DESIGN AND IMPLEMENTATION OF A TWO-AXES LINEAR POSITIONING SYSTEM FOR RAPID PROTOTYPING APPLICATIONS

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DESIGN AND IMPLEMENTATION OF A TWO-AXES LINEAR POSITIONING SYSTEM FOR RAPID PROTOTYPING APPLICATIONS

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ABSTRACT

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LINEAR POSITIONING SYSTEM FOR RAPID PROTOTYPING
APPLICATIONS

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In this study, a two axes linear positioning system for testing and applying different rapid prototyping techniques was designed and manufactured. A cable/ pulley mechanism is utilized in the system for transmitting motion from motors into linear motion. Use of a cable/ pulley mechanism overcomes the problems resulting from the utilization of conventional drive systems like ball screws and decreases the overall cost of the system.

The carriage elements of both axes were designed and manufactured by using investment casting. The molds used in casting were also designed and manufactured within this study. The designed system is controlled by a servo motion control system composed of a motion controller, DC servo motors and linear encoders. All elements of the motion control system were selected, integrated and programmed within the scope of the study.

Keywords: Linear Positioning, Servo Motion Control, Rapid Prototyping, Cable/ Pulley Mechanisms

ÖZ

HIZLI PROTOTİPLEME UYGULAMALARI İÇİN İKİ EKSENLİ BİR DOĞRUSAL KONUMLANDIRMA SİSTEMİNİN TASARIMI VE UYGULAMASI

YAZICIOĞLU, Faruk

Yüksek Lisans, Makina Mühendisliği Bölümü
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Bu çalışmada, farklı tipte “hızlı prototipleme” tekniklerinin denenmesi amacıyla iki eksenli bir doğrusal konumlandırma sisteminin tasarımı ve üretimi gerçekleştirilmiştir. Sistemde, motorlardan alınan hareketin doğrusal harekete çevrilmesi amacıyla bir kablo/ makara mekanizması kullanılmaktadır. Bir kablo/ makara mekanizmasının kullanılmasıyla, bilyeli vidalar gibi konvansiyonel sistemlerin yol açtığı bazı sorunların önüne geçilmiş ve sistemin toplam maliyeti düşürülmüştür.

Her iki eksenin arabaları tasarlanmış ve hassas döküm yöntemiyle imal edilmiştir. Hassas döküm işlemi için gerekli olan kalıplar da yine bu çalışma dahilinde tasarlanmış ve üretilmiştir. Tasarlanan sistem, bir hareket denetleyicisi, DC servo motorlar ve doğrusal sayıcılardan oluşan bir hareket denetleme sistemiyle kontrol edilmektedir. Bu çalışma bünyesinde, hareket denetleme sisteminin bütün parçaları seçilmiş, birleştirilmiş ve programlanmıştır.

Anahtar Kelimeler: Doğrusal Konumlandırma, Servo Hareket Kontrolü, Hızlı Prototipleme, Kablo/ Makara Mekanizmaları

To my family...

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INTRODUCTION

1.1 Introduction

In recent years, the competition in all fields of industry has intensified tremendously. This intense competition requires the time needed for a product to reach a customer to be decreased as much as possible. Today, in the harsh competition environment a product gets old just a few months after it first appears on the market. This fast depreciation of products' shelf life brings out the requirement of creating new designs as quickly as possible. This requirement creates a big pressure in product development departments of manufacturing companies since prototyped of new models must be created as quickly as possible.

These requirements and the developments in Computer Aided Design (CAD) systems has resulted in a new area called Rapid Prototyping (RP), which can be defined as the automated production of physical models directly from CAD models. This technology that has emerged in late 1980's grew rapidly over the past 20 years. Today there is a significant amount of research activity on this field throughout the world.

1.2 Objective of the Study

This study is a part of a TÜBİTAK supported research project (project number: 105M135) conducted in Mechanical Engineering Department at METU. The aim of the project is to design and manufacture a rapid prototyping machine.

The project consists of three different parts; design of a rapid prototyping software, design of a rapid prototyping machine and design of a material deposition system for the machine. The rapid prototyping machine basically consists of a two-axis linear positioning system for positioning the material deposition head on the plane of manufacture and a platform moving along vertical axis on which the model is constructed.

Aim of this study is to design and construct a two axes linear positioning system for the rapid prototyping machine under development. The linear positioning system should satisfy the requirements determined for the machine.

It is desired to obtain a system whose accuracy is sufficient to be used for rapid prototyping applications. The system is desired to be low-cost, low-weight and it should be able to work under difficult conditions such as high temperature or humidity.

1.3 Outline of the Thesis

In this study, current rapid prototyping systems are analyzed and a two-axis linear positioning system for a rapid prototyping machine is designed and produced. The following chapters are organized to introduce and investigate the design process.

In chapter 2, rapid prototyping systems are introduced. The basic principles of rapid prototyping are explained and different rapid prototyping techniques are discussed in a comparative manner. Finally the elements forming a rapid prototyping system are explained in detail.

In chapter 3, linear positioning systems are discussed. The main elements of a linear positioning system are introduced and widely used systems for these elements are presented.

Chapter 4 explains the design process of the linear positioning system. Firstly, the system requirements are determined, and then the design of the drive system and control system satisfying the determined requirements are presented.

Chapter 5 includes the implementation of the design and case studies. The manufacturing process of the mechanical elements of the system and the tuning process of the control system are explained. Finally sample outputs of the system are presented.

Chapter 6 concludes the thesis by giving a summary of the whole work and presents some recommendations for future work and further improvements.

CHAPTER 2

RAPID PROTOTYPING

2.1.Introduction

Rapid prototyping is the name given to a group of technologies that performs the automated production of physical models directly from CAD models. It is also known as solid freeform fabrication, three dimensional printing, desktop manufacturing or layer manufacturing.

Unlike other conventional manufacturing processes which are subtractive, i.e. performed by subtracting unnecessary parts from a block of raw material, rapid prototyping is an additive process in the manner that the parts are formed by adding new layers on each other. These layers are either formed during the production of the model or they can be prepared separately by using conventional production techniques.

In order to understand the rapid prototyping processes background information on prototyping is necessary.

2.2. What is Prototyping

A prototype is a vital part of the product development process. A prototype can be defined as “the first or original example of something that has been or will be copied or developed; it is a model or preliminary version [1].”

The practice of prototyping has been performed since mankind first started to create tools to make their lives easier. Every engineering design needs to be verified in many different aspects such as functionality, ease of use and appearance before it reaches the end user (Figure 2.1). At this point, prototypes play a very important role in reducing the overall cost and risk of the design. Usually one or more prototypes of a design are produced where each prototype is an improvement of the previous one. In this way the problems and deficiencies in the design are corrected and the final product which is ready for production is obtained.

Figure 2.1 A Handmade Prototype of a Sports Car

In the early years, prototype manufacturing was completely based on handwork where the prototypes of objects were created by skilled craftsmen. With the advance in computers and Computer Aided Design (CAD), especially starting from 1980's, prototyping started to move to the virtual environment. Nevertheless, the growing use of virtual prototyping did not cause the need for solid prototypes to diminish. A physical prototype still keeps its value as a look and feel object, since a virtual prototype cannot represent the feeling of a solid object.

2.3. A Brief History of Rapid Prototyping

Actually, the idea of layered manufacturing is not very new. Even the idea of RP, as we understand today goes back to only 1980's, the main idea of layered manufacturing goes way back to the 18th century [2].

According to Beaman [2], the early roots of the main idea behind rapid prototyping technology can be found in two technical areas, topography and photosculpture. The idea of layered manufacturing of topological maps was first introduced in 1892 by Blanther. He proposed a method of forming topological contour planes by cutting wax plates on contour lines and then stacking and smoothing the wax plates. Another similar idea was introduced in the field of photosculpture which arose in the 19th century in attempts to create exact three dimensional replicas of objects.

The evolution of prototyping can be inspected in three phases. The first phase of prototyping that can be referred as *Manual Prototyping* began several centuries ago. The prototypes created in this era are not very sophisticated and they are usually extremely labor intensive and time consuming [3].

The second phase of prototype production starts in the early 1980s with the widespread usage of computers in design and manufacturing. This phase can be called Soft or Virtual Prototyping. Virtual prototyping has given new perspectives to designers as new and more powerful computer tools became available day by day. Today, computer models can be "stressed, tested, analyzed and modified as if they were physical prototypes"[3]. Virtual prototyping, significantly reduces the time and money spent for prototype production by making the prototyping of very complex designs possible.

Although virtual prototyping has many advantages compared to physical prototypes on cost, complexity and time, the presence of a physical prototype is still required in many different applications. This requirement combined with the requirement of creating physical prototypes in a short time, led to the emerging of *Rapid Prototyping*, which is described as the third phase of prototyping. With this technology, physical prototypes of complex parts can be produced from a wide variation of materials in a relatively short time.

First commercial rapid prototyping systems started to appear in late 1980s and since then, more than twenty different rapid prototyping techniques have emerged [4]. Today, rapid prototyping is one of the most rapidly developing areas of manufacturing engineering. This industry has undergone an impressive growth over the past few decades. The graph in Figure 2.2 [5] shows the impressive growth in unit sales in recent years.

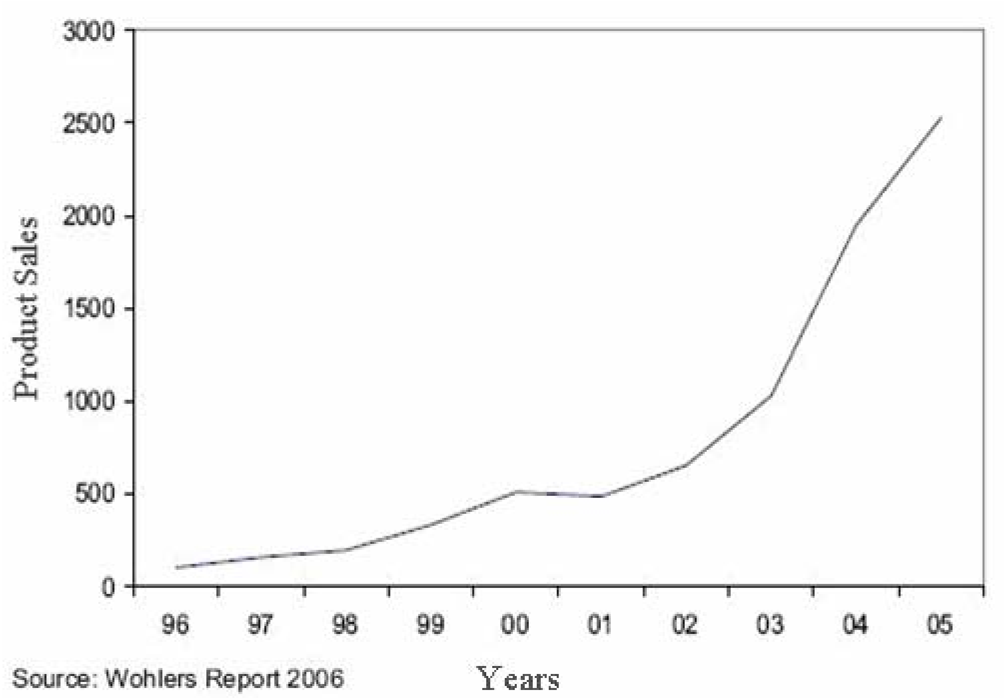

Figure 2.2 Growth of 3D Printer Market **[5]**

Most analyses indicate a strong growth for 3D printers over the next several years. If the worldwide economy remains relatively strong, an estimated 15,000 3D printers are expected to sell annually by 2010 [5].

2.4. Basic Principles of Rapid Prototyping

Although there are more than twenty different RP techniques, the basic idea behind all of these techniques is common. The main principle of rapid prototyping is the idea of layered manufacturing, where the model is produced layer by layer.

The first step in the RP process is preparing the 3D model of the part in a Computer Aided Design/ Computer Aided Manufacturing (CAD/CAM) system. Then, the CAD file is converted into a format called the STL (STereoLithography) file format. This file format was created by 3D Systems, the company that produced the first commercial RP system. The STL file approximates the surfaces of the model by triangles. A computer program analyses the STL file and slices the model into cross-sections. At the final stage, these cross-sections are created and stacked one on top of another by using different types of materials and production techniques [4].

2.5. Applications of Rapid Prototyping

Rapid prototyping, allowing the automated, toolless and patternless production of parts with complex geometry, is a very promising manufacturing technology. Although the parts produced by rapid prototyping cannot reach the accuracy and surface quality of machined parts, there are certain advantages that make rapid prototyping an indispensable production technique.

Today, due to the limited amount of materials, rapid prototyping is mostly used for concept modeling applications. This technology offers many advantages to product designers as it makes the production of a model, no matter how complex, a fairly easy task. With the improvements in recent years, especially with the use of new materials such as metals, the usage of rapid prototyping for direct manufacturing of end products and molds has begun.

Use of rapid prototyping offers many benefits to both designers and engineers. Over the last 25 years, the shape and form complexity of products introduced to the market have increased drastically [6]. With the introduction of rapid prototyping technology, product designers can increase the complexity of their designs with fewer restrictions for manufacturing. In the future, wider use of this technology will significantly reduce the constraints on new designs such as angles, parting lines or high production time and cost.

2.6. Classification of Rapid Prototyping Systems

Today, there are many different Rapid Prototyping techniques that are used around the world. While there are many different ways of classifying these techniques, a classification based on the production technique is found more appropriate. In this manner, all major RP systems can be categorized into four groups as: photopolymer techniques, material deposition techniques, powder binding techniques and object lamination techniques [7]. The details and major systems using these techniques can be described as follows:

2.6.1. Photopolymer Curing Techniques

A photopolymer is a kind of polymer, whose mechanical and chemical properties are changed as a result of a chemical reaction triggered by exposure to light energy. In photopolymer techniques, layers of photopolymers are cured in desired regions by using an appropriate light source.

2.6.1.1. Stereolithography (SLA)

Stereolithography (SLA) is the first commercial rapid prototyping technique, developed by American 3D Systems Company. In this technique, a special photopolymer resin in liquid form is stored in a container. A platform moving along vertical axis is initially placed at a position just below the surface of the liquid photopolymer. Then a laser beam traces the surface of the photopolymer according to the geometry of the cross-section of the object. The photopolymer in areas that are hit by the laser beam solidifies, forming the cross-section of the object. Then the platform is lowered into the container by a distance equal to the layer thickness and the same process is repeated until the whole part is complete (Figure 2.3). After completion of the process, the platform is elevated form the container and the model is drained. The support structures that are placed in required positions of the model are removed manually. In most cases the level of curing is not adequate and the part needs to be further cured by UV light in a special oven [8].

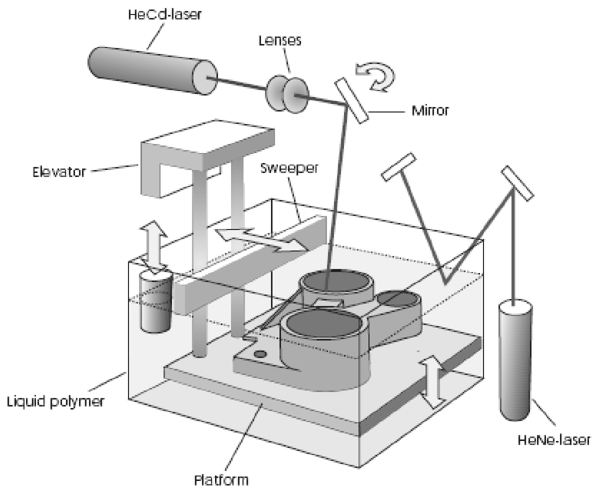

Figure 2.3 Stereolithography Process **[8]**

Stereolithography is considered to provide the best surface quality and accuracy among all rapid prototyping systems.

