in mind that this is a very superficial survey. There are scores of additional distinct methods and variations, described in patents and other sources.

2.1.1.12 Polymer Materials

Design Controlled Automatic Fabrication (DesCAF)

This process has been under development by Light Sculpting Inc. since at least 1986. It may be thought of as a stereolithography variation in the same way the SGC method is. The technique utilizes photopolymer which is exposed and completely cured a layer at a time through a mask. In contrast to SGC which uses an in-line, xerographically generated mask, this method uses a standard laser printer to generate masks off-line. Photo plotters had been previously used, and while expensive, produced amazing resolution. The masks are punched for registration purposes by an accessory machine for subsequent presentation to the rapid prototyping system. Thousands of masks are required to fabricate an object, but the method can yield higher resolution than any other RP technology and has a very high fabrication rate once the masks are generated and available. How long the masks will last is one interesting question since they come in contact with the surface of the photopolymer.

In the long run, the method could have some strong advantages if breakthroughs can be made in supporting technologies which result in replacing the photo masks with dynamic equivalents such as liquid crystals or deformable mirror

devices (DMD's). Actually, many variations in stereolithography technology being investigated today use similar machine architectures.

Electro setting Materials

Researchers at the US Navy Taylor Research Laboratory have discovered that when an electric field is imposed on certain appropriately doped conventional materials such as epoxies, silicones, paints, etc., the materials can be made to change from a liquid into a solid, relatively more rapidly in areas where the electric field is present.

If a method could be found to produce conductive electrodes of object cross sections using a conventional printer, the possibility exists that a very simple and extremely low-cost method of rapid prototyping may result. That would be a good trick: If specifications are to be at least competitive with existing rapid prototyping methods, the state of the art would be required to be advanced in five or more interactive technologies simultaneously. It's not likely that the thrust of this work will be in the RP arena; more likely electro setting will provide a method of volume manufacturing of objects that possess properties that vary throughout their geometries.

2.1.1.13 Metals

Many groups have worked on the direct deposit of metals to form final objects. Several basic techniques are having been investigated: inkjet-based, weld deposition, masked deposition and several variations on laser fusing or laser powder forming technologies.

Inkjet-based

These technologies are also sometimes referred to as liquid metal jet printing (LMJP) or ballistic particle manufacturing, and are analogous to methods that utilize polymers discussed elsewhere. The principal difference is the replacement of the material. Inere Inc. worked on this process in one guise or another from the mid-80's until 2000 when the company was dissolved. The University of California also has had a similar long-term project. So far, the objects formed are crude and have unacceptable material properties for RP applications. The work at the University of California is being commercialized for the specialized application of depositing

solder for electronic circuitry applications by Rapid Analysis and Development Co., however. Several other companies are also pursuing this market, including MicroFab Technologies, Inc.

Because metals in the melted state have very low viscosity, they're difficult to control once they leave the nozzle. Patents assigned to Semi-Solid Technologies offer the possibility of using eutectic alloy mixtures which have high viscosity and may be more controllable. The technique is very much like fused deposition modeling. The thrust of the work appears to be towards the fabrication of near net shape castings and the like, however.

Weld Deposition

Several companies and universities have worked in this area for a number of years. Among them are Babcock & Wilcox (very early work), Nottingham University and Tufts University. The method generally involves moving an arc welding rod robotically or by conventional positioning means to build up structures out of the melted metal. So far, accuracy, finishes and material properties are not acceptable.

Masked Deposition

Carnegie Mellon University researched this technology over several years. In masked deposition, thin layers of metal are deposited by plasma spraying metal particles from a torch through a laser-cut paper mask. The particles instantly cool and bond to the substrate or the previous layer of the object. Techniques have been worked out to form support structures, etc. Interestingly, a Helisys LOM machine could be used as a front-end to generate the masks. The main problems seem to be poor bonding of layers and internal stresses built into the objects.

2.2 CONTROL SYSTEM

Rapid prototyping machines are numerically controlled like CNC milling machines. As Rapid prototyping machines' working principle is additive, their operation method is inverse of CNC metal cutting machinery like CNC milling machine. In order to achieve the desired complex operation of Rapid prototyping machines, CNC based control is a must. Detailed information about Computerized Numerical Control is explained in the following sections.

2.2.1 Numerical Control

Numerical control or numerically controlled (NC) machine tools are machines that are automatically operated by commands that are received by their processing units. NC machines were first developed soon after World War II and made it possible for large quantities of the desired components to be very precisely and efficiently produced (machined) in a reliable repetitive manner. These early machines were often fed instructions which were punched onto paper tape or punch cards. In the 1960s, NC machines largely gave way to CNC, or computer numerical control, machines.

Numerical Control (NC) was the precursor of today's Computer Numerical Control (CNC), which controls the automation of machine tools and the inherent tool processes for which they are designed. The CNC machine tool is the servo actuator of the CAD/CAM (Computer Assisted Design/Computer Assisted Manufacturing) technology both literally and figuratively. CNC inherits from NC the essential character of by-the-numbers interpolation of transition points in the work envelope of a multi-axis motion platform, based on the separation of programming from operations. The set of instructions, or "program" (usually an ASCII text file in which, in its simplest form, a line of text specifies the axial coordinates of a point in the work envelope) is prepared from a blueprint or CAD file and transferred to the memory of the CNC via floppy drive, serial data interface or a network connection. Once stored in the CNC memory and selected, the program is executed by pressing the appropriate key on the machine operator panel.

2.2.1.1 Historical notes

The need of the U.S. Air Force for templates more precise than could be obtained by state-of-the-art methods of the late 1940s inspired John Parsons, President of the Parsons Works of Traverse City, Michigan, to propose that a by-the-numbers technique (commonly used by machinists of that era) be placed under servo control with positional data generated by a computer, thereby providing much more data than would be practical by means of hand calculations. His concept was to machine to set points as guides for subsequent manual finishing, that is, to speed up a manual process so more points could be included.

Mr. Parsons' project was enjoined by the Servo Mechanisms Laboratory of the Massachusetts Institute of Technology and redefined as interpolative positional control that caused the cutting tool to traverse a series of straight lines between defined points at a prescribed rate of travel. Thus, the cutting tool would be almost constantly on the programmed contour and would spend very little of its time making non-cutting moves.

In the M.I.T. scheme, a contour of constantly changing curvature was represented as a poly-line with the intersections between line segments being points on the curve, and the axial coordinates of these points were listed for execution in sequential order in the part program (much like the figure which results from connecting-the-dots in an activity book). The shorter the line segments the more accurately the poly-line would approximate the actual curve. Thus, M.I.T. retained separation of programming from operations while redefining the servo control as interpolative, rather than discretionary, positioning. M.I.T. demonstrated the first ever NC machine tool to a select group from the military, the aerospace industry, the machine tool industry and the technical media in September, 1952.

At the time when M.I.T. was developing numerical control, engineers at General Motors were putting position transducers on the lead screws of a conventional engine lathe and recording the motion of the axes as the machinist put the machine through its paces to make a work piece. The machine was also fitted with a servo system that took data from the recording to reproduce the same sequence of motion to produce a second, third and more parts. This technique is called record/playback. Record/playback is different from numerical control in that the program is produced by the machinist in the process of making the first part. The Air Force wanted numerical control and not record/playback because 1) the latter put

the machinists who were union members in charge of program production, thus union strikes could result in unacceptable delays in military production, and 2) numerical control demonstrated the capability of producing complex parts that were not possible by the conventional manual methods used in the record/playback technique. The Air Force used its deep pockets to get its way and while American manufacturing may have been better served by the simpler Parsons concept or by record/playback, today this is a moot issue.

The electronic files used to control NC and CNC machines are often in a format called G-Code, after Gerber Scientific Instruments, a manufacturer of photo plotters and developer of the file format. The X-Y two-dimensional motion of photo plotters was extended to include the third Z axis, and along with special codes, allows milling machines to be steered in more than three axes. Many of the lines of text in the control files start with the ASCII letter G, thus the name; however, there are other commands that start with the letter D and M, as well as X and Y for coordinates. The file format became so widely used that it has been embodied in an EIA standard.

2.2.1.2 Today

An entire manufacturing technology known as CAD/CAM has developed around the NC concept and, in addition, CNC with its powerful microprocessors and other enabling technologies proffered from the personal computing phenomenon has enabled the NC concept to branch into many variants, even a variant that is essentially record/playback. The latter of which are known in the industry as "teach lathes".

In addition, powerful and well-crafted human/machine interfaces allow the machine operator to prepare programs by means of interactive displays which request only the definition of the machining operation and its required parameters (such as a "pocket" and its dimensions) and not the actual tool paths with all the calculations that are there required. Anyone who knows machining concepts and blueprint interpretation can produce programs at the machine without the need for CAD/CAM. Nonetheless, the vast majority of programs are now produced with the aid of CAD/CAM and, for most users, CNC today (for all its gigahertz microprocessors and megabytes of real time kernel software) is conceptually little different from the first NC demonstrated by the M.I.T. in 1952.

If there is a notable difference in concept, it is that CNC is no longer just for the spindle/cutting tool process of stock removal. It is for any processes that can be carried on machine tool motion platforms and that benefit from the separation of programming from operations, that is, from the CAD/CAM technology. These include lasing, welding, Rapid prototyping, friction stir welding, ultrasonic welding, flame cutting, bending, spinning, pinning, gluing, fabric cutting, sewing, tape and fiber placement, routing, picking and placing (PnP), sawing and undoubtedly, the industrial processes of tomorrow.

2.2.1.3 Motion Control

The most basic function of any CNC machine is automatic, precise, and consistent motion control. All forms of CNC equipment have two or more directions of motion, called axes. These axes can be precisely and automatically positioned along their lengths of travel. The two most common axis types are linear (driven along a straight path) and rotary (driven along a circular path).

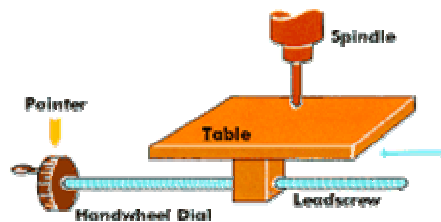


Figure 11 A conventional machine's slide is moved by an operator turning the handwheel. Accurate positioning is accomplished by the operator counting the number of revolutions made on the handwheel, plus the graduations on the dial.

Instead of causing motion by manually turning cranks and hand wheels as is required on conventional machine tools, CNC machines allow motions to be actuated by servomotors under control of the CNC, and guided by the part program. Generally speaking, the motion type (rapid, linear, and circular), the axes to move, the amount of motion and the motion rate (feed rate) are programmable with almost all CNC machine tools. Figure 11 (above) shows the motion control of a conventional machine tool. Figure 12 (below) shows the makeup of a linear axis of a CNC machine.

