DESIGN, PROTOTYPE, AND CONTROL OF 5-AXIS DESKTOP CNC MILLING MACHNE

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DESIGN, PROTOTYPE, AND CONTROL OF 5-AXIS DESKTOP CNC MILLING MACHNE

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Syed Arslan Hassan NAQVI

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I certify that in my opinion the thesis submitted by Syed Arslan Hassan NAQVI, titled "DESIGN, PROTOTYPE, AND CONTROL OF 5-AXIS DESKTOP CNC MILLING MACHNE" is fully adequate in scope and quality as a thesis for the degree of Master of Science.

Prof. Dr. Kerim CETINKAYA ....

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This thesis is accepted by the examining committee with a unanimous vote in the Department of Manufacturing Engineering. June 27, 2014

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The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Graduate School of Natural and Applied Sciences, Karabuk University.

Prof. Dr. Mustafa BOZ ....

Director of Graduate School of Natural and Applied Sciences

ABSTRACT

M. Sc. Thesis

DESIGN, PROTOTYPE, AND CONTROL OF 5-AXIS DESKTOP CNC MILLING MACHNE

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Graduate School of Natural and Applied Sciences
Department of Manufacturing Engineering

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CNC (Computer Numerical Control) machine is the heart of many manufacturing industries and technical training institutes worldwide, but large CNC machines are not always desired. Using only 3-axis machines is sometimes not enough, and cheaper 4 or 5-axis CNC machines are needed. In this study, a prototype of cost-effective, efficient, and reliable 5-axis desktop CNC milling machine was designed and constructed. The construction process is explained step by step and the list of parts necessary for this is also given. The electronic connection mechanism and setting in Mach3 programme is also elaborated. The procedure for controlling this machine and for machining complicated 3-dimensional parts using G codes and Mach3 programme is also explained in detail. The process of writing G codes manually for the desired shape of the workpiece is described and some sample codes along with the machined parts are also added. The constructed machine can be successfully used for machining soft and lightweight materials. The machine is well suitable for small-scale applications and educational purposes. The machine would also assist design and several other engineering students in building their own CNC machines and in learning how to control 5-axis CNC milling machines.

Keywords : 5-Axis CNC, prototype, control, g code, mach3.
Science Code : 708.1.090

ÖZET

Yüksek Lisans Tezi

5 EKSEN MASAÜSTÜ CNC FREZE TASARIMI, PROTOTİPİ VE KONTROLÜ

Syed Arslan Hassan NAQVI

Karabük Üniversitesi
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CNC (Bilgisayarlı Sayısal Denetim) makinesi, dünya çapında birçok imalat sanayi ve teknik eğitim kurumlarının kalbidir, ama büyük CNC makineleri her zaman arzu edilmez. Sadece 3-eksenli makineleri kullanmak bazen yeterli değildir ve daha ucuz 4 veya 5 eksenli CNC makinelerine ihtiyaç vardır. Bu çalışmada, uygun maliyetli, verimli ve güvenilir 5-eksenli masaüstü CNC freze makinesi bir prototip olarak tasarlanmıştır. Yapım süreci adım adım açıklanmış ve bunun için gerekli parçaların listesi, elektrik-elektronik bağlantılar ve Mach3 programında gerçekleştirilen set ayarları verilmiştir. Bu makinenin kontrol prosedürü, G kodları kullanılarak karmaşık üç boyutlu parçaların işlenmesi ve Mach3 programı ayrıntılı olarak açıklanmıştır. Iş parçasının arzu edilen şekli alması için manuel olarak G kodları yazma işlemi tarif edilmiştir ve ayrıca makine parçaları ile birlikte bazı örnek kodlar da ilave edilmiştir. Yapılan makine yumuşak ve hafif malzemelerin işlenmesi için kullanılabilir. Makine küçük ölçekli uygulamalar ve eğitim amaçlı kullanımlar için oldukça uygundur.

Makine ayrıca tasarım mühendisliği ve diğer bazı branşlardaki mühendislik öğrencilerine kendi CNC makinelerini yapmada 5-eksenli CNC tezgâhının nasıl kontrol edileceğini öğrenmede yardımcı olacaktır.

Anahtar Kelimeler : 5-Eksenli CNC, prototip, kontrol, g kod, mach3.
Bilim Kodu **:** 708.1.090

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ABBREVATIONS

NC : Numerical Control

CNC : Computer Numerical Control

CAD : Computer Aided Design

CAM : Computer Aided Manufacturing

MCU : Machine Control Unit

DNC : Direct Numerical Control

TPI : Teeth per Inch

MCU : Machine Control Unit

CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION OF PROJECT

With the on-going development of technology and economy, new industrial requirements such as high precision, good quality, high production rates and low production costs are increasingly demanded. Most of such requirements, including dimensional accuracy, conformance to tolerances of finished products and production rate can be met with better machine tools. With the help of CNC technology, machine tools today are not limited to human capabilities and are able to make ultra-precision products down to nano scales in a much faster manner [1].