2.6.1.2. Solid Ground Curing (SGC)

Unlike Stereolithography and SLP, where the cross-section of a part is formed by tracing a laser over the surface, SGC technique utilizes a stationary UV lamp and a mask to cure the photopolymer in desired regions. The mask is generated by using electrophotography. This process consists of two cycles; mask generation and layer fabrication. The mask is generated on a glass plate by using a method similar to laser printing. Black photocopying toner transferred onto the electrostatically charged glass plate in the desired shape. Then this mask is positioned on top of the thin photopolymer layer spread onto the building platform. The photopolymer layer is exposed to a strong UV light passing through the mask. The mask provides the curing of photopolymer in the desired pattern. The UV light is strong enough to eliminate the need for further curing. After the layer is formed, the remaining uncured liquid photopolymer is vacuumed from the environment and the remaining cavities are filled with melted wax in order to provide support to the model. The wax is hardened by cooling the model. In the last step, the produced layer is machined by using a milling head in order to obtain a uniform thickness. Then the mask is cleared from toner and a new mask for a new layer is formed to repeat the process [9].

2.6.2. Material Deposition Techniques

In material deposition techniques, the layers are formed by spraying or plastering a material in liquid or cemented form from a nozzle or a group of nozzles. The hardening of the material can be achieved by cooling or a chemical reaction. More than one nozzle can be used for deposition of materials or for deposition of support material. Different from other production techniques, material deposition techniques provide the ability to produce multi-material, complex parts by depositing different materials in different regions of a same layer.

2.6.2.1. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) is the second widely used rapid prototyping technique after Stereolithography [5]. In this technique, plastic material in filament form is extruded through a thin nozzle which is heated in order to melt the plastic. The molten plastic in cemented form is plastered onto the surface of a platform in order to form the layers. The plastic solidifies and hardens immediately after it is deployed from the nozzle. Entire workspace is sealed from the environment and heated up to a degree just below the melting point of the plastic. In this way, surface quality of the model is increased and a better control on the process is obtained.

There are several material options that can be used in this process including investment casting wax and polyamide. The introduction of ABS plastic as a production material has increased the popularity of this method considerably. There are also efforts for producing ceramic parts using this FDM. Ceramic powder mixed with the polymer used in extrusion gives the produced part ceramic properties. The polymer is burnt out in a post process operation.

For the production of overhanging geometries, fabrication of support structures is required. In early models, supports were produced from the production material and they were manually broken after the production. Recent models have a second deposition nozzle for depositing a different material for support fabrication. There are two different support materials available. The Break Away Support System (BASS) utilizes a support material that can be easily broken off from the produced part. Another support material called Water Works is quickly dissolved in water based solvent. In this way, support structures that cannot be reached manually can be easily removed [10].

2.6.2.2. Multi Jet Modelling (MJM)

Multi Jet Modelling can be described as the adaptation of "hot melt ink-jet printing" technology, which is used mostly in outdoor advertisement applications, to the field of rapid prototyping. In MJM, the molten material, fed to the print head by a pump, is sprayed from 352 nozzles. These nozzles are actuated by a piezo-electric actuation system. The material used in this process is a wax-like thermopolymer including paraffin.

In order to maintain a standard layer thickness and to obtain a smooth layer, an abrasive roller heated up to 130˚C and turning at 600 rpm is passed over each layer after deposition.

In MJM technique, thin and dense supporting sticks made from the same material with the model are used where a support is necessary. These support structures are broken manually by using a brush after the model is completed. In order to ease the support removal, the produced models are cooled down to about 10˚C.

2.6.2.3. Direct Metal Deposition (DMD)

Direct Metal Deposition is another technique utilizing a CO_2 laser in order to produce models from metallic materials. Unlike the PMD technique, where the production material is in wire form, this technique utilizes powdered metals. In this technique, the metal powder supplied to the focus of a laser beam through a deposition head. The metal powder particles molten by the laser are deposited onto the platform, forming the model layer by layer (Figure 2.4). An inert gas is used to shield the molten metal from atmospheric oxygen in order to prevent corrosion and control material properties [7].

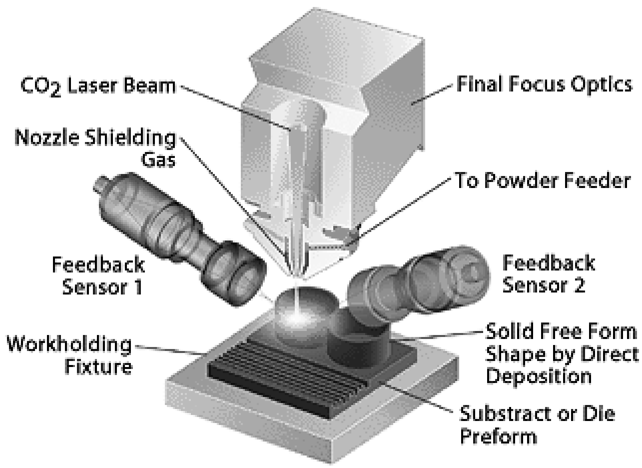

Figure 2.4 Direct Metal Deposition Process [7]

A wide variety of materials like steel, aluminum, copper or titanium can be used in this process. Also composite models can be produced with the use of different metal powders in different locations of a model.

The products that are produced using this technique are generally in final shape but they generally require surface finishing. This technique is widely used in direct manufacturing of complex parts as well as the repairing of damaged parts like turbine blades or injection molds.

There are a few different companies and research organizations working on similar techniques. Laser Engineered Net Shaping (LENS) is a very similar technique which utilizes titanium powder in manufacturing of complex parts used in aerospace industry [7].

2.6.2.4. Other Material Deposition Techniques

In addition to the major techniques discussed, there are many different techniques that can be classified under this title. These techniques have some differences in materials or deposition techniques, but the main behind all of these techniques is the deposition of building material, usually in molten form, from a deposition head. Some major material deposition techniques are: Liquid Metal Jet Printing (LMJP), Ballistic Particle Manufacturing (BPM), Pligraphy, Electrochemical FABrication (EFAB), Micro-Droplet Fabrication (MDF) and Bioplotter [7].

2.6.3. Powder Binding Techniques

In powder binding techniques, the building material in powder form is spread as a thin layer. The powder grains are bound together by applying heat or chemical adhesives according to the cross-section of the model. Unbound powder grains support the overhanging parts, eliminating the requirement of support structure fabrication. Plastic, metal, ceramic or mixtures of these materials can be used as the building material in these techniques.

2.6.3.1. Selective Laser Sintering (SLS)

In SLS technique, a layer of thermoplastic material is spread over the building platform. A laser beam traces the surface of the powder material according to the geometry of the cross-section. The powder grains in touch with the laser beam are molten and bound together by the heat, forming a solid cross-section. Then, the building platform is lowered by one layer thickness and a new layer of powder is spread over the previous one by a roller. The same process is repeated until the fabrication of the model is complete.

The powder for each new layer is supplied by a system that is working in a similar way with the building platform. The powder that is spread onto the building platform by a roller is supplied by elevation of a piston. Excess powder, which is not bound by laser beam; act as a supporting structure for the overhanging parts. This excess powder is brushed off or vacuumed after the building process is complete.

The workspace is kept at a temperature just below the melting point of the building material. This provides the powder grains to be bound faster and easier.

A wide variety of materials like plastics, ceramics or metals can be used in SLS applications. Composite products can also be fabricated by mixing different materials. This technique can be used in fabrication of both functional prototypes and final production parts. Generally no final curing is required for the produced parts but the strength of the products may not be adequate for some applications due to their porous nature. Mechanical properties of the products can be increased by infiltrating another material or by heat treatment. Also the porous structure of the products makes this technique ideal for applications like filter production [11].

2.6.3.2. 3 Dimensional Printing (3DP)

3 Dimensional Printing technique, which was originally developed at MIT, is very similar to SLS. The main difference of 3DP is the method used to bind powder grains. Unlike SLS, the powder particles are bound by a liquid adhesive sprayed from an inkjet print head. The adhesive compound is sprayed from the multi-jet print head. The powder grains in required regions are bound together forming a layer of the object. After one layer is fabricated, the platform is lowered by one layer thickness, a new layer of powder is spread and the process is repeated. Just like SLS, no additional support generation is required, since the excess powder supports the model.

There are many material alternatives for 3DP. This technology is licensed to five different companies. Each one of these companies has the license for the use of a single material only. Only the license for ceramic powder is given to more than one company. One of these companies, ZCorp, uses starch, plaster and composite plaster based powders. Also their machines can fabricate casting molds by using plaster-ceramic based powder. Metals with low melting temperatures like aluminum, zinc or titanium can be casted directly with these molds.

The systems using ceramic material are mostly used for production of investment casting molds. Another use of such systems is in filter production. Filters produced with these systems can have ten times more performance compared to the ones produced with conventional methods.

Three Dimensional Printers are mostly used for concept modeling applications due to their significant advantages such as fast production and low model cost. Another unique property of this technique is the ability to produce multi color models by using standard ink-jet printing cartridges [7].

2.6.3.3. Other Powder Binding Techniques

Many different powder binding techniques are currently under development. Most of them are variations of SLS technique. Some different techniques utilize masking and UV curing for binding powder particles. Some of the most significant ones can be listed as: EOSINT, Selective Laser Melting (SLM), Electron Beam Melting (EBM), Selective Mask Sintering (SMS), LaserCUSING Combined Processing and Laserforming.

2.6.4. Object Lamination techniques

In this group of technologies, the models are fabricated from solid state laminated materials which are in the form of thin sheets. The boundary of the cross-section is cut from the sheets and the layers are bonded on top of each other. The laminated materials used in kind of systems can be paper, plastics, foam (polystyrene) or metals. This group of technologies has some limitations in production of internal cavities.

2.6.4.1. Laminated Object Manufacturing (LOM)

In this technique, the cross-sections of the object are cut from paper by using a CO_2 laser. In this process, a special paper covered with a polymer based adhesive on one side is used. The paper is unwound from a roll and laid onto the building platform. A heated roller passes over the paper in order to bind the paper to the previous layer by melting the adhesive on the lower surface of the paper. Then, the profile of the cross-section is traced by a laser. After the profile is formed, the unused regions of the paper which are to be removed after the production are cross-hatched in order to make the removal process easier. This technique can be considered as a selfsupporting technique, since these excess regions provide support for overhanging regions. Prior to the completion of one layer, the building platform is lowered by one layer thickness and a new layer of paper is laid by the rotation of the paper roll. The process is repeated until the fabrication of the whole model is completed. Since the process generates a considerable amount of smoke, the building chamber must be sealed and a proper ventilation system using either a chimney or a charcoal filter should be used.

The models fabricated by this technique have a moderate finish and accuracy level. They resemble the look and feel of wooden models and they can be processed in the same manner. Also, the process requires manual removal of excess paper blocks, which can be very time consuming for complex parts [4].

2.6.4.2. Solidimension 3D Printing

The lamination material used in this technique is PVC used in advertisement industry. The material supplied from a roll is bound to the previous layer by using a special glue and then, the boundary of the cross-section is cut with a knife. The excess areas that are to be removed upon completion of the model are prevented to be bound by using a special anti-glue. The models produced by this technique are stronger than those fabricated from paper [7].

2.6.4.3. Other Object Lamination Techniques

Other than the techniques mentioned above, there are some other variations of object lamination techniques. One of the major differences among these techniques is the difference in sequence of layer cutting and bonding processes. In some techniques layers are bonded before the cutting process, whereas in some other techniques layer are bonded after the cutting process. Some of these techniques can be listed as: Kira Shape Adhesive and Hot Press (SAHP), Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM), Offset Fabbing, Trusurf, Stratoconception and CustomLAM [7].

2.7. Rapid Prototyping System Elements

Rapid prototyping is truly an interdisciplinary engineering field. In order to develop a RP system a number of different technologies like 3D CAD modeling, special materials, laser systems and control systems should be used together. In this manner, "RP systems are truly mechatronic in nature" [12]. A typical rapid prototyping system basically consists of two main elements: a rapid prototyping software and a rapid prototyping machine.

2.7.1. Rapid Prototyping Software

The rapid prototyping software imports the CAD data file generated by CAD software, identifies and fixes the problems that can be generated from the nature of the original file format, and converts the data into the STL file format. Then the generated STL file is sliced into cross-section layers and the CAM data required for the fabrication of the cross-sections is generated.

Most major RP vendors develop their own RP software to be distributed with their machines. These software packages are specific to the machines that they are provided with and therefore they are not sold separately. There are also a number of different rapid prototyping software packages developed by independent companies. These software packages have a modular structure allowing the modules required for performing certain specific tasks to be sold separately.

2.7.2. Rapid Prototyping Machines

Rapid prototyping machine is the second element of a rapid prototyping system. The components forming a typical RP machine may be classified into two sub-systems as a fabrication system and a positioning system. While the design of the fabrication system varies according to the different techniques, the design of the positioning system is similar for all RP machines. The positioning system is composed of a two-axes linear positioning system and an elevator mechanism that provides the passage between different layers.

In almost all RP machines, the positioning system is placed in an overhanging configuration. The production head is placed on one of the axes and it is positioned on the workspace in order to trace the required cross-section.

The design of the elevator mechanism, consisting of a platform that moves along vertical axis in fixed increments is fairly simple. Therefore the most important common part of all RP machines is a two-axes linear positioning system which is the subject of this thesis work. Developing such a system gives the ability to carry out production tests using different production techniques which is a key requirement in the development of a rapid prototyping system.

CHAPTER 3

LINEAR POSITIONING SYSTEMS

3.1. Overview of Linear Positioning Systems

A linear positioning system can be defined as a system that converts the rotary motion from a motor into a controlled linear motion. Linear positioning systems have been widely used in many industries for accurate positioning tasks. Due to their wide usage, a lot of different variations of these systems have been developed in time. Linear positioning systems are the backbones of many machine tools from conventional milling machines to fully-automatic CNC machining stations.

During their long years of usage, linear positioning systems have undergone many improvements. Most of these improvements have appeared in control systems due to the rapid developments in electronics. Although the electronic parts changed significantly over the past few decades, the mechanical components of a linear positioning system are mostly the same.

A linear positioning system can be divided into three components as linear motion system, motors and motion control system.

3.1.1. Linear Motion Systems

Any moving object has six degrees of freedom, namely translation along three vertical axes (X, Y, Z) and rotation around any of these. The duty of a linear motion system is to limit these six degrees of freedom to a single one; translation along a single axis [13].

A linear motion system is composed of one or more slides and a drive system that transmits the motion of the motor to the carriage moving on these slides. The slides may have different shapes as rails or shafts according to the application. The linear movement is obtained through the movement of a carriage on these slides. The carriage moves on spherical or cylindrical bearings or low-friction materials like Teflon.

Different transmission systems are used for moving the carriages on the slides. Some of the most commonly used systems are; ball screws, timing belts or cable/pulley systems.

3.1.1.1. Lead Screws / Ball Screws

Lead screws are the most popular transmission systems used for linear positioning systems. These systems have been widely used in the industry due to their low cost and ease of availability. In this kind of systems, linear motion is obtained by the movement of a nut, whose rotation is obstructed, along a screw that is rotated by a motor (Figure3.1).