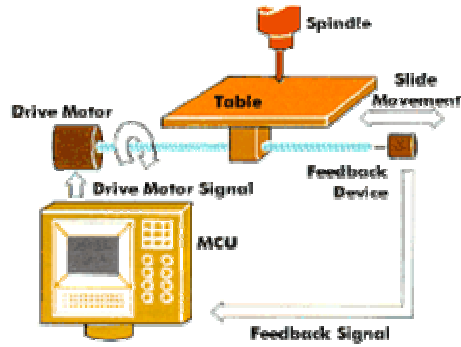


Figure 12 A CNC machine takes the commanded position from the CNC program. The drive motor is rotated a corresponding amount, which in turn drives the ballscrew, causing linear motion of the axis. A feedback device confirms that the proper amount of ballscrew revolutions have occurred.

A CNC command executed within the control (commonly through a program) tells the drive motor to rotate a precise number of times. The rotation of the drive motor in turn rotates the ballscrew. And the ballscrew drives the linear axis. A feedback device at the opposite end of the ballscrew allows the control to confirm that the commanded number of rotations has taken place.

Though a rather crude analogy, the same basic linear motion can be found on a common table vise. As you rotate the vise crank, you rotate a leadscrew that, in turn, drives the movable jaw on the vise. By comparison, a linear axis on a CNC machine tool is extremely precise. The number of revolutions of the axis drive motor precisely controls the amount of linear motion along the axis.

2.2.2 Stepper Motor Basics

2.2.2.1 Technical Description

Stepper motors are electromechanical equipments converting electrical energy into rotation movement. Pulses of electricity drive rotor and connected shaft. They are connected to stepper motor drivers which have high switching capability. This driver gets pulses from a digital controller and each pulse drives the shaft of the motor for a determined angle. This little angle is called step angle and fixed for each motor. The speed and direction of the movement depends on pulse sequence and pulse frequency. A basic shape of a stepper motor is shown in **Figure 13**.

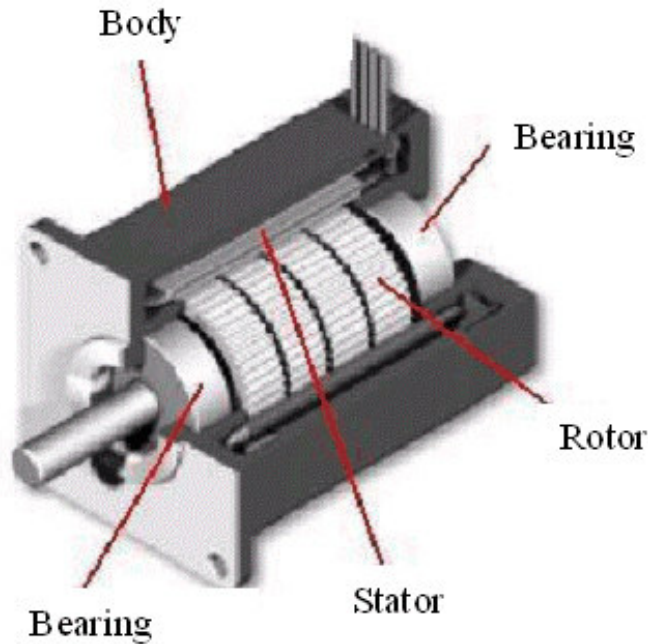


Figure 13 Construction of a stepper motor

The rotation has not only a direct relation to the number of input pulses, but its speed is also related to the frequency of the pulses. Stepper motors vary in the amount of rotation that the shaft turns each time when a winding is energized. The amount of rotation is called step angle as mentioned before and vary from 0.9° degrees (1.8° degrees is more common) to 90° degrees. Step angle determines the number of steps per revolution. A stepper with a 1.8° degrees step angle must be pulsed 200 times ($1.8^\circ \times 200 = 360^\circ$) for the shaft to turn one complete revolution. Sensitivity of a stepper motor increase with the number of steps in one revolution like its cost.

Obviously, a smaller step angle increase the accuracy of a motor. But stepper motors have an upper limit to the number of pulses they can accept per second. Heavy-duty steppers usually have a maximum pulse rate (or step rate) of 200 or 300 steps per second, so they have an effective high speed of one to three revolution per second (60 to 180 rpm). Some smaller steppers can accept a thousand or more pulses per second, but they don't provide very torque and are not suitable as driving or steering motors.

The stepper motor coils are typically rated for a particular voltage. The coils act as inductors when voltage is supplied to them. As such they don't instantly draw their full current and in fact may never reach full current at high stepping

frequencies. The electromagnetic field produced by the coils is directly related to the amount of current they draw. The larger the electromagnetic field the more torque the motors have the potential of producing. The solution to increasing the torque is to ensure that the coils reach full current draw during each step.

Stepper motors can be viewed as electric motors without commutators. Typically, all windings in the motor are part of the stator, and the rotor is either a permanent magnet or, in the case of variable reluctance motors, a toothed block of some magnetically soft material. All of the commutation must be handled externally by the motor controller, and typically, the motors and controllers are designed so that the motor may be held in any fixed position as well as being rotated one way or the other.

It should be noted that stepper motors couldn't be motivated to run at their top speeds immediately from a dead stop. Applying too many pulses right off the bat simply causes the motor to freeze up. To achieve top speeds, the motor must be gradually accelerated.

The acceleration can be quite swift in human terms. The speed can be 1/3 for the first few milliseconds, 2/3 for the next 50 or 75 milliseconds, then full blast after that.

Actuation of one of the windings in a stepper motor advances the shaft. Continue to apply the current to the winding and the motor won't turn any more. In fact, the shaft will be locked, as if brakes are applied. As a result of this interesting locking effect, you never need to add a braking circuit to a stepper motor, because it has its own brakes built in. The amount of breaking power of a stepper motor is expressed as holding torque.

2.2.2.2 Stepper Motor Types

2.2.2.2.1 Variable Reluctance (VR)

VR motors are characterized as having a soft iron multiple rotor and a wound stator. They generally operate with step angles from 5 degrees to 15 degrees at relatively high step rates, and have no detent torque (detent torque is the holding torque when no current is flowing in the motor).

In **Figure 14**, when phase A is energized, four rotor teeth line up with the four stator teeth of phase A by magnetic attraction. The next step is taken when A is turned off and phase B is energized, rotating the rotor clockwise 15 degrees;

Continuing the sequence, C is turned on next and then A again. Counter clockwise rotation is achieved when the phase order is reversed.

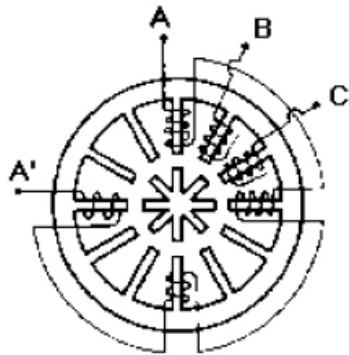


Figure 14 Variable Reluctance Motor

2.2.2.2.2 Permanent Magnet (PM)

PM motors differ from VR's by having permanent magnet rotors with no teeth, and are magnetized perpendicular to the axis. In energizing the four phases in sequence, the rotor rotates as it is attracted to the magnetic poles. The motor shown in **Figure 15** will take 90 degree steps as the windings are energized in sequence ABCD. PM's generally have step angles of 45 or 90 degrees and step at relatively low rates, but they exhibit high torque and good damping characteristics.

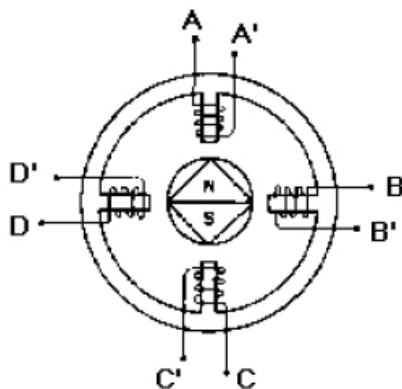


Figure 15 Permanent Magnet Motor

2.2.2.2.3 Hybrid (HB)

Combining the qualities of the VR and the PM, the hybrid motor has some of the desirable features of each. They have high detent torque and excellent holding and dynamic torque, and they can operate at high stepping speeds. Normally, they exhibit step angles of 0.9 to 5 degrees. Bi-polar windings are generally supplied (as

depicted in **Figure 16**), so that a single-source power supply can be used . If the phases are energized one at a time, in the order indicated, the rotor would rotate in increments of 1.8 degrees. This motor can also be driven two phases at a time to yield more torque, or alternately one then two then one phase, to produce half steps or 0.9 degree increments.

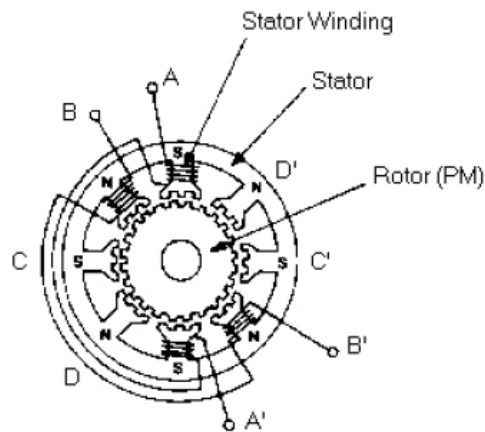


Figure 16 Hybrid Motor

2.2.3 Coil Excitation Types

2.2.3.1 Unipolar Stepper Motors

Unipolar motors are relatively easy to control. A simple 1-of-'n' counter circuit can generate the proper stepper sequence, and drivers as simple as 1 transistor per winding are possible with unipolar motors. Unipolar stepper motors are characterized by their center tapped windings. A common wiring scheme is to take all the taps of the center-tapped windings and feed them +V_m (Motor voltage). The driver circuit would then ground each winding to energize it.

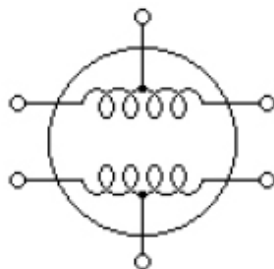


Figure 17 6-wire Unipolar Stepper Motor

Unipolar stepper motors, both Permanent magnet and hybrid stepper motors with 5 or 6 wires are usually wired as shown in the schematic in **Figure 17**, with a center tap on each of two windings. In use, the center taps of the windings are typically wired to the positive supply, and the two ends of each winding are alternately grounded to reverse the direction of the field provided by that winding. (**Figure 18**)

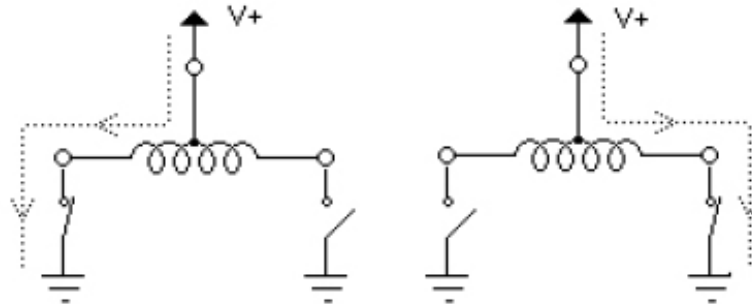


Figure 18 Reversal of Current in one coil of a Unipolar Stepper Motor

In unipolar stepper motors the number of phases is twice the number of coils, since each coil is divided in two. The diagram below which has two center-tapped coils represents the connection of a 4-phase unipolar stepper motor.