Desktop CNC machine is the machine that is similar to the usual CNC machine. Desktop CNC machine is the small CNC machine that can operate like usual CNC machine but the area of the machining is limited. CNC machine is all about using the computer as a means to control machines that carves useful objects from solid block to material. For example, a CNC machine might begin with a solid block of aluminium, and then carved away just the right material to leave with a door handle. There are many types of CNC machine. The common CNC machines are two-axis and three-axis CNC machine. The two- axis machine can move on vertical and horizontal only which are X and Y axis. Three-axis machine can do movement starting with three primary axis which are X, Y and Z axis. The Z axis is being parallel with the spindle. There are other advanced machines with 5 axes, three normal linear axes (X, Y and Z) and two rotary axes (A and B or C).

The CNC machine operation starts with the collecting the data from the programming that extract from the computer-aided design (CAD) and computer-aided manufacturing (CAM). The programs produce the computer file and then will extract the command to operate the machine.The program will be transfer via post-processor and then be loaded into the CNC machine to start the machining. This is the flow of the CNC machine operation (Figure 1.1):

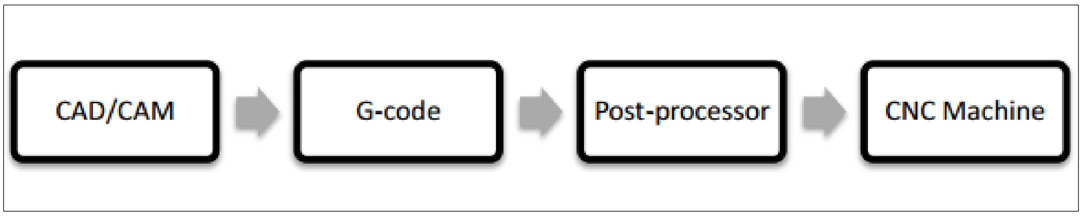


Figure 1.1. Flow of the CNC machine operation [1].

1.2. PROBLEM STATEMENT

Nowadays, the world is becoming highly technology with a lot of things become smaller and thinner. Even now the things especially in engineering and technology have the things in nano and micro size, same goes to CNC Machine; this machine is now has variety of size in the market. All type of machine have own purpose, eventhough the size is big or small. The usual CNC machine can machine the big workpiece depends on the machine´s specifications. The micro CNC machine can only machine the small workpieces also depends on the machine´s specifications. CNC machines are the need of several industries and technical institutions worldwide. Most of the small industries and technical institues don´t require large-scale CNC machines. Majority of the small-scale manufacturing industries and technical training institues use 3-axis CNC machines, because 4 or 5 axis CNC machines are too costly and also difficult to operate, but there must some 4 and 5 axis machines to teach to students their control methods and also CAM programs.

1.3. 5-AXIS CNC SYSTEMS SURVEY

The development of NC machine tools has continued for over fifty years in the manufacturing industry. Currently, the technology is reasonably mature and different companies have developed their unique strengths on different products. China is the largest machine tool manufacturer in the world. It is known to the rest of world for its affordable products [1].

Five-axis CNC machine tools comprise three linear axes and two rotary axes, providing multi-directional manufacturing capability. Manufacturing workpieces with free-form surface, such as dies, turbo blades, or cams using three-axis CNC machine tools requires loading and discharging, which detracts from the accuracy and slows the production process. The frequency of loading and discharging can be decreased using five-axis CNC machine tools, which has led to its wide-scale adoption, supplanting three-axis CNC machine tools [2].

The Industrial Design Engineering department of Technology Faculty at Karabuk University is working on designing, improving and controlling different typent types of CNC machine tools (i.e. Milling, Lathe, Drilling, etc). In the depatment, several students have built the prototypes of their own CNC machine conceptual design. These machines normally include 3 or 4 axes. But, in the recent years students have started to design, built, and control five axis CNC systems.

Three different types of five-axis CNC machine tools were took into the consideration and their prototypes were built at the faculty [2]: (a) typical vertical five-axis machining centre with a double pivot spindle head, A-type, (b) typical vertical five-axis machining centre with a tilting rotary table, B-type, and (c) typical vertical five-axis machining centre with a swivel head and a rotary table, C-type. Figure 1.2 is a A-type 5-axis CNC system with the list of its parts´names.