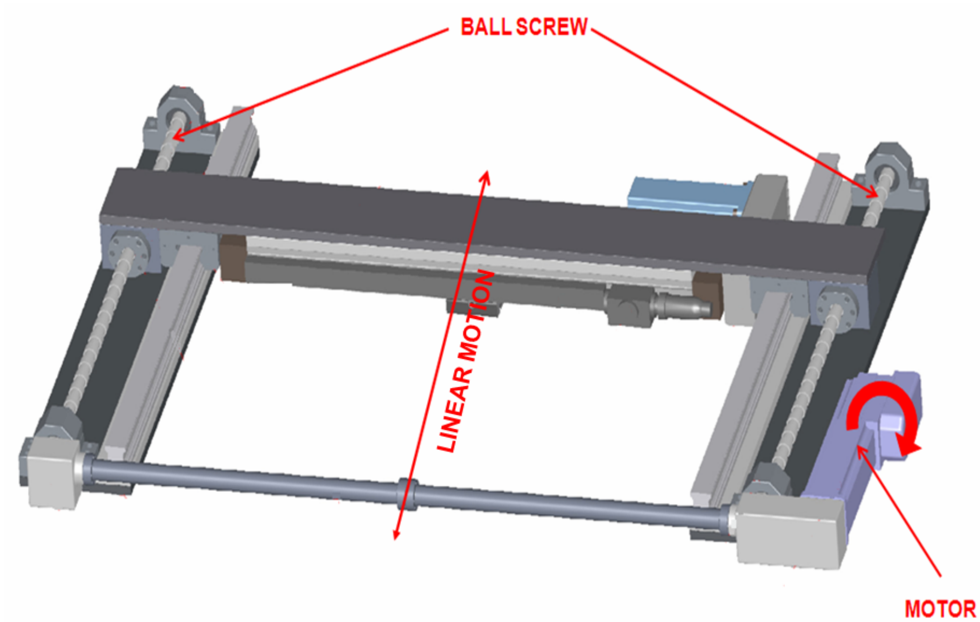

Figure 3.1 A Lead Screw Driven Linear Positioning System

Ball screws are preferred for higher loads and when high speed or accuracy is required. These kinds of screws have a higher accuracy compared to the lead screws owing to the reduced friction. But due to their more complex structure, they are much more expensive than classical lead screws. In recent years, with the rapidly decreasing production costs and increasing need for accuracy, conventional lead screws have started to leave their places to ball screws.

3.1.1.2. Timing Belts

Timing belts are also another widely used alternative for linear positioning systems. They can be used for either low and high loads plus they are considerably economical. In general, timing belts are reinforced toothed rubber belts. In positioning systems with timing belts, the carriage is fastened to the timing belt in one or more points. Linear motion is created by stimulation of one of the pinions on which the timing belt is placed (Figure 3.2).

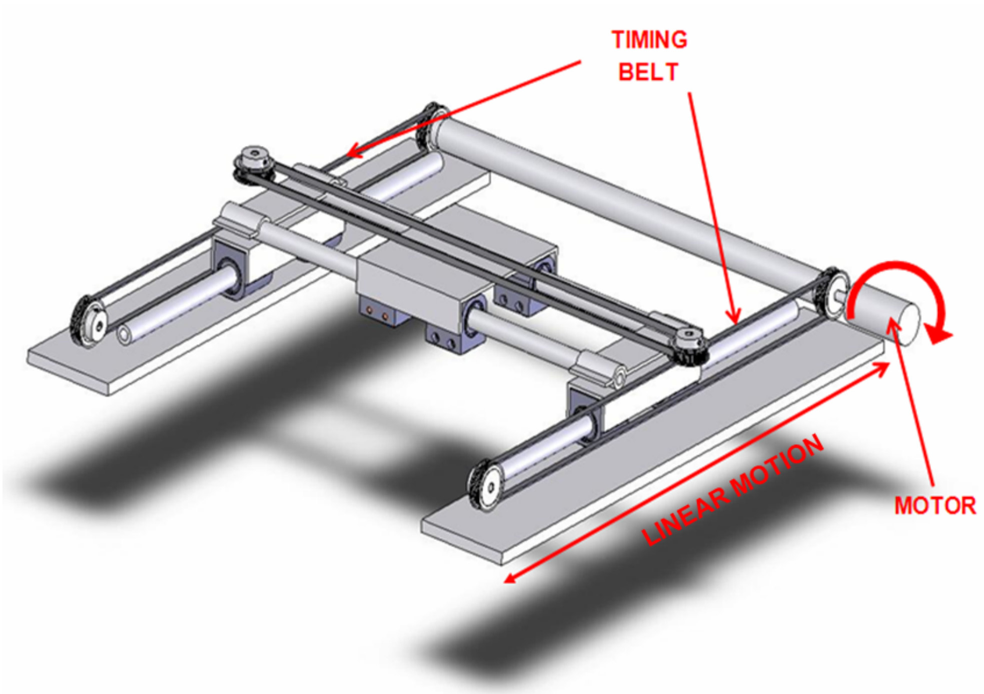

Figure 3.2 A Timing Belt Driven Linear Positioning System

Timing belts have some advantages and disadvantages compared to screw driven systems. First of all, since the belts are manufactured from flexible materials, they tend to elongate under load. This elongation causes belt to loosen from the teeth of the pulley, creating problems in positioning. Although, this elongation problem has been overcome with the use of strong support materials like Kevlar in recent years, the timing belt systems cannot be as stiff as screw-driven systems. On the other hand, depending on the application, timing belt driven systems have a considerable price advantage compared to screw driven linear positioning systems. In a benchmark study carried out for a machine, it is observed that using timing belts reduces the price of the system to almost half of the screw-driven system [14].

3.1.1.3. Cable/ Pulley Systems

Cable/ pulley systems have been used for transmitting motion and power for a very long time. These systems work under the same basic principles since the simple machines of the ancient times. Due to their limited applications and simple principles, these systems have simple configurations (Figure 3.3).

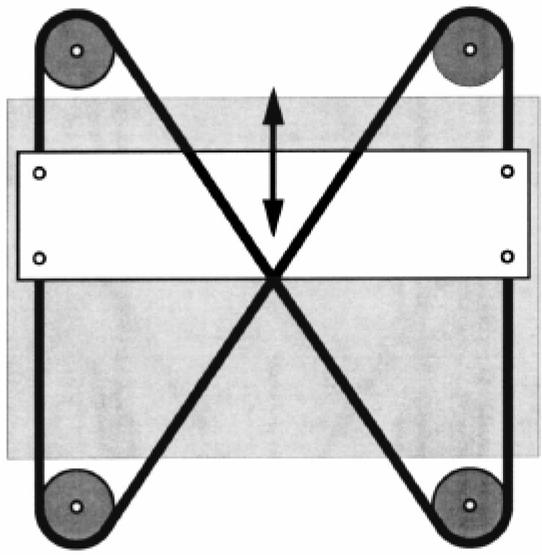

Figure 3.3 A Cable/Pulley Driven Linear Positioning System [15]

The use of cable/ pulley systems for mechanisms offer many advantages such as structural simplicity, compactness, light weight, high stiffness, low friction, low backlash and the ability to absorb shock. Due to these advantages, popularity of cable/ pulley systems has increased drastically in recent years. These systems are widely used for robotic applications such as tendon driven-dexterous robotic hands and haptic interfaces [15].

Utilization of cable/ pulley systems for linear positioning has some advantages compared to other drive systems. Since the force is transmitted by tension in cables rather than contact forces, cable/ pulley systems eliminate the backlash problem that appears in screws and belts. The slippage problem, usually observed in belt drives, is prevented by winding the cable around the pinion many times. Also the cable driven systems do not require lubrication like screw driven systems [16]. Since the drive system is composed of simple elements, the costs of cable/ pulley systems are fairly low too.

3.1.2. Motors

Motors are the elements that create motion in a mechanical system. Three types of motors are widely used for linear positioning systems. Conventionally stepper motors and servo motors have been the two alternatives. In recent years, linear motors have also started to gain usage as a third alternative.

3.1.2.1. Stepper Motors

Stepper motors complete one full turn in a number of steps. The number of steps is determined by the resolution of the motor. The motion is created by changing the polarity of the current that passes through windings. In each current change, the motor turns one step.

Stepper motors have a wide usage in linear positioning systems due to their certain advantages. First of all, stepper motors can be accurately controlled without utilizing feedback devices. Elimination of the need for a feedback system considerably decreases the system costs. In addition, unlike servo motors, stepper motors can be driven digitally. This allows them to be driven directly by using control signals sent from a microprocessor or a computer. Stepper motors are also more reliable and require less maintenance than servo motors.

Stepper motors have some disadvantages as well. They are not suitable for high speed applications requiring speeds more than 2000 rpm. Since they have a constant number of steps in each turn, their rotation is not smooth at low speeds either. They are also noisier and they generate more heat than servo motors.

3.1.2.2. Servo Motors

Servo motors have been used in many applications for a very long time. Contrary to stepper motors, servo motors create a continuous rotary motion. Because of this, they cannot be used without proper feedback systems in controlled applications like linear positioning. There are two different types of servo motors as brush- type servo motors and brushless servo motors.

Brush-type servo motors are the most widely used type of motors in industry. Since they have been produced for many years, their prices have been considerably lowered. Servo motors have a much smoother motion compared to stepper motors. They can be driven by using simple circuits and they can achieve higher speeds than stepper motors without any problem. Nevertheless, the price of a servo system is higher than a stepper system because of the need for proper feedback devices.

Brushless servo motors have been developed by the removal of the brushes which make mechanical contact with a set of electrical contacts on the rotor (called the commutator), forming an electrical circuit between the DC electrical source and the armature coil-windings. Due to this, brushless servo motors have a much less internal friction and they can achieve much higher speeds than brush-type motors. Since the sparks generated from the brushes are not present, they are also safer to use in hazardous environments. Although brushless motors are superior to brush-type motors in performance, they are still too expensive for general applications due to the special materials used in their production and the need for more complex driver circuits.

3.1.2.3. Linear Motors

Use of linear motors in positioning applications has been increased in recent years. They can be considered as an open version of a conventional rotary motor. Linear motors are much more suitable for linear positioning applications since, unlike conventional rotary motors, which require additional mechanical systems for converting the rotary motion into linear motion; linear motors directly create linear motion. This considerably reduces the complexity of the positioning system.

Although linear motors are the best alternative for driving linear positioning systems, their prices are still too high to be feasible for most applications. On the other hand, the usage of linear motors are increasing day by day and according to the projections on the future of linear positioning systems, it is predicted that the future of linear positioning systems will be built on linear motors [17].

3.1.3. Motion Control System

In addition to motors and mechanical devices, a linear positioning system also requires a motion control system. The term, motion control system, can define a wide variety of systems from a very simple on- off control system to a complex system that accurately controls the position, speed and acceleration of a moving system.

A motion control system used in a linear positioning application is composed of a motion controller that provides the coordinated motion of motors, motor drivers that convert the signals from the controller into a suitable form to drive the motors and feedback devices that assure the motion to be completed in the desired manner. The operation of a motion control system can be analyzed in three levels which are [18]:

1. Closed-loop control
2. Motion profiling
3. Motion programming

The first level, closed-loop control assures that the motor follows the commanded position. This is done by using proper feedback devices.

The motion profiling level comprises generation of the desired position function. This function describes the desired position of the motor at every sampling period. The profiling function determines where the motor should be and the closing of the loop forces the motor to follow the commanded position.

The highest level of control,the motion program describes the tasks in terms of the motors that need to be controlled, the distances and the speed. This can be stored in the host computer or in the controller.

The elements of a servo motion control system are the motion controller, motor, driver and encoder. A sample block diagram of a servo motion control system is shown in Figure 3.4.

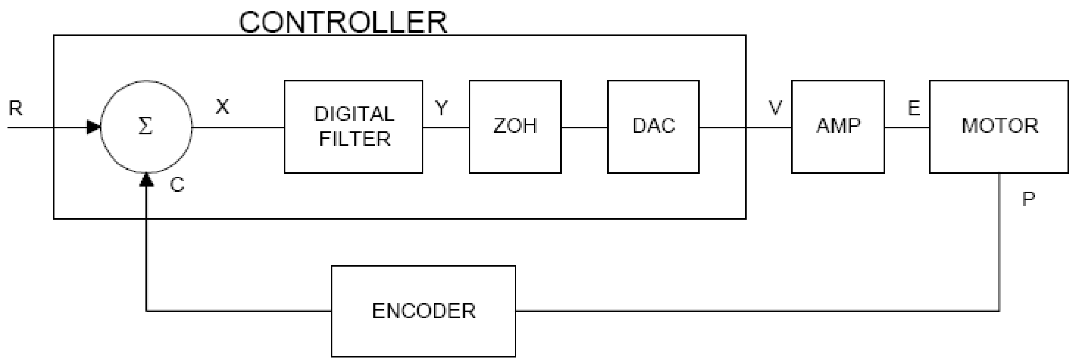

Figure 3.4 Functional Elements of a Motion Control System [18]

3.1.3.1. Motion Controllers

Motion controller is the most important element of a motion control system. In recent years, with the improvements in electronics, motion controllers have become powerful computers. Motion controllers can be PC- based, that is depending on a PC, or stand alone. PC based motion controllers are mostly in the form of a PCI card that operates as part of a PC. Stand-alone controllers are in fact special computers that are designed for motion controlling. This type of controllers can be connected to a PC for communication and programming via serial or Ethernet connection.

As it is shown in Figure 3.1 the motion controller is composed of several different components. The mathematical models of these components can be helpful in designing the control system. The models of the parts can be identified as follows [18]:

DAC: The DAC or D-to-A converter converts a 16-bit number to an analog voltage. The input range of the numbers is 65536 and the output voltage range is +/-10V or 20V. Therefore, the effective gain of the DAC is

$$K = 20/65536 = 0.0003 \text{ [V/count]} \quad (3.1)$$

Digital Filter: The digital filter has three element in series: PID, low-pass and a notch filter. The transfer function of the filter elements are:

PID $$D(z) = \frac{K(Z-A)}{Z} + \frac{CZ}{Z-1} \quad (3.2)$$

Low-pass $$L(z) = \frac{1-B}{Z-B} \quad (3.3)$$

Notch $$N(z) = \frac{(Z-z)(Z-\bar{z})}{(Z-p)(Z-\bar{p})} \quad (3.4)$$

The filter parameters, K, A, C and B are selected by the instructions KP, KD, KI and PL, respectively. The relationship between the filter coefficients and the instructions are:

$$K = (KP + KD) \cdot 4 \quad (3.5)$$

$$A = KD/(KP + KD) \quad (3.6)$$

$$C = KI/2 \quad (3.7)$$

$$B = PL \quad (3.8)$$

The PID and low-pass elements are equivalent to the continuous transfer function G(s).

$$G(s) = (P + sD + I/s) * a/(S + a) \quad (3.9)$$

$$P = 4KP \quad (3.10)$$

$$D = 4T \cdot KD \quad (3.11)$$

$$I = KI/2T \quad (3.12)$$

$$a = (1/T) \cdot \ln(1/B) \quad (3.13)$$

where T is the sampling period and s is the Laplace trnasform parameter.

The notch filter has two complex zeros, Z and z, and two complex poles, P and p. The effect of the notch filter is to cancel the resonance affect by placing the complex zeros on top of the resonance poles. The notch poles, P and p, are programmable and are selected to have sufficient damping.