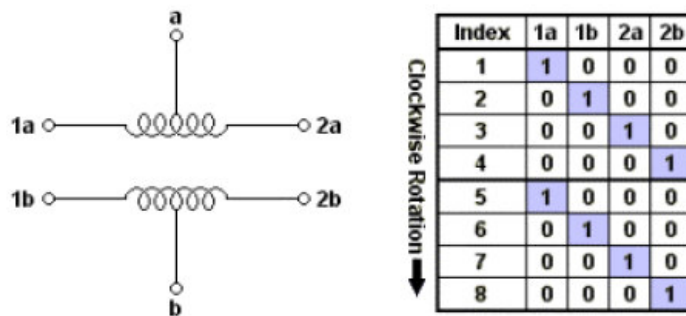


Figure 19 Unipolar Drive Sequence

In addition to the standard drive sequence, high-torque and half-step drive sequences are also possible. In the high-torque sequence, two windings are active at a time for each motor step. This two-winding combination yields around 1.4 times more torque than the standard sequence, but it draws twice the current. Half-stepping is achieved by combining the two sequences. First, one of the windings is activated, then two, then one, etc. This effectively doubles the number of steps the motor will

advance for each revolution of the shaft, and it cuts the number of degrees per step in half.

2.2.3.2 Bipolar Stepper Motors

Bipolar permanent magnet and hybrid motors are constructed with exactly the same mechanism as is used on unipolar motors, but the two windings are wired more simply, with no center taps. Thus, the motor itself is simpler but the drive circuitry needed to reverse the polarity of each pair of motor poles is more complex. The schematic in **Figure 20** shows how such a motor is wired.

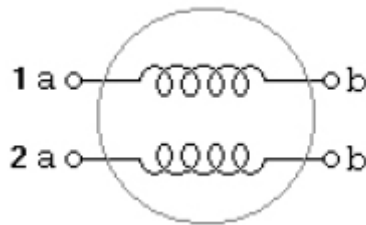


Figure 20 4-wire Bipolar Stepper

Unlike unipolar stepper motors, bipolar units require more complex driver circuitry. Bipolar motors are known for their excellent size/torque ratio, and provide more torque for their size than unipolar motors. Bipolar motors are designed with *separate* coils that need to be driven in either direction (the polarity needs to be reversed during operation) for proper stepping to occur. This presents a driver challenge. Bipolar stepper motors use the same binary drive pattern as a unipolar motor, only the '0' and '1' signals correspond to the polarity of the voltage applied to the coils, not simply 'on-off' signals. **Figure 21** shows a basic 4-phase bipolar motor's coil setup and drive sequence.

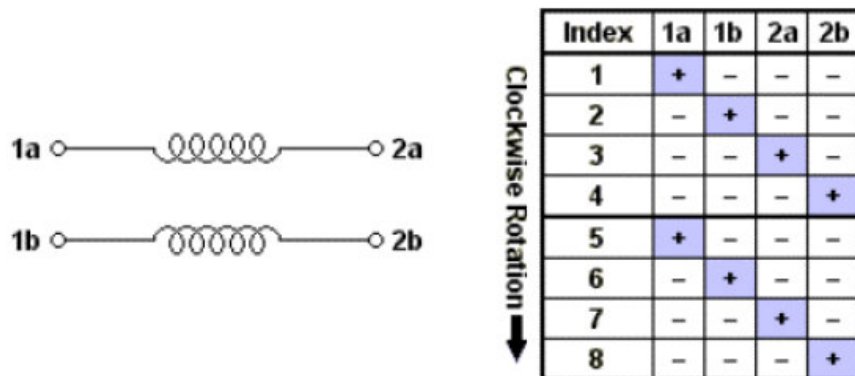


Figure 21 Bipolar Drive Sequence

The Bipolar Controller must be able to reverse the polarity of the voltage across either coil, so current can flow in both directions. And, it must be able to energize these coils in sequence. The mechanism for reversing the voltage across one of the coils is called an HBridge, because it resembles a letter "H" (**Figure 22**).

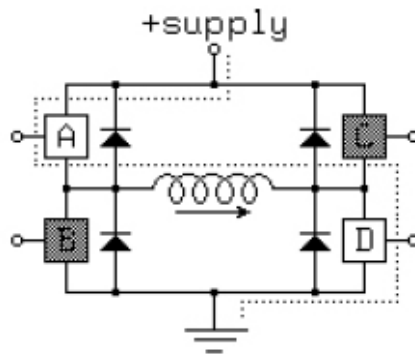


Figure 22 Conventional H-Bridge Circuit

2.2.4 Stepper Motor Drive Sequences

The following table describes 3 useful stepping sequences and their relative merits. The polarity of terminals is indicated with +/- . After the last step in each sequence the sequence repeats. Stepping backwards through the sequence reverses the direction of the motor. Note that these sequences are identical for unipolar and bipolar stepper motors.

Name	Sequence	Polarity	Description
Wave Drive, One-Phase	0001	---+	Consumes the least power. Only one phase is energized at a time. Assures positional accuracy regardless of any winding imbalance in the motor.
	0010	--+-	
	0100	-+--	
	1000	+---	
Hi-Torque, Two-Phase	0011	--++	This sequence energizes two adjacent phases, which offers an improved torque-speed product and greater holding torque.
	0110	-++-	
	1100	++--	
	1001	+--+	
Half-Step	0001	---+	Effectively doubles the stepping resolution of the motor, but the torque is not uniform for each step. (Since switching occurs between Wave Drive and Hi-Torque with each step, torque alternates each step.)
	0011	--++	
	0010	--+-	
	0110	-++-	
	0100	-+--	This sequence reduces motor resonance which can sometimes cause a motor to stall at a particular resonant frequency. Note that this sequence is 8 steps.
	1100	++--	
	1000	+---	
	1001	+--+	

Table 1 . Stepper Motor Drive Sequences

2.2.5 Stepper Motor Control

Amount, speed, and direction of rotation of a step motor are determined by appropriate configurations of digital control devices. Major types of digital control devices are: Motor Drivers, Control Links, and Controllers. These devices are employed as shown in Figure 23. The Driver accepts clock pulses and direction signals and translates these signals into appropriate phase currents in the motor. The indexer creates the clock pulses and direction signals. The computer or PLC (programmable logic controller) sends commands to the indexer.

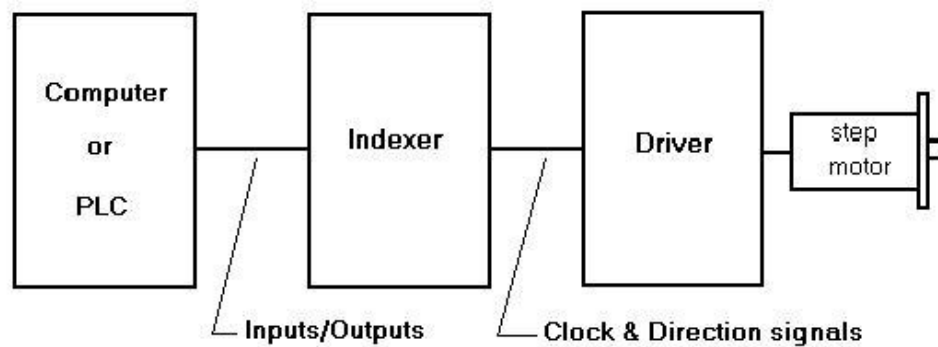


Figure 23 Typical step motor system

2.2.5.1 Modes

There are three commonly used excitation modes: full-step, half-step, and micro-step.

2.2.5.1.1 Full-Step

In full step operation, the motor steps through the normal step angle e.g. 200 step revolution motors take 1.8 steps while in half step operation, 0.9 steps are taken. There are two kinds of full-step modes. Single phase full-step excitation is where the motor is operated with only one phase energized at-a-time. This mode should only be used where torque and speed performance are not important, e.g. where the motor is operated at a fixed speed and load conditions are well defined. Problems with resonance operated at fixed speed and load conditions are well defined. Problems with resonance can preclude operation at some speeds. This mode requires the least amount of power from the drive power supply of any of the excitation modes. Dual phase full-step excitation is where the motor is operated with two phases energized at-a-time. This mode provides good torque and speed performance with a minimum

of resonance problems. Dual excitation, provides about 30 to 40 percent more torque than single excitation, but does require twice the power from the drive power supply.

2.2.5.1.2 Half-Step

Half-step excitation is alternate single and dual phase operation resulting in steps one half the normal step sizes. This mode provides twice the resolution. While the motor torque output varies on alternate steps, this is more than offset by the need to step through only half the angle. This mode has become the predominately used mode by Anaheim Automation because it offers almost complete freedom from resonance problems. Motors can be operated over a wide range of speeds and used to drive almost any load commonly encountered.

2.2.5.1.3 Micro-Step

In the micro-step mode, a motor's natural step angle can be divided into much smaller angles. For example, a standard 1.8 degree motor has 200 steps/revolution. If the motor is micro-stepped with a 'divide-by-10'. Then each micro-step would move the motor 0.18 degrees and there would be 2,000 steps/revolution. Typically, micro-step modes range from divide-by-10 to divide-by-256 (51.200 steps/rev for a 1.8 degree motor). The micro-steps are produced by proportioning the current in the two windings according to sine and cosine functions. This mode is only used where smoother motion or more resolution is required.