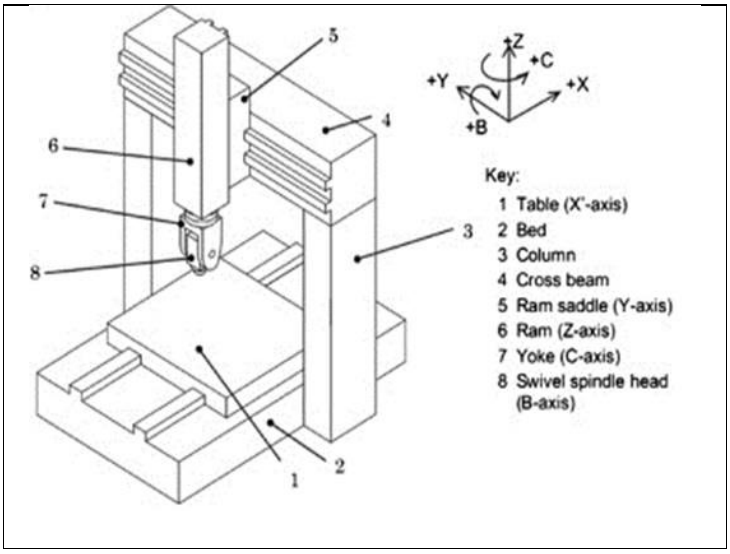


Figure 1.2. A-type 5-axis CNC machine tool [2].

This machine has also been designed and constructed by the student of Bachelor degree. Figure 1.3 shows the machine which has been designed by the student of Design and Construction department of Techniacal Education faculty. This machine is also have five and exactly same axes as the machine in figure 1.2. But this machine was made for large-scale applications, especially for machining car bodies.

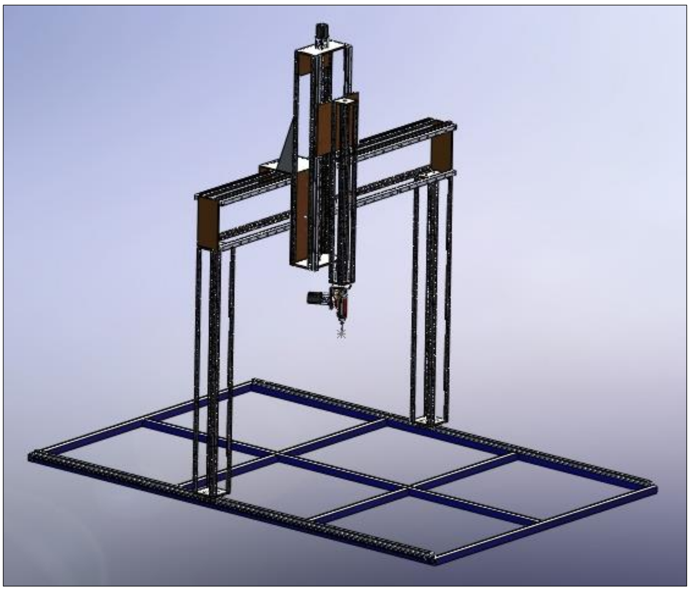


Figure 1.3. 5-axis CNC milling system [3].

Figure 1.4 is a B-type 5-axis CNC system with the list of its parts´names.

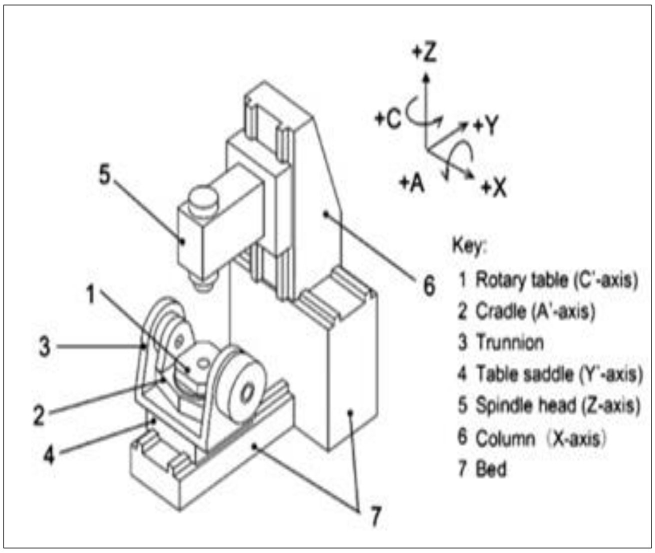


Figure 1.4. B-type 5-axis CNC machine tool [2].

The same kind of machine has also been designed and constructed by the student of Master degree. Figure 1.5 shows the machine which has been designed by the student of Industrial Design Engineering department at the faculty of Technology. This machine is also have five and exactly same axes as the machine in figure 1.4.

Figure 1.5. 5-axis CNC craddle [4].