ZOH: The ZOH, or zero-order-hold, represents the effect of the sampling process, where the motor command is updated once per sampling period. The effect of the ZOH can be modeled by the transfer function:

$$H(s) = 1/(1 + sT/2) \qquad (3.14)$$

If the sampling period is T = 0.001, for example, H(s) becomes:

$$H(s) = 2000/(s + 2000) \qquad (3.15)$$

However, in most applications, H(s) may be approximated as one.

3.1.3.2. Motor Drivers

Motor drivers, or amplifiers, are special circuits that convert the control signals generated by motion controller into proper signals required to drive the motors. Motion controllers generally operate and transmit signals at low voltages. Motor drivers amplify these low voltage signals to a level that the motor can operate.

Motor drivers have different properties according to the type of the motor used. The components and the complexity of the amplifiers change considerably from one motor type to another.

Brushless servo motors require a complex drive system. In brushless servo motors, the motor cannot commutate the windings, so the motor driver and the control software must control the current flow correctly for smooth operation of the motor. There are two different types of brushless servo motors; sensor and sensorless. Sensorless motors are used for on- off applications. They are cheaper but they require more complicated drivers [19].

Stepper motors are similar to brushless DC motors in the way that they operate, that is, the motor should be commutated through the entire drive cycle. There are two main types of stepper motors; unipolar and bipolar. These types differ in the way that the windings inside the motor are connected. A stepper motor is driven by energizing the coils inside the motor in a sequential manner. For example a common unipolar stepper motor has four drive connections and one or two extra wires that are connected either to the supply voltage or to the ground. When each drive connection is energized, one coil is driven and the motor rotates one step. The process is repeated in a sequential way until all drive connections are energized.

The amplifiers used for brush type servo motors are simpler than those for stepper and brushless servo motors. They can even be driven by simply connecting to a power supply, but special amplifiers are required for driving them in a controlled manner.

A motor amplifier can be configured in three different modes as voltage drive, current drive and velocity loop. The operation and modeling in the three modes can be desccribed as follows [18]:

Voltage Drive: In this mode, the amplifier acts a voltage source with a gain of Kv [V/V]. The motor position P, can be related to the input voltage V with the transfer function:

$$P / V = K_v / K_t \cdot s(sT_m + 1)(sT_e + 1) \qquad (3.16)$$

with s denoting the laplace transform where,

$$T_m = RJ / K_t^2 \qquad (3.17)$$

and

$$T_e = L / R \qquad (3.18)$$

and the motor parameters and units are

K_t = Torque constant [Nm/A]

R = Armature Resistance [Ω]

J = Combined inertia of motor and load [kg.m2]

L = Armature Inductance [H]

The block diagram of a voltage drive is given in Figure 3.5.

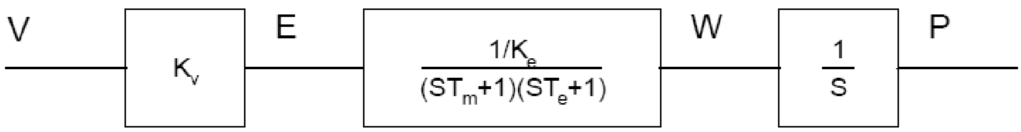

Figure 3.5 Mathematical Model of the Motor Amplifier in Voltage Mode

Current Drive: In current drive mode, the amplifier generates a current I, proportional to the input voltage, V, with a gain of K_a. In this case, the transfer function between the motor position and the input voltage is:

$$P / V = K_a K_t / Js^2 \qquad (3.19)$$

The block diagram of a current drive is given in Figure 3.6.

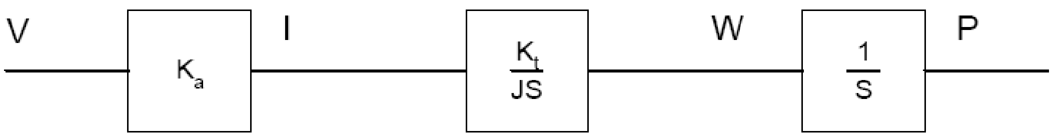

Figure 3.6 Mathematical Model of the Motor Amplifier in Current Mode

Velocity Loop: In some cases, the motor drive system may include an additional velocity loop. In such systems, the motor velocity is fed back to the amplifier by a tachometer. For this type of system, the transfer function between the observed velocity ω and the input voltage V can be expressed as:

$$\omega / V = [K_a K_t / Js] / [1 + K_a K_t K_g / Js] = 1 / [K_g (sT_1 + 1)] \qquad (3.20)$$

In this equation the velocity time constant T_1 can be expressed as:

$$T_1 = J / K_a K_t K_g \qquad (3.21)$$

Therefore, the transfer function between P and V becomes:

$$P/V = 1/\lfloor K_g s(sT_1 + 1)\rfloor \tag{3.22}$$

The block diagram of a velocity loop is given in Figure 3.7.

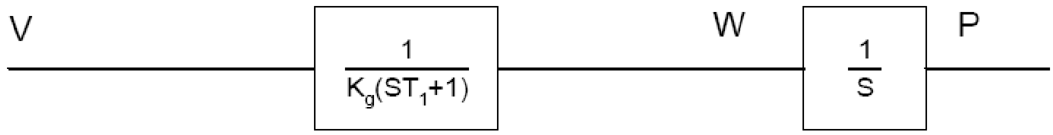

Figure 3.7 Mathematical Model of the Motor Amplifier in Current Mode

3.1.3.3. Feedback Devices

The last piece of a motion control system is the feedback system. Feedback system is required in order to analyze whether the motion was completed in the desired manner or not. The feedback device measures the position, speed or acceleration of the moving element and sends this data to the controller. The controller then analyses this information in order to decide whether a correction is required in the initial control data.

The most commonly used feedback devices are encoders. Encoders are simple position sensing devices. Any servo motor operated positioning system requires encoders in order to determine the final positions of the motors. In some cases, where the position of load does not resemble the position of the motor due to mechanical backlash, a second encoder on the load is necessary. The systems utilizing stepper motors do not require encoders since the position of the stepper motor can be determined by counting the number of steps.

There are also switches that identify the limits of the axes or a specific home position of a linear positioning system. Home switches are necessary for calibrating the system at start-up or after a certain time of operation.

CHAPTER 4

DESIGN OF THE LINEAR POSITIONING SYSTEM

4.1. System Requirements

The first step in design of the linear positioning system is the determination of system requirements. Since the positioning system is designed for a specific application, namely rapid prototyping, the requirements were determined accordingly.

The first parameter in the design is the determination of workspace dimensions. For this purpose, the technical specifications of desktop rapid prototyping systems were examined. In such systems, the workspace should be large enough for producing models for as many different industries as possible. On the other hand, the dimensions of the machine should be kept below a certain limit in order to place the machine in an office environment. As a result of this examination, the dimensions of the workspaces of most widely used commercial systems were detected as: Dimension 768: 203 x 203 mm, Dimension 1200: 254 x 254 mm and Z Printer 310 Plus: 203 x 254 mm. In accordance with these dimensions, the dimensions of the workspace were chosen as 250 x 250 mm.

In every positioning application, the accuracy of the system is very important. Every system is designed to be as accurate as possible but accuracy has a price. Therefore, it is required to find the optimal accuracy/price balance in a system. Since the linear positioning system is designed for a rapid prototyping machine, the accuracy requirement for these machines is the key factor in determining the required accuracy. In rapid prototyping applications, the quality of the produced model is mostly dependent on the thickness of the layers. This thickness is determined by the rapid prototyping technique used in the machine, mainly the characteristics of the material. Since the prototyping technique to be used with this system and therefore the material characteristics are not finalized at this stage, the system should be designed as accurate as possible.

Another criteria that is considered in the design is the required speed of the system. The speed values of rapid prototyping systems differ according to the production technique. Usually laser based systems operate at high speeds. But for some techniques such as FDM, a high speed system is not desired since it may decrease the surface quality of the produced parts. At this stage of the project, a rapid prototyping machine that utilizes a deposition or lamination technique is planned to be developed, therefore the required speed of the system is low.

Weight of the system is another constraint in the design of the linear positioning system. The linear positioning system is composed of moving and stationary parts. Weight of the moving parts should be kept as low as possible in order to decrease inertia. On the other hand, stationary parts should be heavy to increase the rigidity of the system. Since the system is planned to be used for testing different rapid prototyping techniques, it should be strong enough to carry different elements that could be required for different fabrication systems. Therefore the system should be designed to have the least weight without losing much strength.

Just like all designs, the cost of the linear positioning system should be kept as low as possible without constraining the requirements.

4.2. Design of the Linear Motion System

4.2.1. Layout of the Linear Motion System

The first step of the design is the determination of system layout. Since the system is designed for rapid prototyping applications, the layout is determined according to the requirements of a rapid prototyping machine. In rapid prototyping machines, like all machine tools, there is a tool or a fabrication head that is overhanging on top of a platform on which the model is placed. There are a few alternatives for the layout of the system. The motion of both axes can be placed on the platform, one of the axes can be placed overhanging or both axes can be placed to the top. As it was discussed in earlier chapters, in rapid prototyping machines motion of the third axis is provided by a moving platform. Since the platform is not fixed, placing the moving axes on the platform would increase the weight of the moving elements. Therefore, placing both axes to the top in an overhanging layout would be the best solution.

4.2.2. Design of the Motion Transmission System

After the layout of the system is determined, the next step in design is the selection of the transmission system. As a result of the literature survey on transmission methods used in linear positioning systems, three alternative systems were chosen for the final design; a ball screw drive, a timing belt drive and a cable/ pulley drive. Each of these systems has its own advantages and disadvantages described in the preceding chapter.

Also an analysis on the systems used in commercial RP systems was conducted. Since these machines are commercial products, the details of the motion transmission systems utilized in these machines are not provided in technical specifications. For this purpose, the machine that is available in METU, Stratasys Dimension FDM machine was examined. It was observed that the machine utilizes a simple cable/ pulley drive system for motion transmission.

At the end of the analysis, cable/ pulley system was chosen to be the best alternative among all. Although cable/ pulley systems have some limitations such as they are not suitable for high loads or very high accuracy applications, a cable/ pulley system is very suitable for a system like this due to its low cost, ease of manufacturing, and assembly advantages.

In this system, linear motion is created by means of a steel cable. As the cable/ pulley configuration may change among different applications, the main principles are the same. The movement of a cable/pulley system, namely the head axis of the designed system is shown in Figure 4.1. The carriage, which is the moving element, moves along two steel bars by the guidance of linear bearings. The cable is wound around a transmission pulley which is connected to the motor via a timing belt. Both ends of the cable are fixed to stationary elements. As the transmission pulley rotates, the carriage moves along the shafts.

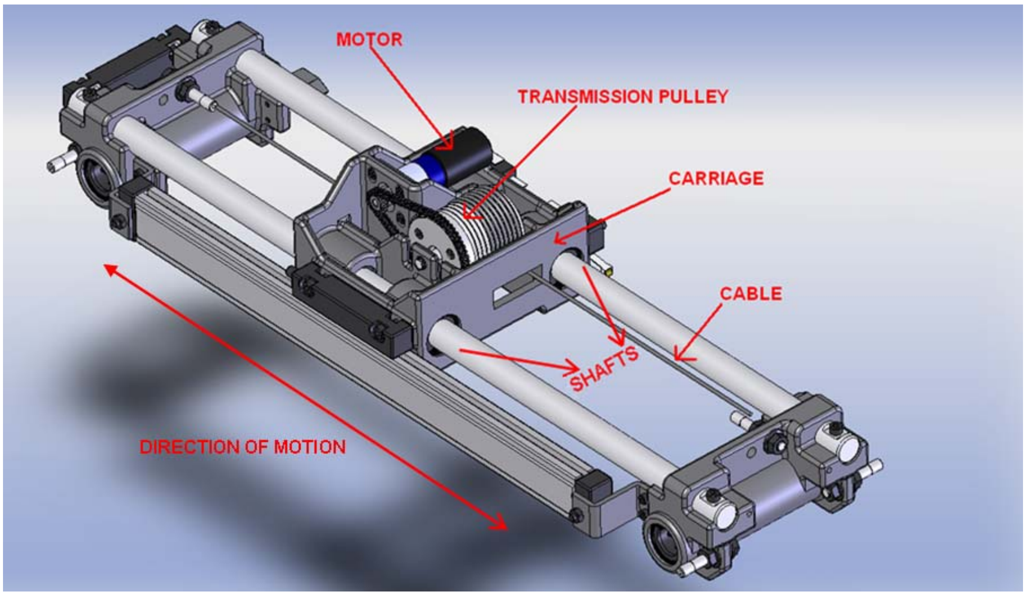

Figure 4.1 The Cable Driven Motion Transmission System

The transmission pulley is designed specifically for the purpose of transmitting the rotary motion of the motor to the linear motion of the carriage. The cable should be wound several times around the pulley in order to prevent slippage. For this reason, the pulley is designed to have a threaded shape. Though the friction between the steel cable and the pulley would prevent slippage to a certain degree, prevention of slippage cannot be depended on solely friction. In cases where a sudden change in the direction of motion occurs, the wire may slip form the surface of the pulley. As an additional precaution, the cable is fixed to the pulley by passing through a hole drilled vertical to the rotation axis. In this way, slippage of the cable is completely prevented. The pulley is manufactured from aluminum in order to decrease the weight of the moving parts and take the advantage of high friction coefficient between steel and aluminum.

The cable used for transmission is selected in order to increase the friction force. As a result of the market survey, two alternative cable diameters were chosen to be appropriate for the system; 2 mm and 3 mm. The length of the transmission pulley is limited to 41 mm due to space limitations. Therefore, increasing the cable diameter would decrease the number of windings on the pulley. Calculations made on the contact area for these two cables gives that using 2 mm cable creates the maximum contact area and therefore maximum friction force (Appendix B.1). For that reason, 2 mm cable is selected for transmission. The cable is wound around the transmission pulley four times in order to obtain an adequate friction force.

The motor is coupled to the transmission pulley by means of a timing belt and two timing belt pulleys. For this purpose, a timing belt of 3 mm pitch is used. The small pulley that is attached to the motor has 14 teeth and the large one attached to the transmission pulley has 44 teeth. In this way, a transmission ratio of 3.14 is obtained in the transmission system.

Since the force is transmitted through the tension in the cable, a proper method of adjusting the tension in the cable should be developed. For this purpose, two M6 x 30 screws are fixed to both ends of the cables. These screws are passed through the holes on the supporting blocks and they are fixed with nuts placed on both sides of the block. With this system, the length of cable can be changed by ± 30 mm on both sides in order to adjust the tension (Figure 4.2).