2.3 INFORMATION ABOUT MECHANICAL COMPONENTS

2.3.1 Ballscrews

There are many benefits in using ballscrews. Such as high efficiency and reversibility-backlash elimination, high stiffness, high lead accuracy, and many other advantages. Compared with the contact thread lead screws as shown in (Figure 27), a ballscrew add balls between the nut and spindle. The sliding friction of the conventional screws is thus replaced by the rolling motion of the balls. The basic characteristics and resultant benefits of ballscrews are listed in more details as follows:

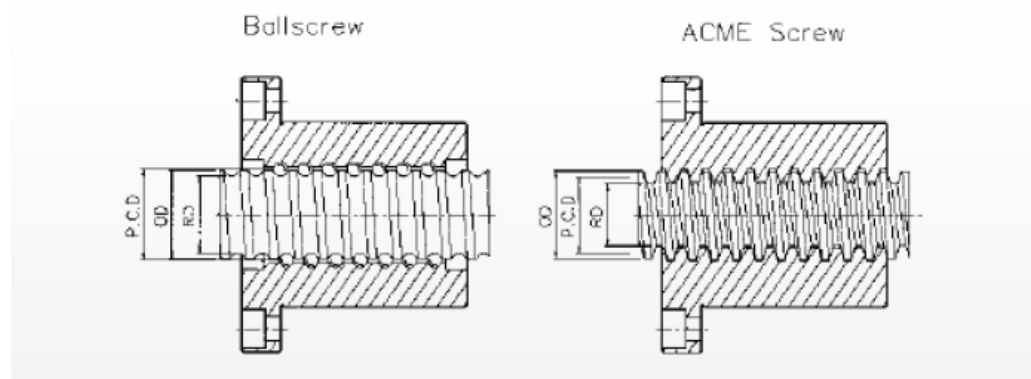


Figure 24 Basic configuration of ballscrews and contact thread lead screws

2.3.1.1 High efficiency and reversibility

Ballscrews can reach efficiency as high as 90% because of the rolling contact between the screw and the nut. Therefore, the torque requirement is approximately one third of that for conventional screws. The mechanical efficiency of ball screws are much higher than conventional lead screws. Ballscrews have super surface finish in the ball tracks which reduce the contact friction between the balls and the ball tracks. Through even contact and the rolling motion of the balls in the ball tracks, a low friction force is achieved and the efficiency of the ballscrew is increased. High efficiency renders low drive torque during ballscrew motion. Hence, less drive motor power is needed in operation resulting in lower operation cost.

2.3.1.2 Backlash elimination and high stiffness

Computer Numerically Controlled (CNC) machine tools require ballscrews with zero axial backlash and minimal elastic deformation (high stiffness). Backlash is eliminated special designed Gothic arch form balltrack (Figure 29) and preload. In

order to achieve high overall stiffness and repeatable positioning in CNC machines, preloading of the ballscrews is commonly used. However, excessive preload increases friction torque in operation. This induced friction torque will generate heat and reduce the life expectancy.

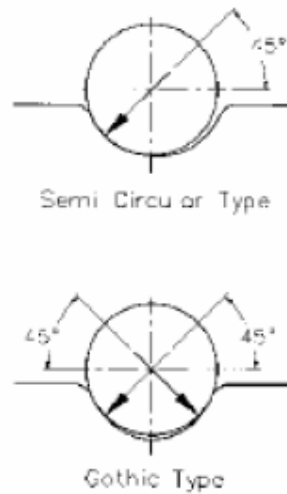


Figure 25 Typical contact types for ballscrews

2.3.1.3 Predictable life expectancy

Unlike the useful life of conventional screws is governed by the wear on the contact surfaces, ballscrews can usually be used till the metal fatigue. By careful attention to design, quality of materials, heat treatment and manufacture, ballscrews have proved to be reliable and trouble free during the period of expected service life. The life achieved by any ballscrew depends upon several factors including design, quality, maintenance, and the major factor, dynamic axial load (C). Profile accuracy, material characteristics and the surface hardness are the basic factors which influence the dynamic axial load. For machine tool applications it is recommended that the life at average axial load should be a minimum of 1×10^6 revs (or 250,000 meters). High quality ballscrews are designed to conform with the B rating (i.e. 90% probability of achieving the design life). Fifty percent of the ballscrews can exceed 2 to 4 times of the design life.

2.3.1.4 Applications for Ballscrews

Ballscrews are used in the following fields:

1. CNC machinery: CNC machine center. CNC lathe. CNC milling machine. CNC EDM. CNC grinder, wire cutting machine, boring machine, special purpose machine, etc.
2. Precision machine tools: Milling machine, grinder, EDM. tool grinder, gear manufacturing machine, drilling machine, planer, etc.
3. Industrial machinery: Printing machine, paper-processing machine, automatic machine, textile machine, drawing machine, etc.
4. Electronic machinery: Robot measuring instrument, X-Y table, medical equipment, surface mounting device, semi-conductor equipment, factory automation equipment, etc.
5. Transport machinery: Material handling equipment, elevated actuator, etc.
6. Aerospace industry: Aircraft flaps, thrust open-close reverser, airport loading equipment, missile fin actuator, etc.
7. Miscellaneous: Antenna leg actuator, valve operator, etc.

2.3.2 Linear Guideways

Ballscrews cannot carry the load by itself. At this point linear guideways will help the ballscrews by taking the load over them. Linear guideway assemblies are designed for high accuracy, large capacity, high reliability and excellent operating characteristics. Recirculation system provides smooth linear motion with low noise.

Linear Guideways offer the following features:

- High accuracy
- Smooth operation
- Large load capacity
- Low noise
- Low friction
- Interchangeability
- High Reliability
- Easy installation
- Sealed carriages
- Competitive price.

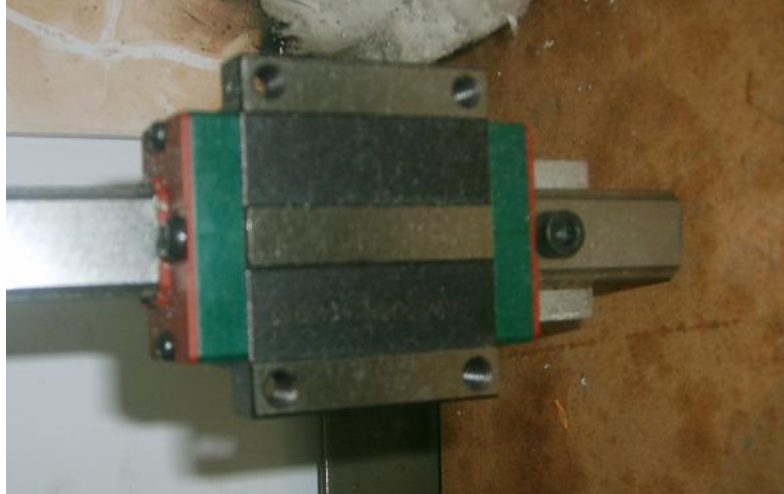


Figure 26 The linear guideway used at the system, manufactured by HIWIN.

3 DESIGN AND PRODUCTION OF THE RP SYSTEM

In the design procedure of the new RP system the first step is to make a decision of the prototyping method of the system. As described at the previous sections there are several rapid prototyping techniques. Most of them use laser beams, photosensitive elements and some of them have just mechanical features. As this project is not an interdisciplinary project, the chance of success is much higher if the new RP machine has mechanical features. FDM rapid prototyping technique is chosen as it is perfect for offices and design workshops and all the features are just mechanical. As mentioned; there is a plastic type filament that is fed through the heat resistances and melted. This melt plastic has to be drained on the work table in order to form the solid model, layer by layer.

There are certain features that have to be implemented, in order to design a FDM rapid prototyping machine. There are 3 axes movement(X,Y,Z) in a FDM machine. The mechanical movements have to be precise, and the human intervention has to be minimal. In order to satisfy this feature computer numerical control has to be implemented as mentioned before. A PC is used as the controller and signal generator. The generated signals are transferred to the drivers through the parallel port of the computer to the interface. After then motor drivers have to be implemented to the system. And with these drivers the motors will be driven. For the movement of head at X. Y and Z direction three motion sources are needed. This motion sources can be DC motors, stepper motors, servo motors or linear motors. Stepper motors are chosen because of their suitable cost and accuracy range. Servo motors are faster and as they have feedback circuits the position accuracy is certain but they are much more expensive than stepper motors also driver units are expensive like themselves. For this application as there is no much load, an open loop system with a stepper motor will satisfy the accuracy.

A chassis has to be designed for assembling the required mechanical parts, motors etc. In the chassis design, 5mm. sheet steel metal, L profiles are used, and welded each other, in order to keep the expenses minimal. But for a professional machine sigma profiles are suggested in order to create more reliable and convenient base. Sigma profiles are generally made of aluminum, they are light with respect to steel, and the geometry of the profile provides high resistance to the heavy loading.

Also there are special assembling joints, these joints provide easy installation, and they do not need extra machining.

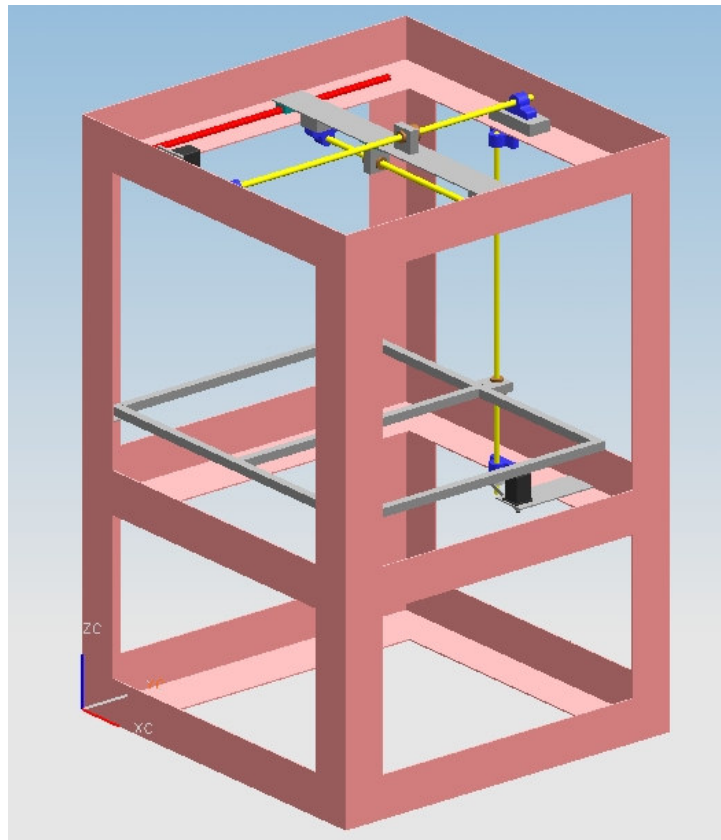


Figure 27 General view of the preliminary design made by computer aided design techniques.

After the design of the chassis and the decision of stepper motors as motion source, driver units of these motors were built. Also these drivers need to communicate with the computer; to do this parallel port interface card was produced. Stepper motors need direct current (DC). In order to supply the direct current, high rating power supply unit (PSU) was built. After the installation of controller units and power unit to a case, stepper motors are ready to be tested. TURBOCNC program was used to generate signals for direction and step amount from parallel port.

Afterwards the electrical and electronic works, motion source can be easily and accurately controlled. Now three motions should be combined to move the head all directions smoothly. At this point there are not many choices to convert rotary motion to linear motion. Best and most common way is to use ballscrews and linear

guideways. Ballscrew and linear guideway calculations are made to choose the needed materials.

For the FDM type rapid prototyping machines the temperature of the ambience has to be controlled, and settled to a certain level. In order to achieve this, electric resistances are assembled to the chassis and the body is insulated with a special ceramic fiber element.

3.1 STEPPER MOTOR, DRIVERS AND PARALLEL PORT INTERFACE

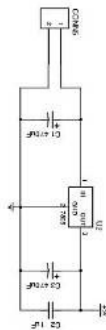
Minebea-Matsushita Motor Corporation's 23KM-C723-13V model stepper motors are selected for the system, the specifications of the motors are listed below;

Step Angle	1.8 Degrees
Drive Sequence	Bi-Polar
Rated Current	2 Ampere
Holding Torque	1.2 Nm

Table 2 . Stepper Motor parameters

For three axes, three stepper motor drivers produced firstly. All of these drivers contain two LMD18245T motor driver circuits which can support maximum 3A at 55V. Each driver needs direction and step signals. These signals will be sent from the computer's parallel port to interface board and then to drivers.

ORCAD is used to design PCBs.



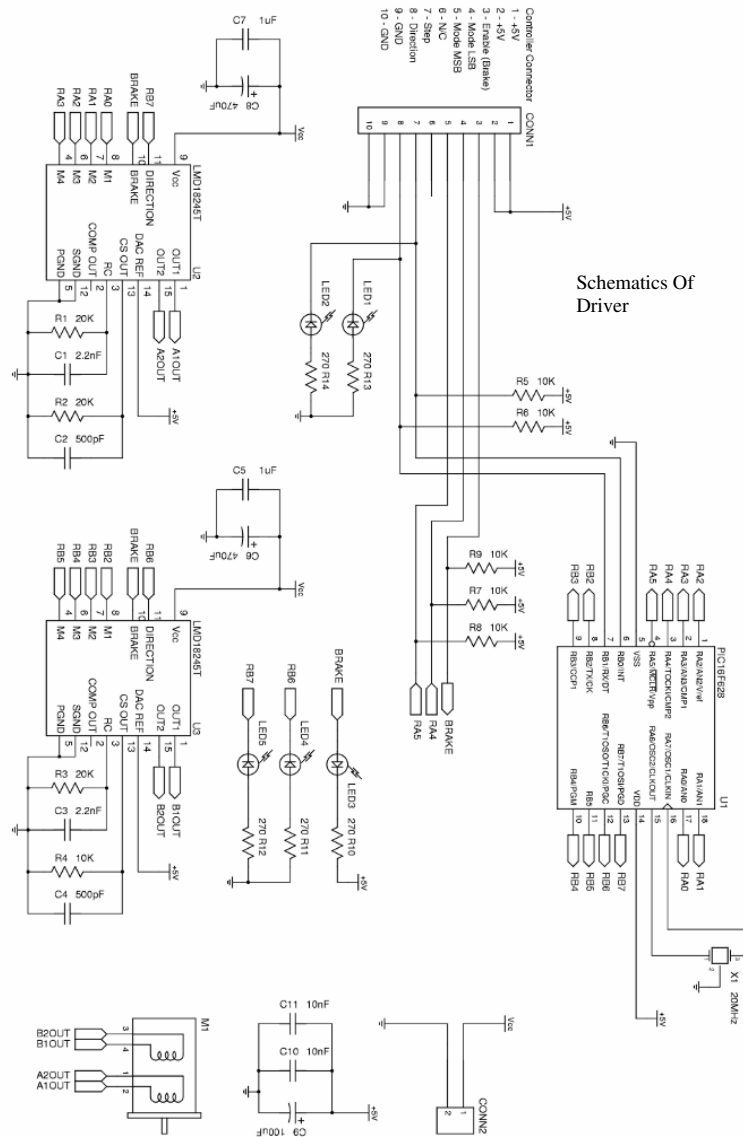


Figure 28 Schematics of stepper driver and parallel port interface

3.1.2 Making the PCBs

High-quality PCBs (printed circuit boards) can be easily produced, from a laser-printer or copier printout of the desired copper pattern, using an ordinary clothes iron and most importantly, the correct paper type.

There are many methods that can be used to make a PCB. Most of the traditional methods involve applying a "mask" over the desired portions of the copper, and using an acid or etchant that can't easily penetrate the mask material to remove the unwanted copper from the remainder of the surface, although direct mechanical milling-away of the unwanted copper is also sometimes used.

Another popular method- which also works with laser printouts is photographic in nature: A transparent positive or negative image of the mask is created, usually photographically, and is used to expose, with a special light, a PCB coated with a photo-sensitive etchant-resistant material. That seems to be the preferred method, for getting the best quality, finest traces, most repeatability.

The reason that this toner transfer method works is that the toner in most laser printers and copiers is composed mainly of plastic, and the etching chemicals (acids) that are used will eat copper but will not eat plastic.

Type of paper

The type of paper used is the key. Almost all types of paper will work. to some degree. But there are usually two problems:

- 1) Print quality: Some papers print with tiny or large pinholes in the toner, which greatly degrades the quality of the finished copper traces.
- 2) Removability: The paper has to be able to be removed, relatively easily, without causing any damage to the pattern on the copper.

Glossy, coated inkjet-printer-type paper has been found to work very well, since the coating on the paper will usually separate from the paper, especially when soaked in water.

Etchant Chemicals

Hydrogen Peroxide (H_2O_2) and Sodium Hypochlorite ($NaOCl$) are mixed as the ratio of 1:4. This mixture releases the Chlorine 2as that is dangerous so etching should be made at out door.

The Complete Procedure:

1. Creation of the copper-side pattern with ORCAD program. Pattern should be drawn reversed.
2. Printing the pattern, using the darkest laser printer settings.
3. Running the pattern through the laser printer a second time but without printing anything over the pattern portion, so the fuser can reheat it. makes the later process of removing the paper much easier.
4. Cutting the pattern out all the way around the pattern.

5. Scrubbing the board with an "artificial steel wool" pad (nylon abrasive pad), equivalent to '0' steel wool, usually in two orthogonal directions.



Figure 29 PCB surface after rubbing with abrasive pad

This step does two things:

- a. It removes oxidation, stains, scratches, etc. so the copper surface of the PCB is all uniformly nice and shiny.
- b. It makes the copper surface somewhat less than perfectly smooth. The nylon abrasive pad makes many tiny scratches in the copper. This apparently helps the toner to stick to the copper.

6. Scrubbing the board with a paper towel soaked with acetone solvent. Keep doing it until no more discoloration is seen on the paper towel.
7. Laying the board with the copper side facing up on a rigid, flat, heat-resistant surface, such as a smooth piece of wood or plywood and laying the paper pattern face down on the copper, lining it up exactly light.
8. Placing the clothes iron on the back of the pattern. Heat the whole board without steam.
9. Peeling off the paper, or at least the top layer or two. If the paper underneath is still a little dry, put the board back into the water, for another ten minutes or more.
10. Rubbing the remaining paper off with thumb pressure or a toothbrush or other soft brush.
11. Rinse the board and wipe the board dry with a clean paper towel.
12. Making any necessary corrections, using a etch-resistant marker pen.
13. Etching by using the mixture, in a Tupperware-style plastic food container.

14. Washing the board in "Lacquer Thinner" solvent, rubbing with a paper towel, to remove the toner instantly.
15. Drilling the holes.
16. Checking the connections and short-circuits.

3.1.3 Soldering The Components

25 Watt soldering machine is used to solder the components on the PCBs.

3.1.4 PIC Programming

A serial port basic PIC programmer is used to program PIC16F628a. Microchip's MPLAB compiler compiled the ASM code for the PICs (see Appendix) to hex file and IC-Prog 1.05d uploaded this hex file to PICs. This firmware written for micro-stepping and it can divide original steps to 1/8 so 200 steps/rev stepper motor becomes 1600 steps/rev. This will increase the accuracy of the stepper motors and also reduces the distortion.



Figure 30 PIC Programmer and PIC16F628A

3.2 POWER SUPPLY UNIT

425 VA transformer, rectifier and capacitors are used to set up the power supply.

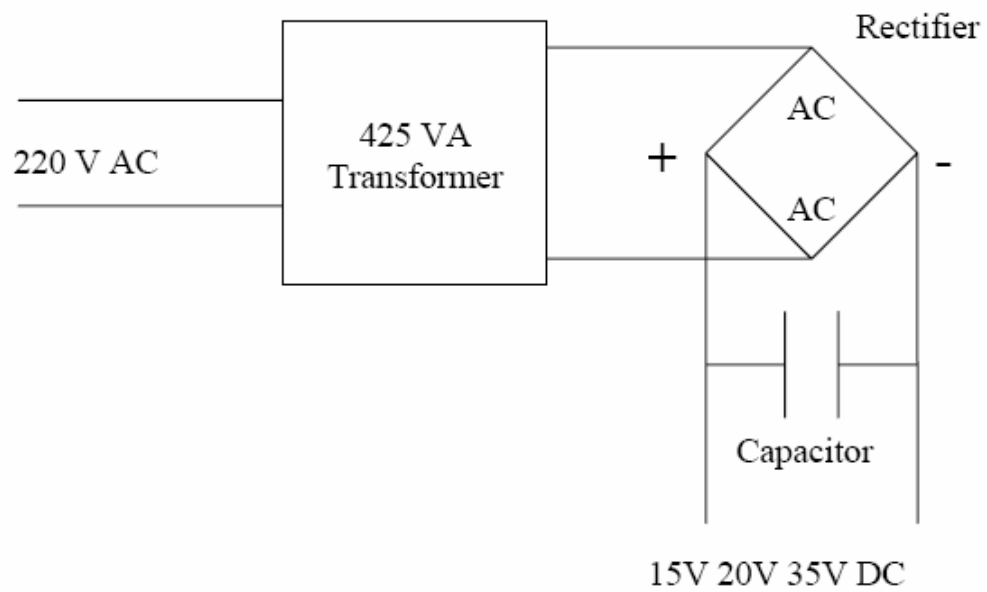


Figure 31 Schematics of the power supply unit

3.3 SOFTWARE

TURBOCNC is used for control software. This software can directly read G and M codes and converts them to signals that are needed for stepper motor drivers. Detailed information can be obtained from users' manual of the program. The

parameters of the step motors are adjusted. There are options for adjusting the step increment, acceleration, step range, maximum speed, starting speed etc.