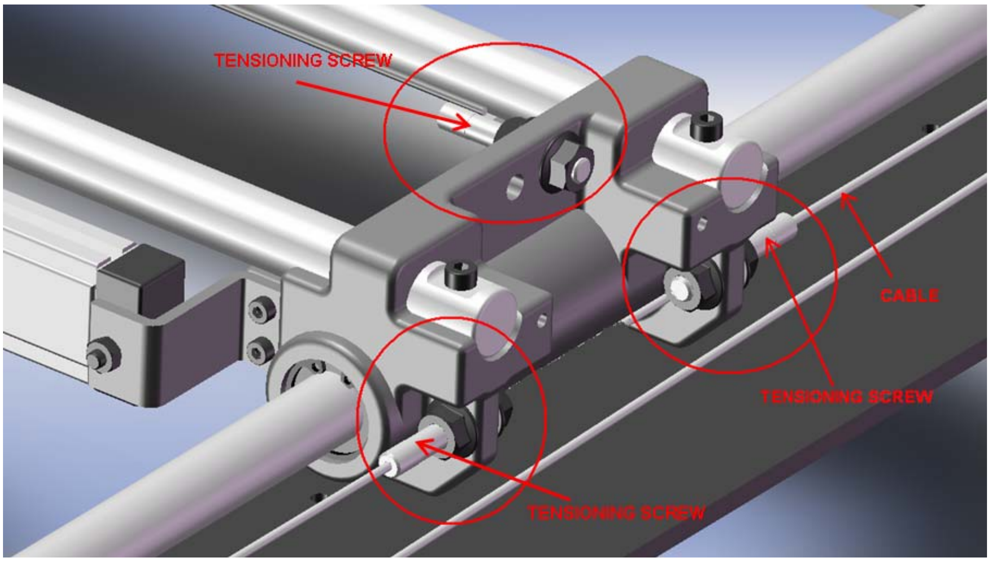

Figure 4.2 Tensioning Screws for Adjusting the Tension in Cable

The layout of the cable/ pulley system is different for two axes due their different geometries. For the head axis, the cable is simply fixed to the blocks on two ends, whereas for the main axis, several pulleys are required for transmission of motion from the motor to the carriage. The details of the axes are described in the following sections.

4.2.3. Design of Head Axis

The head axis, which is named as axis X, carries the fabrication head. For this purpose, special carriage is designed for this axis. This part carries the motor and transmission pulley and it slides on linear bearings. Since the system is designed for application and testing of more than one rapid prototyping techniques, different fabrication systems should be able to be attached to the carriage. Fabrication heads for different production techniques can be mounted to the bottom of the carriage (Figure 4.3).

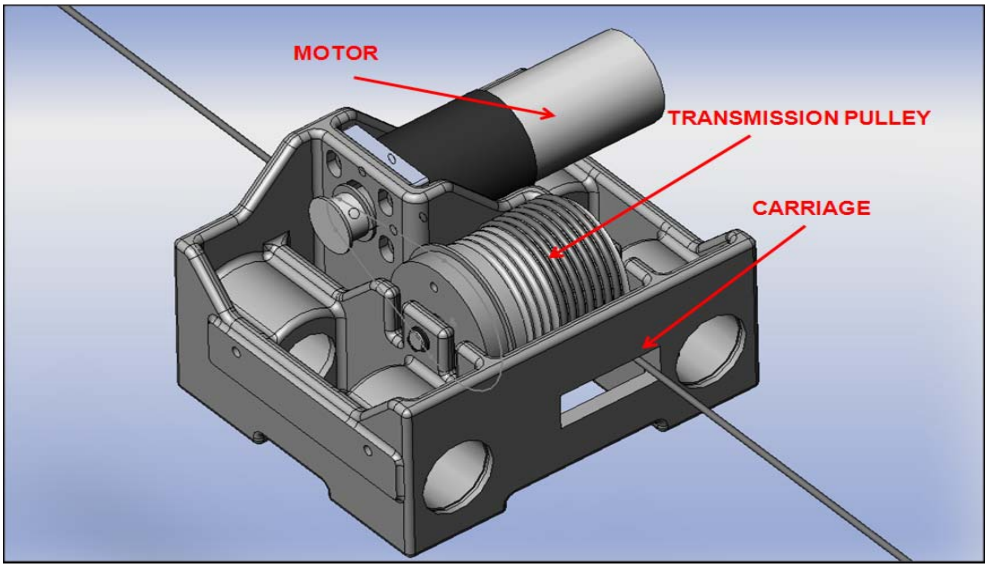

Figure 4.3 Head Axis Carriage

The carriage moves along two 16 mm diameter steel bars. The bars are fixed to two supporting blocks on two sides of the axis. These supporting blocks are also the moving elements of the second axis. The bars are fixed to the supports by means of 4 mm set screws. The linear encoder and axis limit switches are also attached to the carriage (Figure 4.4).

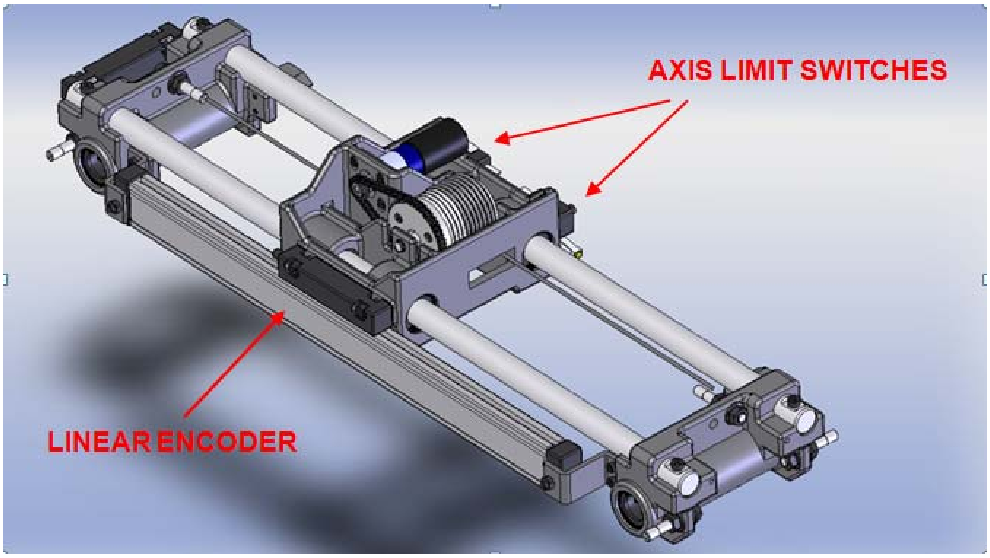

Figure 4.4 Head Axis Assembly

4.2.4. Design of Main Axis

The main axis, named as axis Y, provides the motion of the head axis. The moving elements of this axis, identified as carriages, are two symmetrical support blocks. These blocks also act as the fixed elements of the head axis (Figure 4.5).

The presence of two moving elements makes the transmission of motion harder for this type of axis configuration. Two carriages are separated by a distance of 450 mm and they need to be activated simultaneously. There are several solutions for this problem. One solution is driving only one of the carriages. The other carriage moves passively just providing guidance. The disadvantage of such a solution is jamming of the passive carriage due to the deflection resulting from the long distance between carriages.

The way to overcome this jamming problem is driving both carriages simultaneously. For this purpose, two different motors can be used for driving two carriages but this method increases the overall system cost due to one extra motor. This method also causes serious control problems since two motors driving the carriages must be driven simultaneously to prevent jamming. In order to handle this problem in a cheaper and simpler way, the motion from one motor can be transmitted to both carriages by means of a shaft and a couple of gears, but this increases the overall system weight and the use of gears increases the possibility of mechanical backlash in the system.

At this point, the advantage of using cable/ pulley mechanism emerges. The motion of a single motor can be easily transmitted to both carriages by means of a cable and several pulleys. This method solves the problem in a very cheap manner without increasing the weight or complexity of the system.

In the drive system of the main axis, the motor and the transmission pulley are placed on a separate motor block which is stationary. This configuration differs from the head axis, where the motor and the transmission pulley are mounted on the carriage. In order to transmit the motion from the motor to both carriages in the same direction, two separate cable/pulley circuits were designed. One circuit is connected to the motor through the transmission pulley and the other one moves with the motion of the carriages (Figure 4.5).

As it can be seen on Figure 4.5, when the motor turns clockwise, the cable connected to the transmission pulley, which is represented by red arrows, pulls the carriage on the right side towards the motor block. With the movement of the right carriage, the second cable which is represented by blue arrows pulls the carriage on the left side concurrently in the same direction. In this way, the motion from the motor is transmitted to both carriages simultaneously.

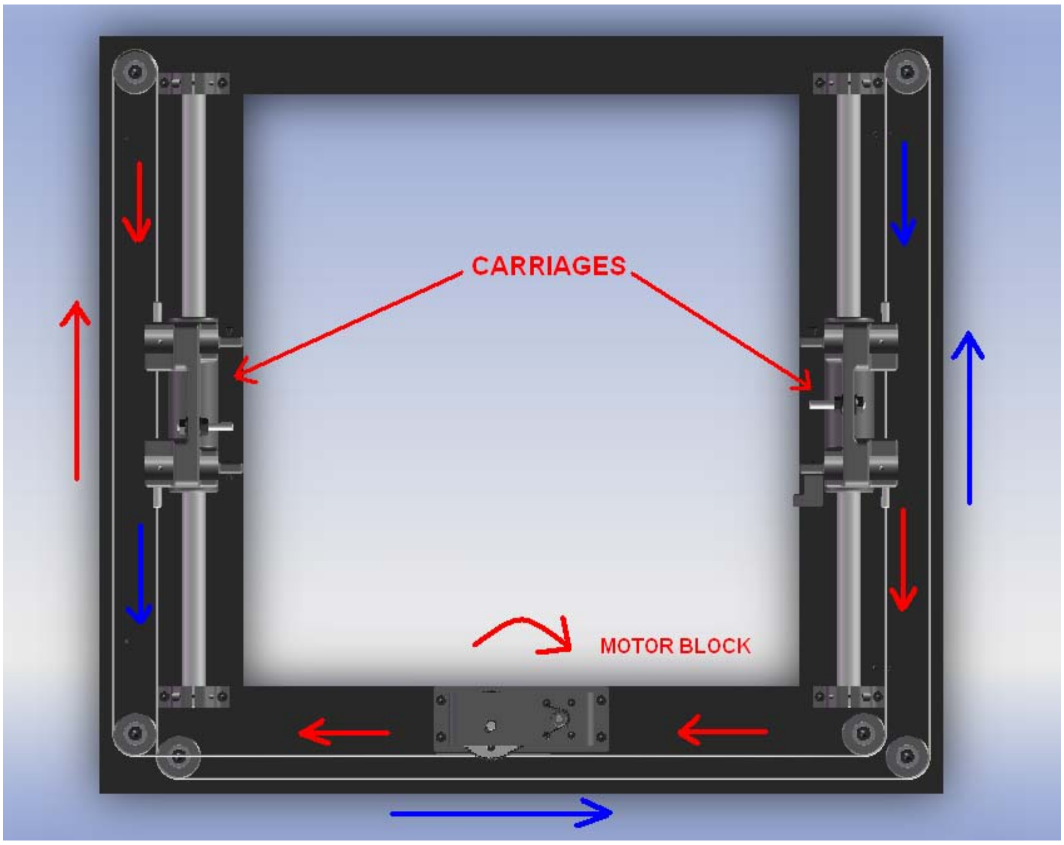

Figure 4.5 Outline of the Cable/ Pulley System

The pulleys of the drive system, the bars guiding the motion and the motor block containing the motor and the transmission pulley are fixed on a plate. The pulleys are mounted on metal supports above the plate. In order to prevent the two cable circuits from overlapping, one of the pulleys is placed 13 mm higher than the rest. The linear encoder and axis limit switches are also mounted on the plate.

Steel cables have a minimum turning radius in order to prevent crimping of the wires forming the cable. This radius depends on the diameter of the cable and the configuration of the wires forming the cable. Diameters of the pulleys are determined according to the properties of the selected cable as 30 mm.

The assembled system is shown in Figure 4.6 where the carriage of the head axis is labeled with red and the carriages of the main axis are labeled with yellow.

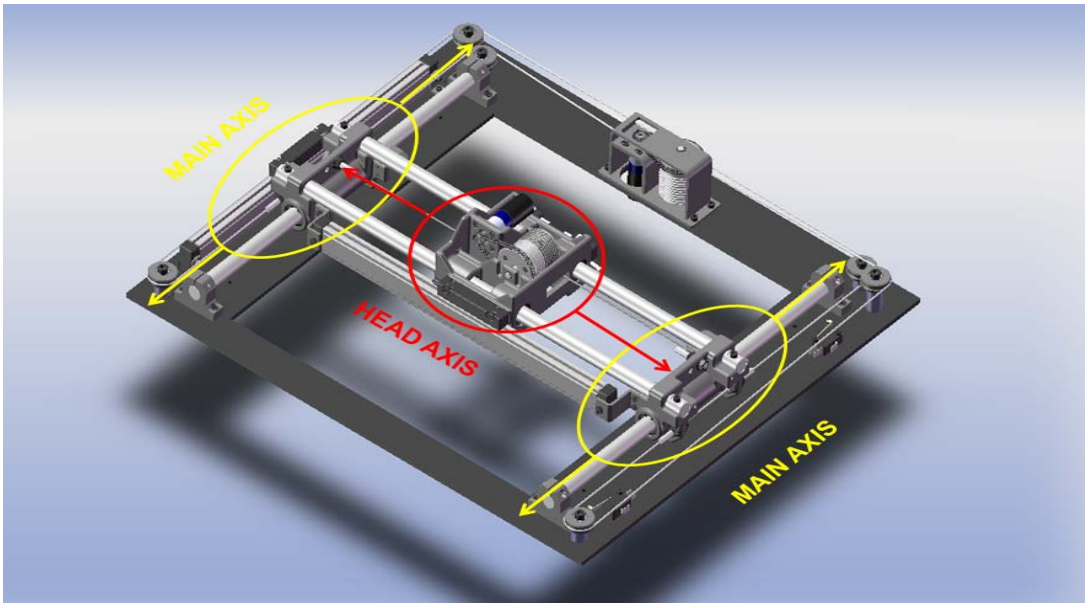

Figure 4.6 Assembly View of the System Showing the Two Axes Motion

4.3.Control System

The system is controlled by a servo motion control system. A typical motion control system is composed of a motion controller, motors, motor drivers and proper feedback devices.

4.3.1. Elements of the Control System

4.3.1.1. Motion Controller

The main and most important element of the motion control system is the motion controller. Since the designed system has two axes, a two axes motion controller would be suitable for the system. But considering the fact that the system is designed for testing different RP techniques, additional axes could be necessary for some cases. For example a FDM system utilizes two additional motors for deposition of fabrication and support material. Therefore, a four axes motion controller is selected for the system.

For the designed system, Galil DMC-2143 four axis Ethernet motion controller is used. The controller utilizes Ethernet and serial communication for communication with I/O devices. It incorporates a 32-bit microcomputer and provides features like PID compensation with velocity and acceleration feedforward. It has 8 uncommitted inputs and 8 outputs. The controller is fully programmable by using its own command language containing over 200 commands.

4.3.1.2. Motors and Motor Driver

The first step in selection of the motor for the system is the determination of the motor type. At this stage the brushless type servo motors were left out due to their high costs and the selection was made between brushed-type servo motors and stepper motors.

Stepper motors have advantages such as they omit the requirement for feedback and they are digitally controllable. However, in the designed system, a proper feedback system is necessary in order to prevent any positioning error that may arise from slippage in the cable/ pulley mechanism. Also the usage of a motion controller eliminates the control advantages of a stepper motor. For these reasons, utilization of stepper motors will not create any advantage for the design. Therefore brushed-type servo motors which create a smoother motion were preferred.

Considering the characteristics and requirements of the system, Maxon RE-Max 29 22 Watt motors were selected for the movement of the axes. The motors were coupled with Maxon planetary gear head with gear ratio of 28:1.

The selected motor driver should be compatible with the motion controller. For this purpose, Galil AMP-20440 amplifier was selected. It is a brush type servo amplifier that is capable of driving four servo motors with a power capacity of 200 Watts per channel. The amplifier is a transconductance amplifier and it supplies a current proportional to a given command signal.