There are two modes for running the machine. First one is direct numerical control, in which the user can run the pre-prepared g-codes and the other one is manual operation. But for our application direct numerical control is a must as there is a continuous melting process occurring while the head unit moves on X-Y axes.

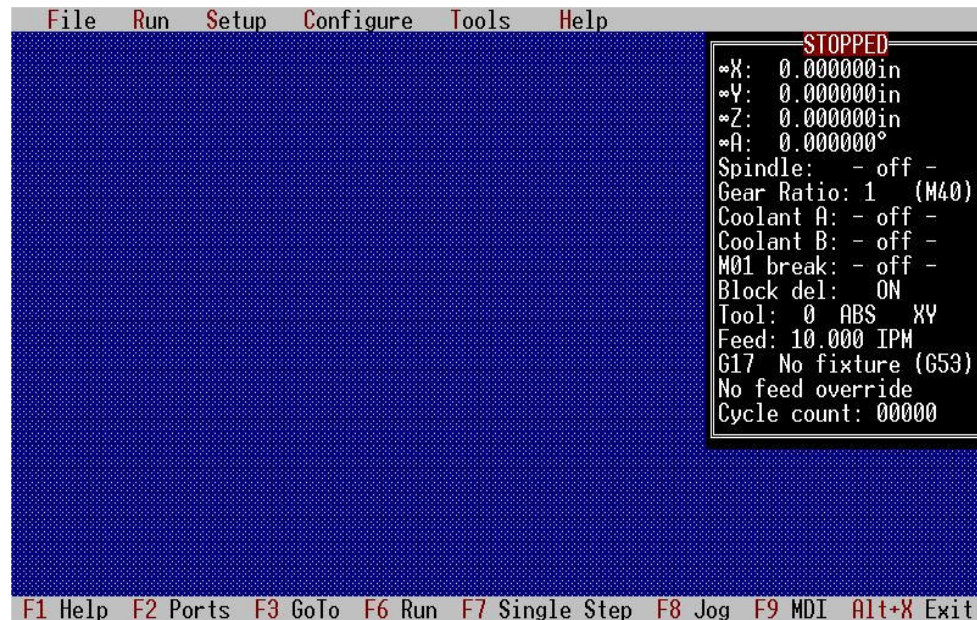


Figure 32 Screen-shot of the TURBOCNC software.

3.4 MECHANICAL COMPONENTS AND ASSEMBLY

The first step for mechanical design is to decide the working area-volume of the machine. Generally the FDM rapid prototyping machines' working dimensions are 254 x 254 x 254 mm. But we have decided to make a larger working

area in order to manufacture larger prototypes. So the working area is decided to be 800x800x600 mm.

5 mm thick steel sheet metal is used to manufacture the chassis of the machine. Sheet metals are welded and fastened each other in order to form the required platforms and bases for the dynamic components of the system. Computer generated view and a picture can be seen below.

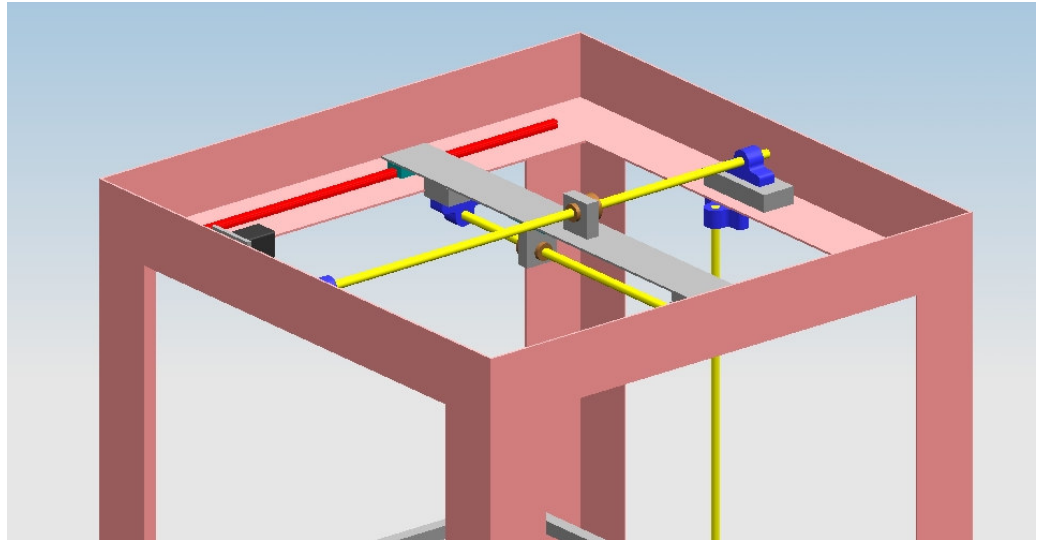


Figure 33 CAD model of the preliminary design.



Figure 34 Picture taken during the test runs.

For the precise motion control, linear guideways and ballscrews are used, and assembled to the system as shown in the figures.

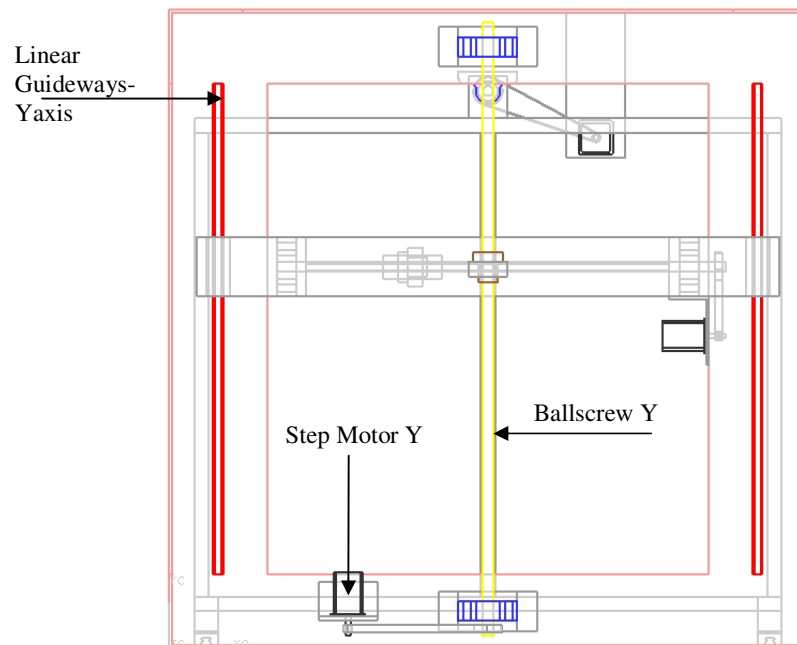


Figure 35 Top view of the system, showing the components of the Y axis.

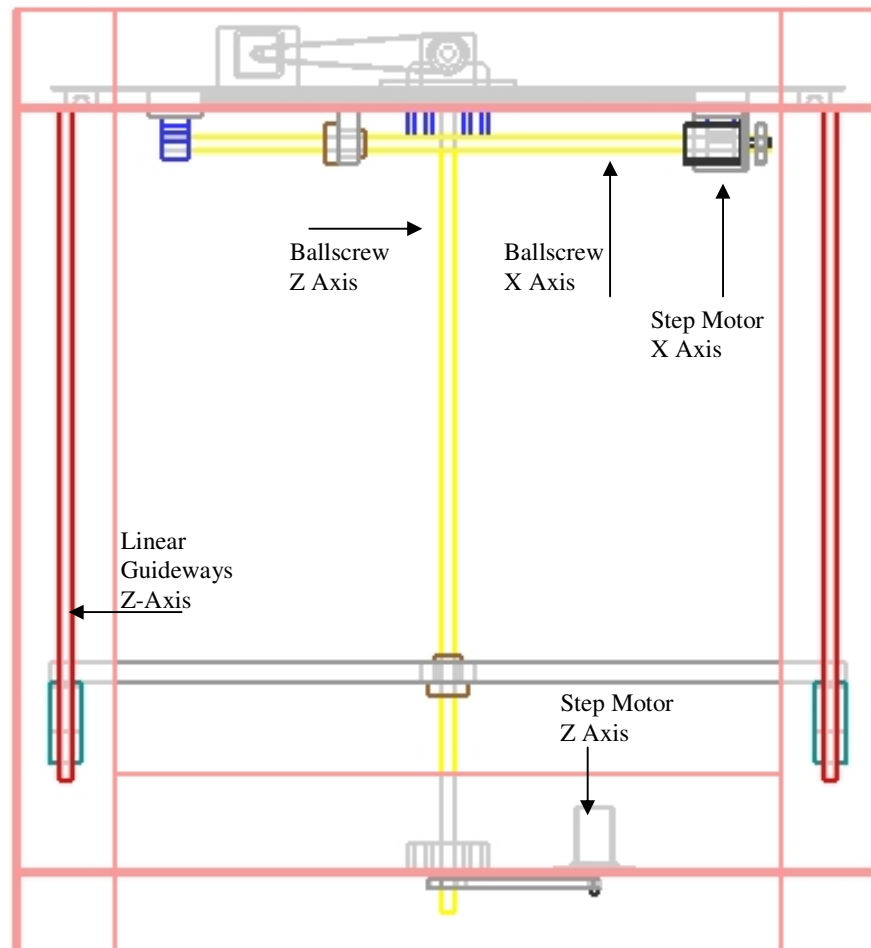


Figure 36 Side view of the system showing the components of X and Z axes.

HIWIN-HGW20C CZA type linear guideways are used. Each guideway can hold a 2000 kg of load without any accuracy loss. The ballscrews have 20 mm diameter and 5 mm pitch length.

After installation of the linear guideways and ballscrews, step motors are assembled. Section views of the machine axes and assembly are shown on the following figures.

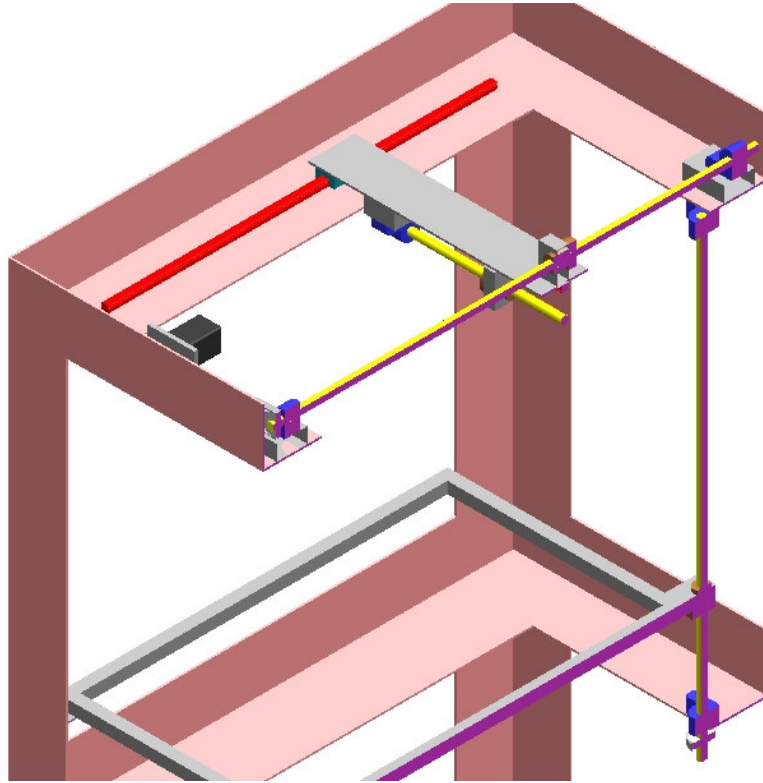


Figure 37 Section view of the system for better visualizing of Y axis components

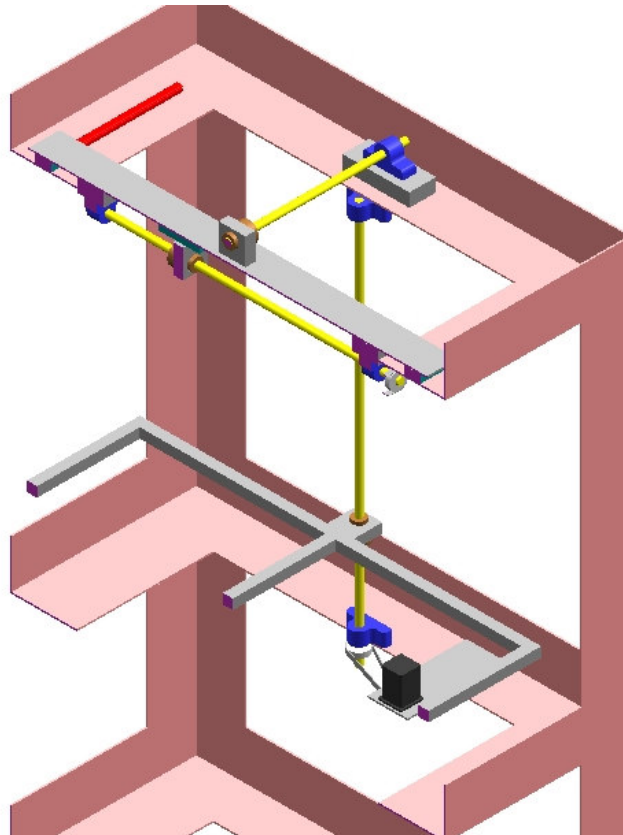


Figure 38 Section view of the system for better visualizing of X and Z axis components.

Each axis is equipped with precise motion control components, a simple parts list table is shown below;

AXIS	LINEAR GUIDEWAYS	BALLSCREWS	STEP MOTOR	RIM
X	1	1	1	1
Y	2	1	1	1
Z	2	1	1	1

Table 3 . Precise motion control components.

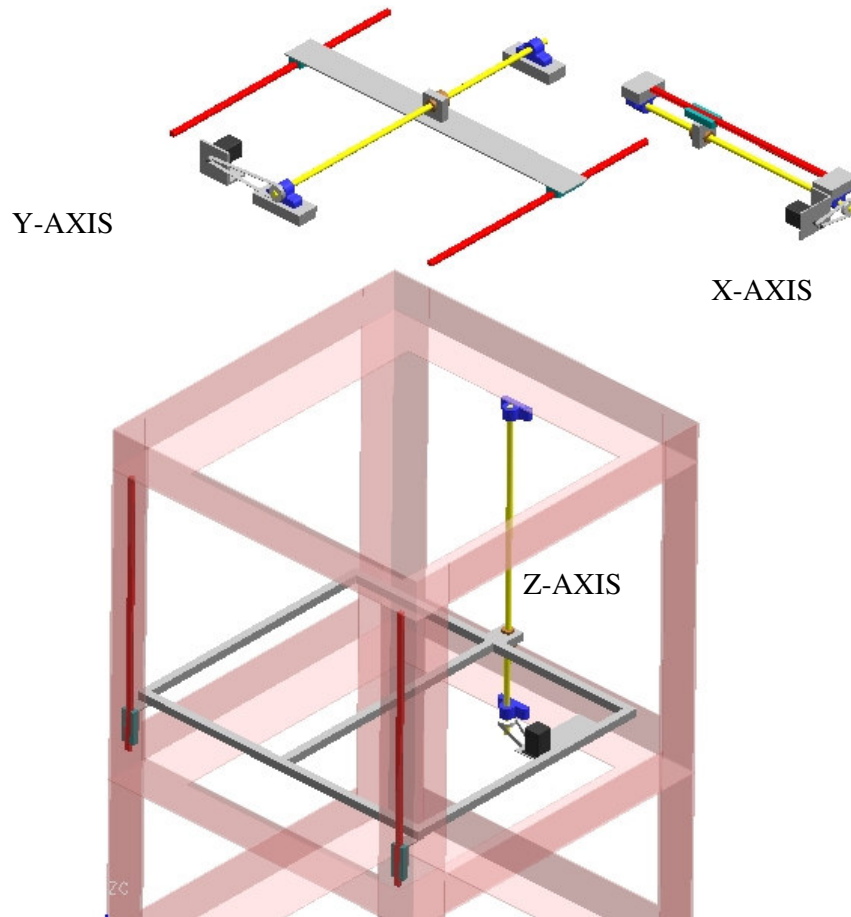


Figure 39 Simple explode view of the axis assemblies.

The specifications of the ballscrews, stepper motor driving parameters and the rim ratio directly affects the precision of the motion. For the theoretical precision calculation we have list these parameters and calculate the accuracy of the machine.

Also after installation the speed of the machine is measured with a chronometer and it is 50cm/minute. The parameters and the calculations are shown below;

	Steps/Revolution	Ballscrew Lead (mm)	Ratio of Rim	Accuracy (mm)	Accuracy (Micron)
Full-Step	200	5	3,66	0,00683	6,83
Half-Step	400	5	3,66	0,00341	3,41
1/4 Step	800	5	3,66	0,00170	1,70
1/8 Step	1600	5	3,66	0,0000853	0,853

Table 4 . Accuracy calculations.

As the system doesn't carry a heavy head unit and will not be subjected to any external loadings, selected step motors torque satisfies the requirements. But it is obvious that if a higher speed needed the step motors has to be upgraded as well as drivers.

4 RESULTS

In this project, future's production technique namely Rapid Prototyping has been surveyed. The RP technology and techniques, numerical control principals, stepper motors, ballscrews and linear guideways are clearly explained.

The preliminary design of the mechanical components made by CAD software and during the project period the manufacturing done following the preliminary design. The chassis is manufactured in order to ensure the required support to the mechanical components. Welding and fastening techniques are used to assemble the 5 mm thick sheet steel to each other. Outer dimensions of the machine are 1400x1400x2000mm. And the working area is 800x800x600 mm. The inner surfaces are isolated for effective temperature control. 3x 400 watt resistances mounted to body and temperature control system is designed. Proper linear guideways and ballscrews are selected and they are assembled to the chassis in order to provide precise and smooth motion. The drivers are manufactured by a colleague depending on an open source driver circuit. PIC program is uploaded to the driver and other required electric-electronics parts are manufactured. After placing them in to a computer box, the connection of the step motors to the drivers made. The step motors are assembled to the chassis and the necessary connections to the ballscrews with rims are made.

Connection with the computer is made by the parallel port and the interface card. And after this connection established test runs of the system is done. Some pictures may be seen below, showing the mechanical assembly of the axis and step motors, and the two dimensional test runs.

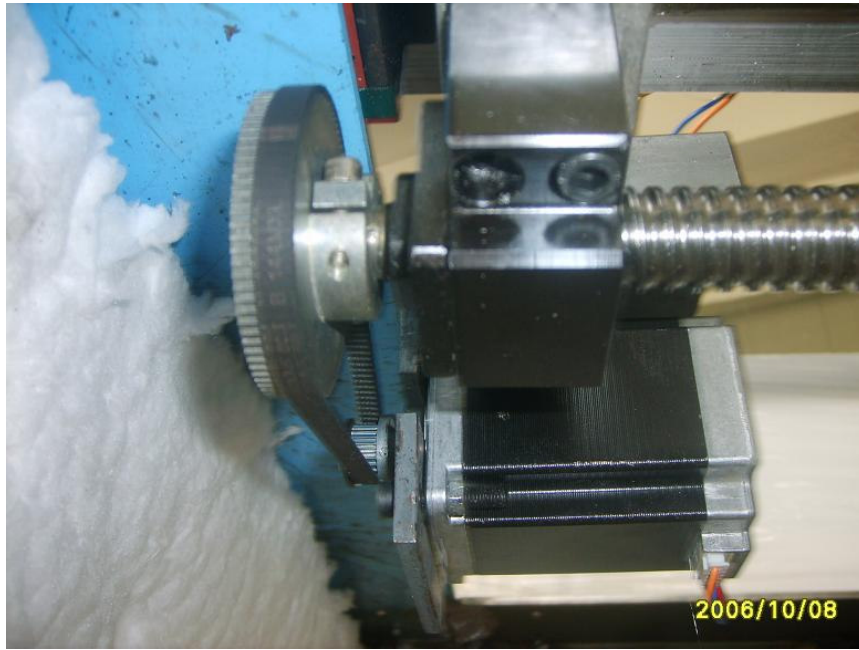


Figure 40 Picture of the X axis step motor and rim.



Figure 41 Picture of the Y axis step motor and rim.