4.3.1.3. Motors and Motor Driver

There are two alternatives for encoders, rotary and linear. Rotary encoders are connected to the output of the motor shaft and they measure the position of the motor. On the other hand, linear encoders are connected directly to the load so they measure the exact position of the load. Although the slippage of the cable is prevented by fixing the cable to the transmission pulley, there is always a risk of slippage for cable/ pulley systems. Therefore, it is safer to measure the position of the load rather than the position of the motor for a cable/ pulley system. Considering this, the system is equipped with two linear encoders fixed to the carriages of two axes. The linear encoders utilized in the system have a resolution of 5 μm and they have a measuring stroke of 270 mm. With the utilization of these encoders together with the selected motion controller and motors, the designed system has an accuracy of 5 μm, which is much higher than the determined lower limit for system requirements.

The motion controller utilized in the system has a feature of connecting auxiliary encoders to the axes. In applications like this case, or when the system has a considerable mechanical backlash, two encoders are used for a single axis. One of the encoders is connected to the motor and the other one is connected to the load. In cases where the load encoder is sufficient for positioning, the motor encoder can be used in order to improve the stability of the motor. Since no serious stability problems were observed during operation of the designed system with a single load encoder, the use of an auxiliary encoder was not preferred in order to keep the cost of the system low.

Simple micro switches are used for determining the limits of the axes. For each axis, one of the limit switches is also used as a homing switch.

4.3.1.4. Mathematical Model of the Control System

Since the parameters of the system and the mathematical model of the control system are known, the analytical model of the system can be constructed. The objective of this analysis is to select the filter parameters in order to close the position loop with a crossover frequency of $\omega_c = 500$ rad/s and a phase margin of 45 degrees. The parameters of the two axes are the same except the inertia values. The inertia values are approximated by the calculations from the solid modeling peorgram. The main axis is composed of many different elements that may decrease the accuracy of the inertia calculation. Therefore, the calculations are made for the head axis only.

The system parameters are:

$K_t = 25.8 \times 10^{-3}$	[Nm/A]	Torque constant
$J = 1.5 \times 10^{-6}$	[kg.m^2]	System moment of inertia
$R = 2.36$	[Ω]	Motor resistance
$K_a = 3.3/10 = 0.33$	[Amp/V]	Current amplifier gain
$T = 1 \times 10^{-3}$	[s]	Sampling period

Using the mathematical models of the elemnets derived in Chapter 3, the control system can be modeled as follows.

With s being the Laplace transform:

Motor:

$$M(s) = P/I = \frac{K_t}{J \cdot s^2} = \frac{25.8 \times 10^{-3}}{1 \times 10^{-3}} = \frac{17200}{s^2} \qquad (4.1)$$

Amplifier:

$$K_a = 0.33 \quad \text{[Amp/V]} \qquad (4.2)$$

DAC:

$$K_d = 10/32768 = 0.0003 \tag{4.3}$$

Encoder:

$$K_f = \frac{7900}{2\pi} = 1257 \tag{4.4}$$

ZOH:

$$H(s) = \frac{1}{(1 + sT/2)} = \frac{2000}{s + 2000} \tag{4.5}$$

Compensation Filter:

$$G(s) = P + sD \tag{4.6}$$

If all the system elements are combined with the exception of G(s) into one transfer function L(s):

$$L(s) = M(s) \cdot K_a \cdot K_d \cdot K_f \cdot H(s) = \frac{4.28 \times 10^6}{s^2 (s + 2000)} \tag{4.7}$$

The open loop trnasfer function , A(s), is

$$A(s) = L(s) \cdot G(s) \tag{4.8}$$

Now, the magnitude and phase of L(s) at the frequency $\omega_c = 500$ are to be determined:

$$L(500j) = \frac{4.28 \times 10^6}{(500j)^2 (500j + 2000)} \tag{4.9}$$

The magnitude of this function is:

$$\left| L(500j) \right| = 0.0083 \tag{4.10}$$

and the phase is

$$Arg\left[L(500j)\right] = -194^o \tag{4.11}$$

G(s) is selected so that A(s) has a crossover frequency of 500 rad/s and a phase margin of 45 degrees. So,

$$\left| A(500j) \right| = 1 \tag{4.12}$$

$$Arg\left[A(500j)\right] = -135^o \tag{4.13}$$

since

$$A(s) = L(s) \cdot G(s) \tag{4.14}$$

then G(s) must have a magnitude of

$$|G(wj)\ | = |A(wj)/L(wj)| = 120 \tag{4.15}$$

and a phase:

$$Arg[G(500j)] = Arg[A(j500)] - Arg[L(j500)] = -135 + 194 = 59^o \tag{4.16}$$

So, a filter function of the form

$$G(s) = P + sD \tag{4.17}$$

is required in order to obtain a magnitude of 120 and a phase lead of 59 degrees at the frequency 500 rad/s. Therefore:

$$|G(j500)| = |P + (j500D| = 160 \tag{4.18}$$

and

$$Arg[G(500j)] = \tan^{-1}[500D/P] = 59^o \tag{4.19}$$

The solution leads to:

$$P = 120\cos(59) = 62 \tag{4.20}$$

and

$$D = \frac{120\sin(59)}{500} = 0.206 \tag{4.21}$$

Therefore,

$$G(s) = 62 + 0.206s \tag{4.22}$$

The function G is equivalent to a digital filter of the form:

$$D(z) = 4Kp + 4Kd(1 - z^{-1}) \tag{4.23}$$

where

$$P = 4 * Kp \tag{4.24}$$

$$D = 4 * Kd * T \tag{4.25}$$

Therefore,

$$Kp = \frac{P}{4} = \frac{62}{4} = 15.5 \qquad (4.26)$$

and

$$Kd = \frac{D}{4 * T} = \frac{0.206}{0.004} = 51.5 \qquad (4.27)$$

So, these gain values can be used for programming the motion controller.

CHAPTER 5

IMPLEMENTATION OF THE DESIGN

5.1. Manufacturing Process

The designed linear positioning system is composed of more than 200 pieces including the bolts and nuts (Figure 5.1). Although most of these are off-the shelf parts, main parts of the system that are custom designed must be manufactured.

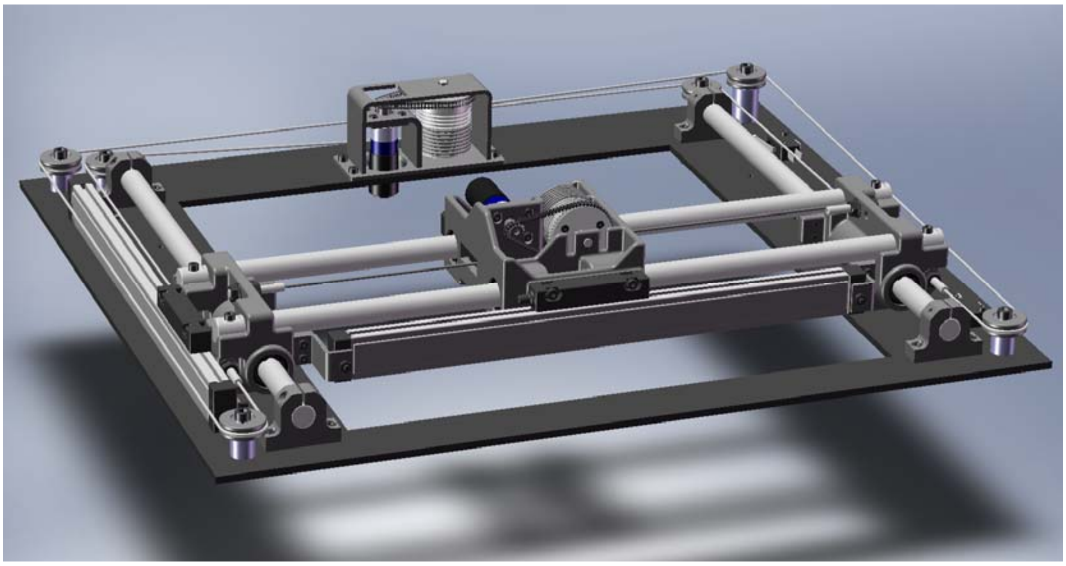

Figure 5.1 Assembly View of the Designed Linear Positioning System

5.1.1. Manufacturing of Cast Parts

The main parts of the system are carriages of the two axes: the carriage of the head axis and the two symmetrical carriages of the main axis. These two pieces carry most of the load on the system. Carriages of the main axis carry the load of the head axis and the carriage of the head axis will carry the different fabrication heads. Therefore these pieces should be strong. On the other hand, these pieces are the main moving parts of the system. This fact brings out the requirement of making these pieces as light as possible. Considering these requirements, it was decided to manufacture these two parts from aluminum. The external dimensions of carriage of the head axis are 120 x 100 x 72 mm and the dimensions of carriages of the main axis are 120 x 59 x 67.5 mm.

There are two alternative methods for manufacturing these two pieces from aluminum; CNC machining and casting. Due to the structural complexities of the parts, there are serious difficulties in manufacturing them using CNC machining. The system is a part of a prototype RP machine and more than one machine is planned to be produced to be used for testing different RP techniques in the future. Considering all these factors, and analyzing the production methods, it was decided to manufacture the main parts of the system by investment casting.

Investment casting is a process that is used for manufacturing parts having complex geometry. In this process, "the mold is made by making a pattern using wax or some other material that can be melted away. This wax pattern is dipped in refractory slurry, which coats the wax pattern and forms a skin. This is dried and the process of dipping in the slurry and drying is repeated until a robust thickness is achieved. After this, the entire pattern is placed in an oven and the wax is melted away. This leads to a mold that can be filled with the molten metal [20]." The wax model is made by injection of the wax into an injection mold.

5.1.1.1. Molds

Injection molds of the parts should be produced in order to manufacture the wax models. Injection molds are fairly complex mechanical systems. An injection mold is separated to at least two halves. There are also additional pieces, like pushing pins, used for removing the injected part from the mold.

The molds designed for the two carriage parts have two halves. The designs of the parts were slightly modified in order to prevent the parts from locking in the mold. Also cores are used for large cavities in order to reduce the additional machining time of the cast parts. The main bodies of the molds were manufactured from 7000 series aluminum by using the 5 axis CNC machining center in Manufacturing Engineering Department of Sabancı University. The cavities of the molds were designed 2% bigger than the original dimensions in order to overcome the shrinkage during the casting process (Figure 5.2).

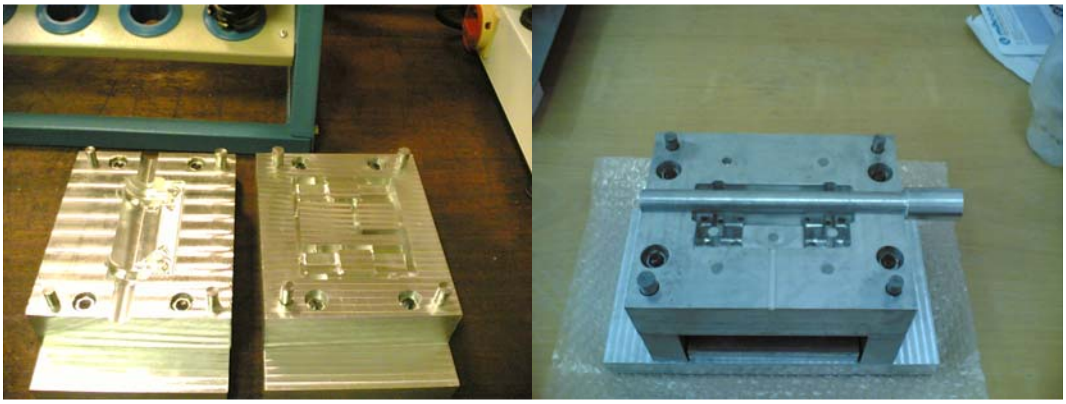

Figure 5.2 Views of the Molds in Manufacturing

The pushing pins were placed on the bottom halves of the molds. The pins were fixed to a plate that moves up and down between the supporting blocks of the mold (Figure 5.3).

These molds were used for manufacturing the wax models of the parts (Figure 5.4). As a precaution against the problems that might arise during casting, more than one set of wax models were produced.

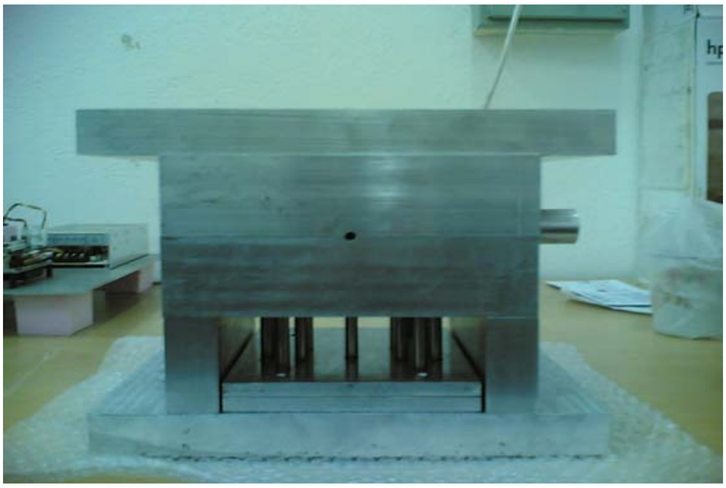

Figure 5.3 An Assembled Mold

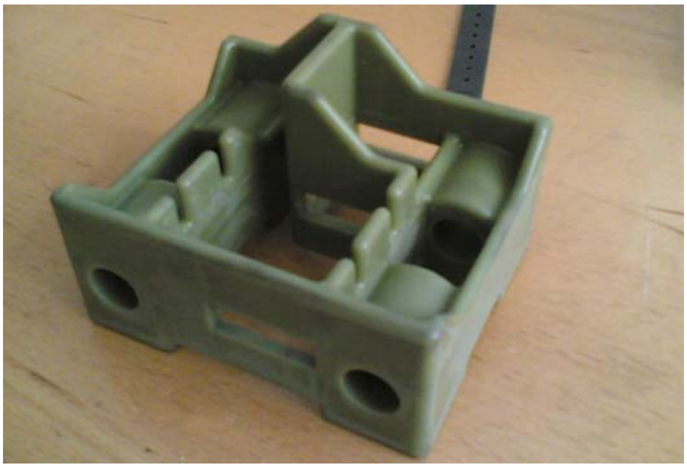

Figure 5.4 Wax Model of the Head Axis Carriage

These wax models were glued around a wax support, forming a cluster. Then these clusters were dipped into refractory slurry several times and sent to the oven for melting the wax. After the wax was molten, the ceramic molds that aluminum would be cast into were obtained. The molds were filled with molten aluminum (ETİAL 171) and the parts were obtained after the molds were broken subsequent to cooling (Figure 5.5). The whole casting operation from the creation of wax models to the production of aluminum parts were carried out in MAKİM A.Ş. in Ostim, Ankara.