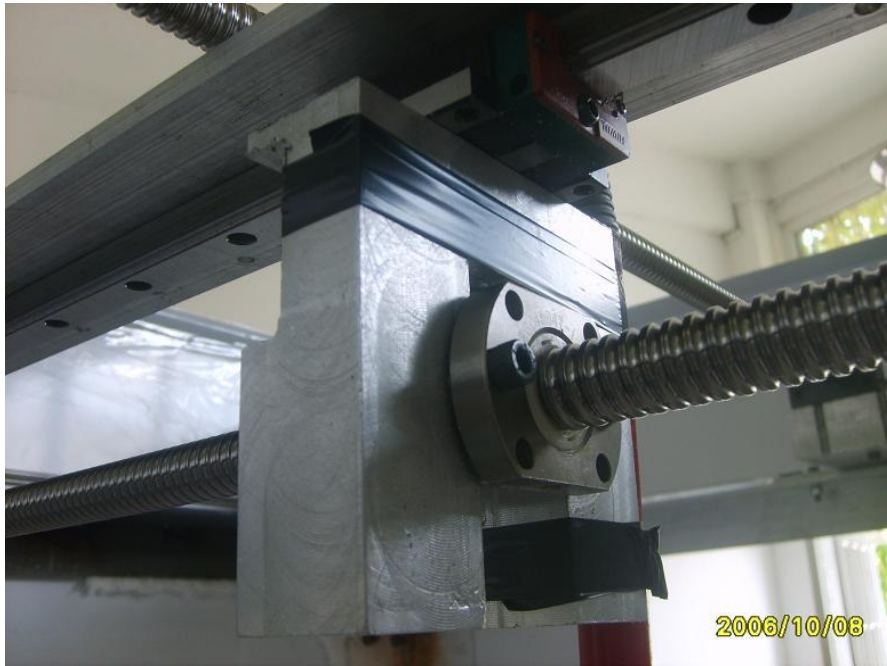


Figure 42 Picture of the X axis ballscrew assembly.

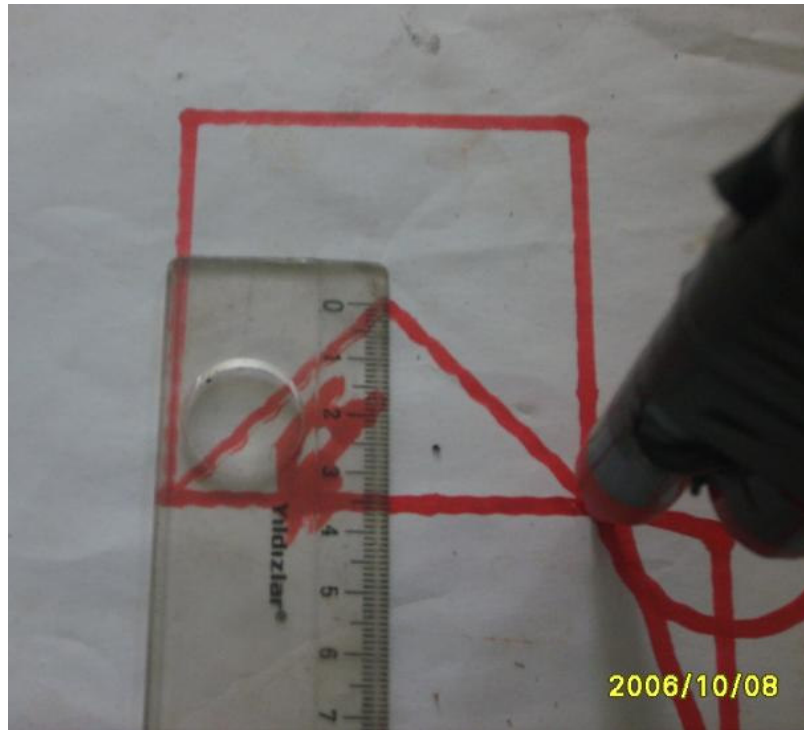


Figure 43 Picture of the test run result, a triangle and a square was drawn by the help of a boardmarker.

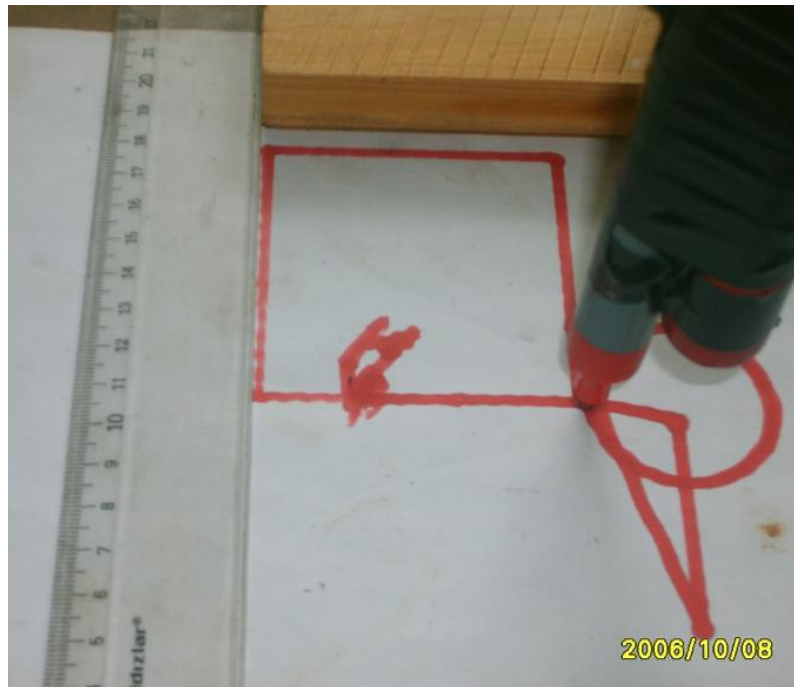


Figure 44 Picture of the test run result, a triangle and a square was drawn by the help of a boardmarker.

5 CONCLUSIONS AND RECOMMENDATIONS

The RP technology and techniques, numerical control principals, stepper motors, ballscrews and linear guideways are clearly explained.

Required chassis is manufactured and isolated for temperature control. Resistances mounted to body and temperature control system is designed. Mechanical assembly for linear guideways and ballscrews are manufactured and assembled to the chassis. Also electric and electronic parts, produced and assembled to the system with the stepper motors and drivers.

As a conclusion, the manufactured mechanical system is not achieved all the goals that targeted at the beginning of the project. Head unit couldn't be implemented and synchronization of the head unit and the 3 axis motion couldn't be completed. But this project achieved most of its target. 3 axis CNC system has been produced and working without a problem. Remaining work is to supply or either manufacture the head unit and provide a synchronized operation with the CNC system.

This project is now a TUBİTAK project, which means the financial problems that occur during the manufacturing and component supplying will be solved with help of the TUBİTAK support. With this financial support, some of the components can be changed and with the new equipments the system won't will operate with a professional efficiency. Recommendations about the improvements will be:

- to buy 3x Professional Driver Units,
- to buy a Professional Controller,
- 3xPower supplies for each of the Step Motors,
- minimum 2 Nm Stepper Motors,
- a better construction of the chassis,
- manufacturing or supplying the head unit

With these new equipments, the project can easily be finalized with satisfying all of its targets very shortly.

REFERENCES

- [1] K. Thrimurthulu , Pulak M. Pandey , N. Venkata Reddy, Optimum part deposition orientation in fused deposition modeling, *International Journal of Machine Tools & Manufacture* 44(2004) 585–594
- [2] P.F. Jacobs, *Stereolithography and other RP&M Technologies: from Rapid Prototyping to Rapid Tooling*, SME, Dearbon, MI, 1995. ISBN 0-87263-467-1.
- [3] B.H. Lee, J. Abdullah, Z.A. Khan, Optimization of rapid prototyping parameters for production of flexible ABS object, *Journal of Materials Processing Technology* 169 (2005) 54–61
- [4] J.M. Rieber, D.G. Taylor, Integrated control system and mechanical design of a compliant two-axes mechanism, *Mechatronics* 14 (2004) 1069–1087
- [5] D.T. Pham, R.S. Gault, A comparison of rapid prototyping technologies, Pergamon, *international Journal of Machine Tools & Manufacture* 38 (1998) 1257-1287,
- [6] S. Au, P.K. Wright, A comparative study of rapid prototyping technology, *Proceedings ASME Winter Conference*, New Orleans, November 1993, vol. 66, pp. 73-82.
- [7] Stratasys Inc., Fused deposition modelling for fast, safe plastic models, 12th Annual Conference on Computer Graphics, Chicago, April 1991, pp. 326-332.
- [8] Stratasys Inc., FDM-1650, Stratasys Inc., 14950 Martin Drive, Eden Prairie, Minneapolis 55344-2020, U.S.A., 1996.
- [9] B. Bidanda, V. Narayanan, R. Billo, Reverse engineering and rapid prototyping, in: R.C. Dorf, A. Kusiak (Eds.), *Handbook of Design, Manufacture and Automation*, Wiley, NY, 1991, pp. 977-991.
- [10] P.F. Jacobs, *Stereolithography and Other RP and M Techniques*, ASME Press, New York, 1996.
- [11] Stratasys Inc., FDM-1650, Stratasys Inc., 14950 Martin Drive, Eden Prairie, Minneapolis 55344-2020, U.S.A., 1996.
- [12] ST Application Note – Stepper Motor Driving
<http://www.st.com>
- [13] Geckodrive Inc. – Stepper Motor White Papers
<http://www.geckodrive.com>
- [14] New Japan Radio Co. (JRC) – Stepper Motor Basics

<http://www.njr.co.jp>

[15] Anaheim Automation – Introduction to Stepper Motor Systems

<http://www.anaheimautomation.com>

[16] Douglas W. Jones – Control of Stepping Motors

<http://www.cs.uiowa.edu/~jones/step>

[17] Efunda Engineering Fundamentals - Rapid Prototyping Techniques

<http://www.efunda.com/>

[18] Manufacturing Engineering Centre – Rapid Prototyping Techniques

<http://www.mec.cf.ac.uk/>

[19] The Learning Factory - Rapid Prototyping Primer

<http://www.mne.psu.edu/lamancusa/rapidpro/primer/chapter2.htm>

[20] Harvest Technologies – Rapid Prototyping

<http://rapid-prototyping.harvest-tech.com>

[21] Castle Island's Worldwide Guide to Rapid Prototyping - Rapid Prototyping

<http://home.att.net/~castleisland/>

[22] Ö.Bentürk, “Preliminary Design And Control Of A Rapid Prototyping Machine”, Engineering Project, İstanbul, 2005.

CURRICULUM VITAE

Name, Surname	Aykut AKALIN
Address	Tunalı Mah. Varlık Sok. No:1/12 26220 Eskişehir
Phone	0 222 322 09 71
E-mail	aykutakalin@gmail.com
Date of Birth	29.10.1981

Education

2003 -	M.S. Mechanical Engineering - Marmara University, Institute for Graduate Studies in Pure and Applied Sciences, Istanbul, Turkey
1999 - 2003	B.S. Mechanical Engineering - Marmara University, Engineering Faculty, Department of Mechanical Engineering, Istanbul, Turkey
1992 - 1999	Eskişehir Kılıçoğlu Anadolu Lisesi, Eskişehir, Turkey

Professional Experience

2001-2003 Company Manager, AKALIN Isı Cihazları Ltd. Şti.

2000-2001 Assistant Engineer, Colgate-Palmolive

Computer Skills

Power user of the following softwares; IDEAS, Mechanical Desktop, AutoCAD, MS Office Applications