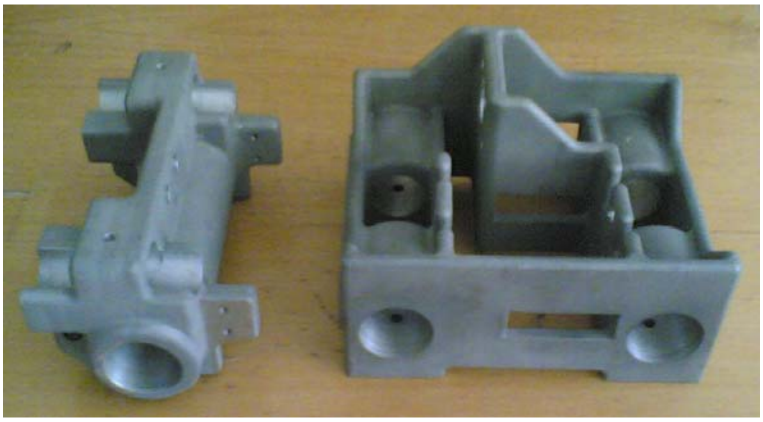

Figure 5.5 Aluminum Cast Parts: Main Axis Carriage (Left) and Head Axis Carriage (Right)

5.1.1.2. Machining of Parts

The cast parts required further machining in order to open the cavities for linear bearings, drill the holes for screws and create the flat surfaces for mounting linear encoder heads (Figure 5.6). The parts were machined by using a 4 axis CNC machining center. Since the parts have a complex geometry, special fixtures were designed in order to machine them properly.

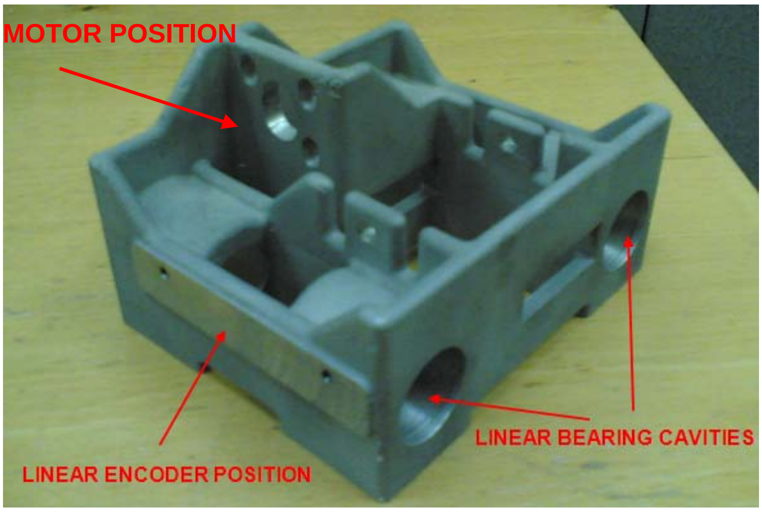

Figure 5.6 Machining Operations on the Part

5.1.2. Manufacturing of Other Parts

Other than the two main parts, the linear positioning system is composed of many different parts, large and small (Figure 5.7). The transmission pulleys of the axes were manufactured by conventional turning, the pulleys of the main axis were manufactured from cestamide, which is a different type of polyamide, due to its ease of machinability.

The motor block of the head axis, mounting elements of the linear encoders and switches were manufactured from sheet metal. The plate on which all the elements are placed was prepared by laser cutting from a 5 mm thick sheet of steel. The shaft supports of head axis were manufactured by electro-erosion.

Figure 5.7 Other Parts of the Linear Positioning System

5.1.3. Assembly of the System

After all the components of the system were collected, they were assembled in order (Figure 5.8). The linear bearings were mounted on the carriages and the carriages were placed on the shafts that are fixed to their fixtures. The most critical part of the assembly was the assembly of the drive system. Serious effort was spent in winding the cables around the transmission pulleys and obtaining the suitable tension on the cables. As the last step, the linear encoders were mounted on their fixtures. The linearity of the encoders is very critical for the accuracy of measurement. Linearity of the encoders were assured by using the plastic apparatus supplied with the encoders. Then the result was checked by using the CMM device in METU-CAD/CAM center and the results were found acceptable.

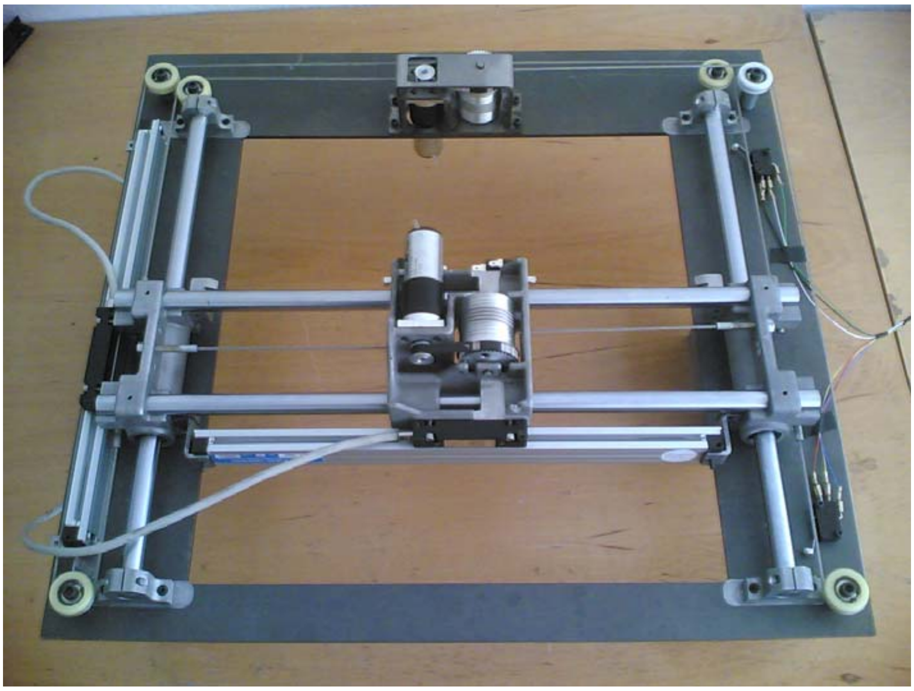

Figure 5.8 View of the Assembled System

5.2. Setting up the Control System

All elements forming the control system should be integrated and adjusted for proper operation. For this purpose, a simple base was designed for placing all the electronic components making up the control system (Figure 5.9). The main components of the system are the motion controller, servo amplifier and their power supplies. Since the servo amplifier is selected from the accessories of the motion controller, it is easily connected to the motion controller via the slot on the controller. In order to minimize any damage that can be resulted from an electrical failure, motion controller and servo amplifier were connected to separate power supplies.

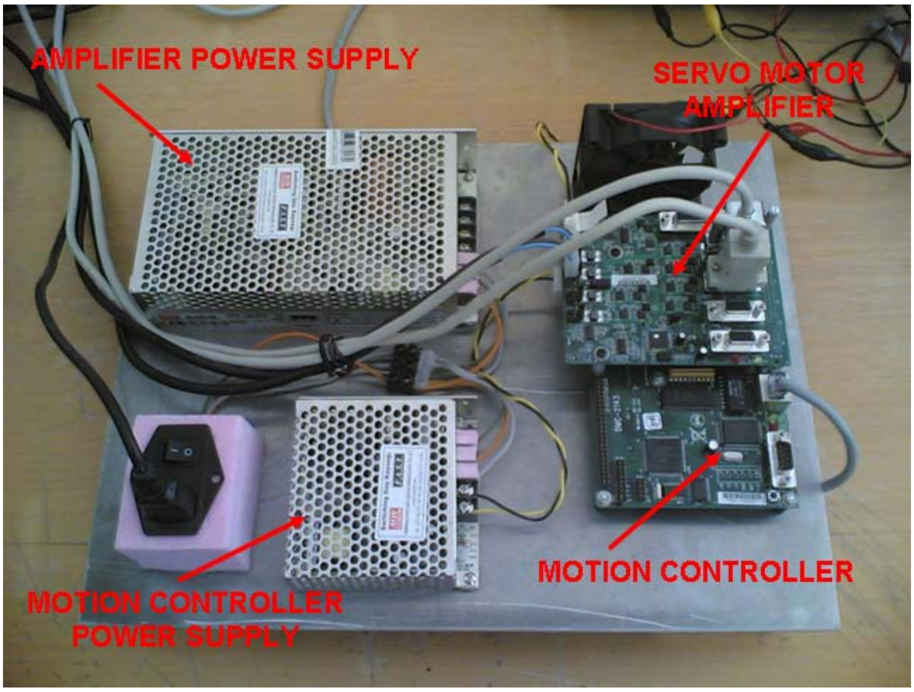

Figure 5.9 Motion Controller, Servo Amplifier and Power Supplies

The servo amplifier utilized in the system requires a minimum load inductance of 0.5 mH, but, the motors used in the system have an inductance of 0.2 mH. Connecting lower inductance motors to the amplifier could cause high amplitude fluctuations in the current supplied to the motors, causing unwanted vibrations and instability in the control process. In order to overcome such a case, two 0.33 mH inductances were connected in serial to each motor.

5.2.1. Tuning the Motion Controller

The motion controller should be tuned by adjusting the PID (proportional, integral and differential) gain parameters. Although there are some commercial software packages for automatic determination of PID parameters for a servo system, the best method for a physical system is to determine the parameters experimentally. A theoretical analysis by using the mathematical model of the system was also performed in order to compare the values with the result of the experimental analysis. The experimental parameters were set by sending the motion control system to different positions and measuring the error.

Since the system is intended to be used for RP applications, overshoot is not acceptable. Therefore, the system is adjusted to be overdamped. The PID parameters for both axes are different from each other due to different drive configurations of the axes.

For the tuning of head axis, the gain values that were obtained from the theoretical analysis of the system were used at first. The calculations of these values are given in Chapter 4. When the system was tuned with these values, i.e. Kp=15.5 and Kd=55.5, the behavior of the system was observed to be underdamped. Therefore, the gain values were revised using an experimental procedure.

As a result of the tuning procedure, proportional, derivative and integral gain for head axis are set as 12, 100, 0.05 and the values for main axis are set as 15, 150, 0.04 respectively.

The inconsistency between the experimental and the theoretical values can be explained by some difficulties in modeling the system. Especially the inertia value that was used in theoretical calculations is only an approximation of the real value. Also, it is very difficult to consider all the factors affecting the characteristics of the system in a theoretical model. For example, since this is a cable driven system, a slight change in the tension of the cable considerably affects the characteristics.

5.2.2. Programming the Motion Controller

The motion control program is the highest level of control in a motion control system. The motion controller utilized in the system provides an easy-to-use programming language that allows the controller to be programmed in order to handle any motion application. Commands can be given directly form a host computer or programs can be downloaded into the memory of the controller for independent execution. In the second case, the host computer can still send commands to the controller, even while a program is being executed.

The controller also provides many commands like conditional jumps, event triggers and if/ else statements, that allow it to make its own decisions. It provides automatic subroutines for detecting and correcting system errors and handling interrupts from external switches as well.

The motion control program implemented to the controller defines the characteristics of the system like PID parameters, acceleration, deceleration and speed of certain motion modes. Different motion modes are programmed in different subroutines and they are identified with labels in the program. These subroutines are executed by sending the appropriate commands from the computer software. There are basically three motion modes. The first motion mode is the homing mode. In this mode the system directly goes to the home position and defines this position as the absolute zero of the coordinate system. In homing mode, the system moves at a speed of 10000 encoder counts per second, this corresponds to 0.05 m/s. The acceleration and deceleration rates are selected higher than the other modes in order the system to be stopped when a limit switch is pressed.

The second mode of motion is the rapid travel mode. This mode is used for fast movement of the head to the position of the cross-section to be built in the workspace. The destination position is sent to the controller from the computer program.

The third mode of motion is the drawing mode. In this mode, the contour of the cross section is formed. The points forming the cross section are sent from the computer program in the form of an array. This mode operates at a fairly low speed of 2000 counts/second, which corresponds to 0.01 m/s.

5.2.3. Case Studies

After the motion control system was tuned and programmed, some case studies were performed in order to see whether the system can draw various shapes properly. For this purpose, a circle and a square were drawn in different layouts

(Figure5.10, Figure 5.11 and Figure 5.12). The resulting shapes were obtained from a computer program that plots the position data coming from the encoders, therefore they represent the output of the system correctly. In the grids of the figures, one square represents a distance of 2000 encoder counts, which, in this case corresponds to a distance of 10 mm.

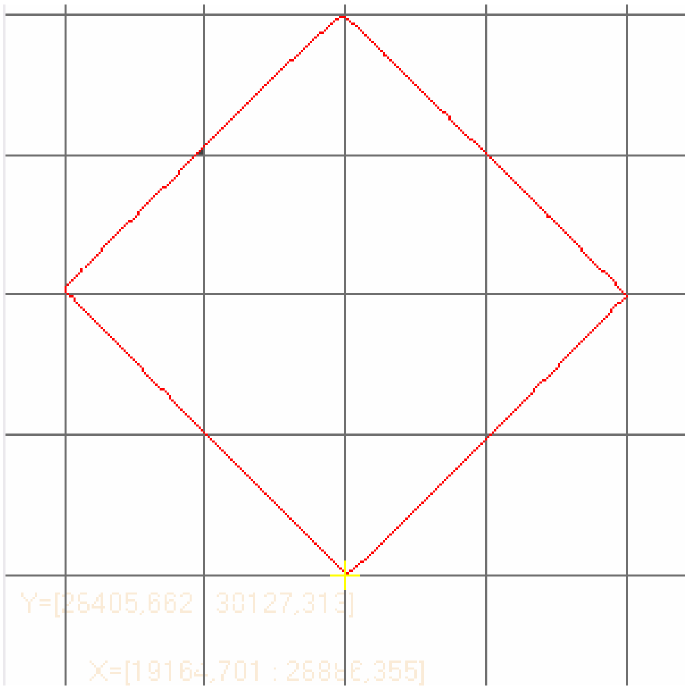

Figure 5.10 Plot of a Square in Diagonal Orientation

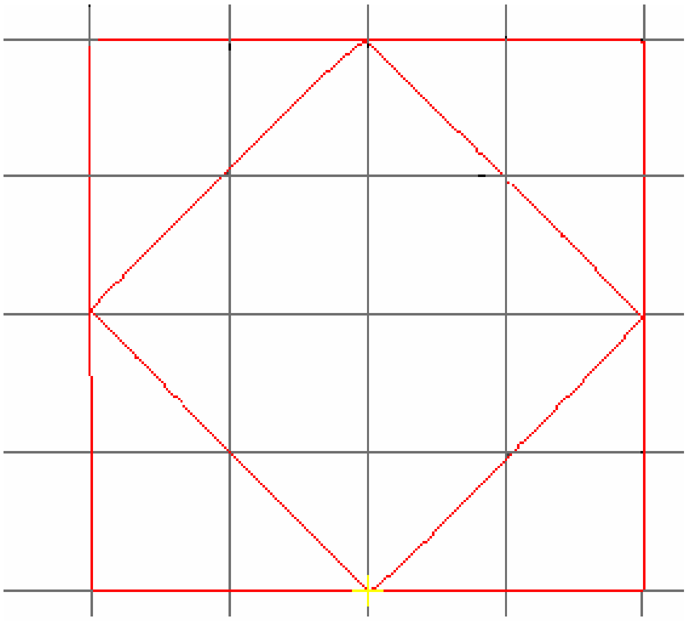

Figure 5.11 Plot of two Squares within Each Other

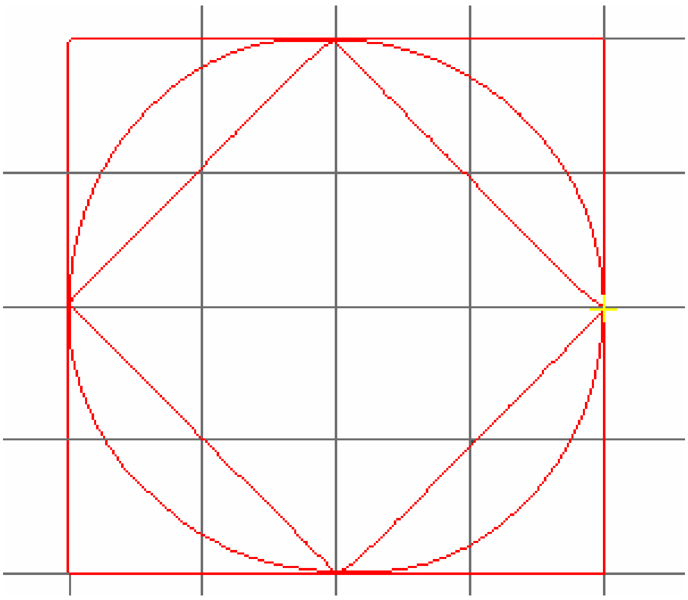

Figure 5.12 Plot of a Circle and Two Squares within Each Other

When the figures above are examined, it is observed that the resulting shapes are fairly adequate although they are not perfect. The fluctuations that can be seen in straight lines are the result of the vibration created by the cable/ pulley mechanism. The main reason of this vibration is the poorly produced pulleys of the second axis. The eccentricities of the pulleys affect the characteristics of the system. Better results can be obtained with better produced pulleys. Also the base on which the system stands is not rigid enough. If the system can be positioned on a separate rigid table, the results would be much more appropriate.

CHAPTER 6

CONCLUSION

6.1. Discussion and Conclusion

In this thesis project, a two axes linear positioning system has been designed and implemented. The designed system is part of a research project supported by TÜBİTAK. The aim of the project is to design a rapid prototyping system that can be used as a base for future research on the area of rapid prototyping.

The designed system utilizes a cable/ pulley drive for transmitting the rotary motion of the motors into linear motion. In this system, force is transmitted to the carriages of the two axes by means of a steel cable wound around a specially designed transmission pulley which is connected to the motor my means of a timing belt.

Within the scope of the thesis, all the pieces of the linear positioning system were designed and manufactured. The main elements of the system, namely the carriages of the two axes were manufactured by using investment casting. The molds used for producing wax models, used for creating investment casting molds were also designed and manufactured.

In order to control the linear positioning system precisely, a servo motion control system was established. The system is driven by two DC servo motors and the feedback is obtained from linear encoders.

The system that is produced as a result of this thesis work can be used as a reliable base for tests and applications of different rapid prototyping systems. It can also be used for many different applications like a plotter or a simple desktop CNC with small additions.

6.2. Recommendations for Future Work

The system produced in this study can be improved in some ways. First of all, the produced system has some problems resulting from poor manufacturing quality of some of the parts, especially the cestamide pulleys of the drive system of the main axis. The eccentricity in the rotation of these pulleys causes the movement of this axis to be jerky. A higher quality manufacturing could significantly improve the movement characteristics of the system.

The mechanical properties and stiffness of the system is highly dependent on the tension on the cables. Especially for the main axis, where there are two different cable circuits, obtaining an equal tension on both cables is important. In this study, the tension on the cables was adjusted according to the measurements made by hand. Using a proper cable tension meter would give a more accurate result and therefore better system characteristics.

The feedback devices utilized in the system are a pair of linear encoders. Although they produce acceptable results, using additional encoders connected to the motors could increase system stability. Such a configuration is also supported by the motion controller used in the system.

The power transmission between the motor and the transmission pulley is another point that could be improved. Although the transmission obtained by using timing belt is adequate, adjusting the proper tension on the belt is pretty difficult due to the complexity of the carriages and lack of space. Also the tension of the timing belts should be checked regularly in order to prevent any slippage. An option of direct drive was considered for solving this problem. In that way, the motor is directly connected to the transmission pulley without any flexible element. Even a design based on this idea was made, but it could not be implemented due to limited time.

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APPENDIX A

TECHNICAL SPECIFICATIONS

A.1. Technical Specifications of DC Servo Motors

Motor Type	: Maxon Re – max 29
Assigned power rating	: 22W
Nominal voltage	: 24VDC
No load speed	: 8780rpm
Stall torque	: 262mNm
Speed/torque gradient	: 33.9rpm/mNm
No load current	:34.2 mA
Starting current	: 10.2A
Terminal resistance	: 2.36Ohm
Max. permissible speed	: 10400rpm
Max. continuous current	: 1.07A
Max. efficiency	: 87%
Torque constant	: 25.8mNm/A
Speed constant	: 370rpm/V
Mechanical time constant	: 4.78ms
Rotor inertia	: 13.5gcm2
Terminal inductance	: 0.199mH

A.2. Technical Specifications of Planetary Gear Head of DC Servo Motors

Gear head type	: Maxon GP 32 A - 114435
Reduction	: 28 : 1
Planetary gear head	: straight teeth
Output shaft	: stainless steel
Bearing at output	: ball bearings
Max. Perm. Radial load, 10 mm from flange	: 140N
Max. Perm. Axial load	: 120N
Max. Perm. Force for press fits	: 120N
Average backlash	: 0.8°
Recommended input speed	: <6000rpm
Recommended temperature range	: -20/+100°C
Mass inertia	: 0.8 gcm2

A.3. Technical Specifications of Motor Amplifier

DC Supply Voltage	: 18-60 VDC
Max Current	: 3.3 Amps (continuous and peak)
PWM Frequency	: 60 kHz
Minimum Load Inductance	: 0.5 mH
Over-Voltage Threshold (OV)	: 69 volts (rests at 66 volts)

A.4. Technical Specifications of Motion Controller

GALIL DMC-21x2 and DMC-21x3 Series

Specifications:

System Processor

- Motorola 32-bit microcomputer

Communications Interface

- Ethernet 10BASE-T. (1) RS232 port up to 19.2 kbaud

Commands are sent in ASCII. A binary communication mode is also available as a standard feature

Modes of Motion:

- Point-to-point positioning
- Position Tracking
- Jogging
- 2D Linear and Circular Interpolation with feedrate override
- Linear Interpolation
- Tangential Following
- Helical
- Electronic Gearing with multiple masters
- Gantry Mode
- Electronic Cam
- Contouring
- Teach and playback

Memory

- Program memory size—1000 lines x 80 characters
- 510 variables
- 8000 array elements in up to 30 arrays

Filter

- PID (proportional-integral-derivative) with velocity and acceleration feedforward
- Notch and low-pass filter
- Velocity smoothing to minimize jerk
- Integration limits
- Torque limits
- Offset adjustments
- Option for piezo-ceramic motors

Kinematic Ranges

- Position: 32 bit (±2.15 billion counts per move; automatic rollover; no limit in jog or vector modes)
- Velocity: Up to 12 million counts/sec for servo motors
- Acceleration: Up to 67 million counts/sec^2

Uncommitted Digital I/O

- 8 buffered inputs for 1–4 axes; 16 for 5–8 axes*
- 8 TTL outputs for 1–4 axes; 16 for 5–8 axes*
- 8 analog inputs and 40 digital I/O with DB-28040 (outputs source 3.3 V. For 24 open collector outputs that sink 5 V, order DB-28040-5V)
- 8 analog inputs available with AMP-205x0 and SDM-206x0

High Speed Position Latch

- Uncommitted inputs 1–4 latch X,Y, Z,W; 9–12 latch E, F, G,H (latches within 0.1 microseconds)*

Dedicated Inputs (per axis)

- Main encoder inputs—Channel A, A-,B,B-,I,I- (±12 V or TTL)
- Auxiliary encoder inputs for each servo axis
- Forward and reverse limit inputs—buffered*
- Home input—buffered*
- High-speed position latch input—buffered*

Dedicated Outputs (per axis)

- Analog motor command output with 16-bit DAC resolution
- Pulse and direction output for step motors
- Amplifier enable output*
- Error output (one per controller)
- High-speed position compare output

(1 output for each set of 4 axes)

Minimum Servo Loop Update Time

	FAST
• 1–2 axes: 250 μsec	125 μsec
• 3–4 axes: 375 μsec	250 μsec
• 5–6 axes: 500 μsec	375 μsec
• 7–8 axes: 625 μsec	500 μsec

Maximum Encoder Feedback Rate

- 12 MHz

Maximum Stepper Rate

- 3 MHz (Full, half or microstep)

Environmental

- Operating temperature: 0–70º C
- Humidity: 20–95% RH, non-condensing

Power Requirements

	1–4 axes	*5–8 axes*
• +5 V	0.8 A	1.4 A
• -12 V	20 mA	40 mA
• +12 V	20 mA	40 mA

- DC-to-DC converter option: 9 V to 18 V for DC12
  18 V to 36 V input for DC24
  36 V to 72 V input for DC48
- Approximate current draw for the DMC-2143 with no external load is about 200 mA for 24 V supply

Mechanical

- 1–4 axes card: 4.25" x 7.0"
- 5–8 axes card: 4.25" x 10.75"

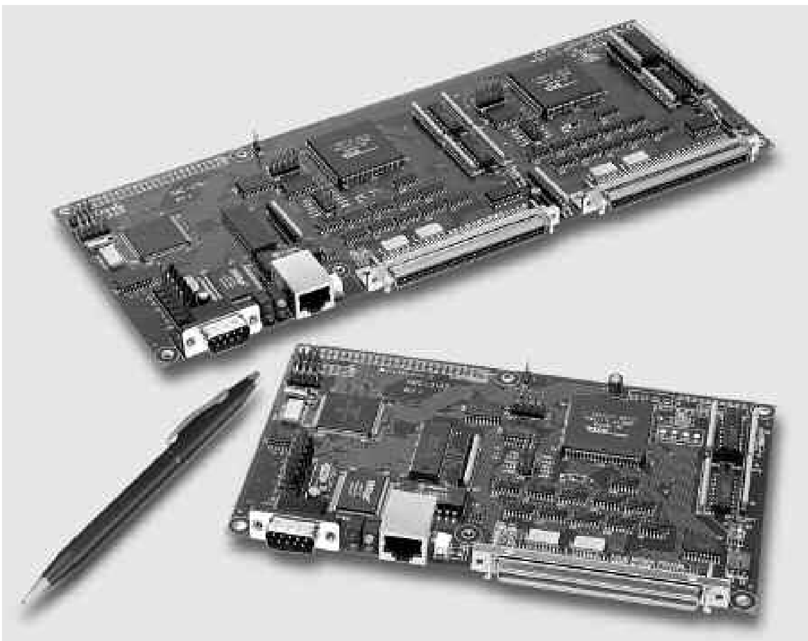

Figure A.1 Galil DMC-21x3 Motion Controller

A.5. Technical Specifications of Linear Encoders

ELECTRONICA ELEKTRA LINEAR SCALE

Electrical output :+5V TTL Square wave for 5 micron system/ Open collector pull up resistor 2.2 kΩ 90° ±10% Phase shifted sine wave for 1 micron system.

Pitch of line grating : 20 microns/ 40 microns (optional)

Resolution : 5 micron (standard by interpolation by 4 in counting device.)

: 1 micron (optional by interpolation & subdividing electronics in counting device.)

Reference Marks : Available throughout the scale length / optional selective

Accuracy : ± 10 μ per meter at reference temperature 20 °C.

Protection : Against dust and splash water, provided by flexible rubber lips.

Supply voltage : VCC + 5 V ±5%

Current : (ICC) ≤ 50 mA

Permissible temperature:

--During storage : -30 °C to + 70°C

-- During operation : 0°C to + 55 °C

Relative humidity : 20 % to 95 % non condensing.

Standard cable length: 3 m upto 820 mm scale length with 9 pin D type male connector.

: 5 m above 820 mm scale length with 9 pin D type Male connector

Max permissible cable: 15 m in step of 5 m (Extension cables of 5 m length)

Permissible traversing speed: 10 m/min for 5 micron system.

3 m/min for 1 micron system.

Luminous elements : IR LED

Sensing element : Phototransistor

Weight of system : 800 g/ m + 350g for slider unit with 3 m long cable.

APPENDIX B

CALCULATIONS FOR DETERMINATION OF CABLE DIAMETER

Two alternative cable diameters are selected for the system as 2 mm and 3 mm. The length of the transmission pulley is 41 mm. and the length of the threaded part is limited to 35 mm. The diameters of the threads on the pulley should be slightly larger than the diameter of the cable in order the cable to fit into the thread properly. For this purpose, if 2 mm diameter cable is used, the threads on the pulley should be formed with a diameter of 2.5 mm and for a 3 mm cable the threads should be formed with a diameter of 3.5 mm. Also a distance of 0.5 mm is left between the threads. Therefore:

For 2 mm cable, the number of windings:

$$N_2 = 35/(2.5 + 0.5) = 11.6 \qquad \text{(B.1)}$$

but since half winding is unusable from both ends, number of effective windings: N_2 =11(Figure B.1).

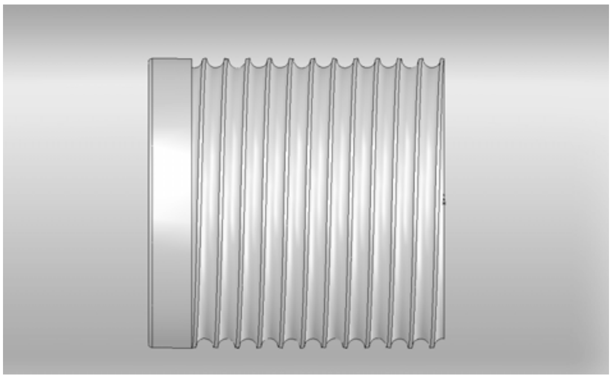

Figure B.1 Pulley for 2 mm Cable

For 3 mm cable, the number of windings:

$$N_3 = 35/(3.5+0.5) = 8.75 \quad \text{(B.2)}$$

for this case, the number of effective windings is N_3=7 since one more winding is unusable due to the thickness of the cable (Figure B.2).

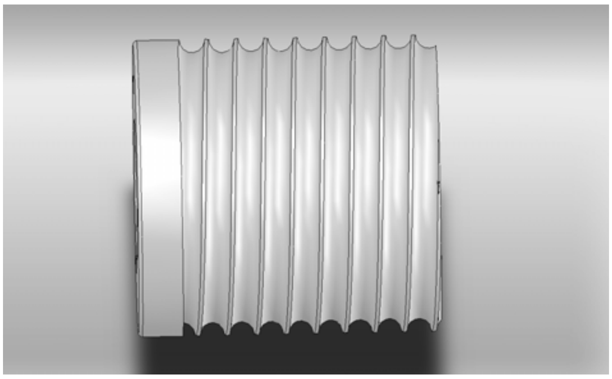

Figure B.2 Pulley for 3 mm Cable

The contact area of the cable and the pulley can be formulized as:

$$A = \frac{P_{cable}}{2} \times P_{pulley} \times N \quad \text{(B.3)}$$

where P_{cable} and P_{pulley} are the perimeters of the cable and pulley, N is the number of windings.

$P_{cable} = 2 \times \pi \times r_{cable}$ and $P_{pulley} = 2 \times \pi \times r_{pulley}$ r_{pulley}=20 mm

For 2 mm cable:

$$A_2 = (\pi \times 1) \times (2 \times \pi \times 20) \times 11 = 4342mm^2 \qquad \text{(B.4)}$$

Similarly for 3 mm cable:

$$A_3 = (\pi \times 1.5) \times (2 \times \pi \times 20) \times 7 = 4145mm^2 \qquad \text{(B.5)}$$

Therefore since $A_2 > A_3$, the utilization of 2 mm diameter cable provides a larger friction surface