Figure 1.6 is a C-type 5-axis CNC system with the list of its parts' names.

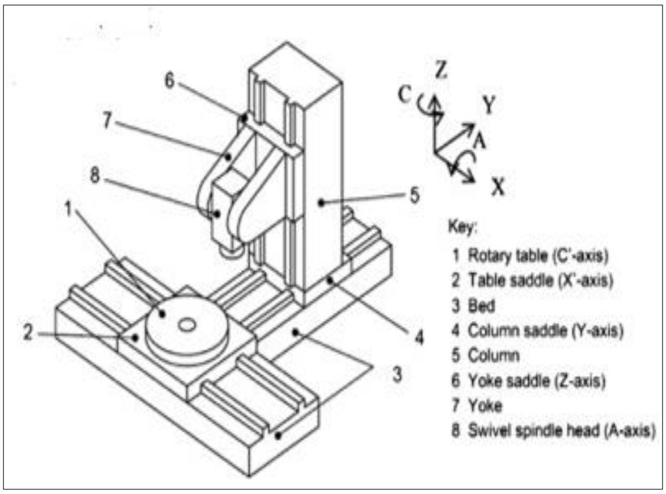


Figure 1.6. C-type 5-axis CNC machine tool [2].

In this study, the prototype of the machine shown in figure 1.6 has been designed, constructed, and controlled. The machine presented in this work has exactly same shape and number of axes, but may with different dimesions. This type of machine has not been designed or constructed by any of the students at Karabuk University.

Figure 1.7 is a personal size 5-axis CNC milling machine from PocketNC. This machine is also manufactured in United States (USA) by the company named, 'THE KNEESLIDER'.

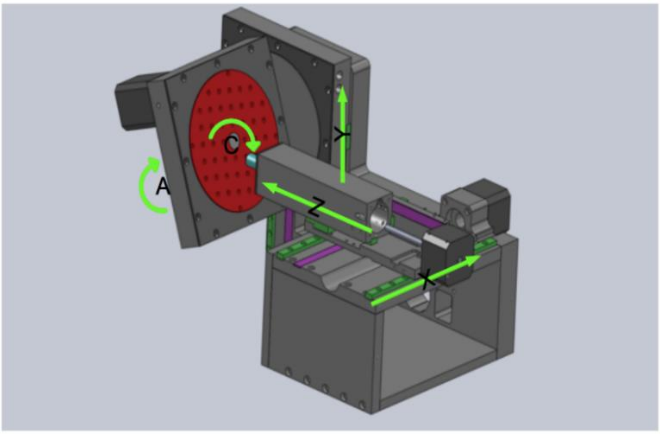


Figure 1.7. CNC Baron Milling Machine [5].

The personal size 5-axis CNC milling machine has not been designed or constructed by any of the students of Karabuk University. This machine is suggested by the author of this thesis for future works.

1.4. GENERAL RESEARCH OBJECTIVES

- Design of 5-axis desktop cnc milling machine
- Fabrication of the machine
- Controlling the machine automatically
- Using CAD/CAM programs to generate G M codes
- Analyze machine´s performance

1.5. SCOPE OF WORK

- Constructing desktop CNC machine with 5 axes
- Do wiring for the connection between machine and computer
- Using Mach3 control program
- Controlling 5-axis CNC machine
- Writinng G and M codes manually
- Performing Accuracy tests
- Machinning different workpieces

1.6. PROJECT OUTCOMES

By the end of this project, the following outcomes are expected:

- Learn how to design & built the prototype of 5-axis CNC machine
- Learn how to connect the wiring of the circuit
- Learn how to use Mach3 control program
- Learn how to control 5-axis CNC machine
- Learn to write G and M codes manually
- Learn how to machine different workpieces

CHAPTER 2

CNC BACKGROUND INFORMATION

2.1. WHAT IS CNC?

Numerical Control has been used in manufacturing for several years. Simply put, Numerical Control is a method of automatically operating a manufacturing machine based on a code of letters, numbers, and special characters. At the beginning, these machines were controlled by a tape, which carried to the machine the codes. A traditional NC system was composed of:

- tape punch
- tape reader
- controller
- NC machine

NC systems offered some of the following advantages over manual methods of production:

- better control of tool motion under optimum cutting conditions
- improved product quality and repeatability
- reduced tooling costs, tool wear, job set-up time
- reduced time to manufacture the product
- reduced scrap
- better production planning and placement of machining in the hands of engineering.

A Computer Numerical Control machine is a numerical control machine with an on board computer. This computer is often referred to as the Machine Control Unit. The machine functions are encoded into the computer at the time of manufacture. The are not erased when the CNC machine is turned off (similar to the operating system of a desktop computer) [6].

2.2. WHY CNC?

Everyone involved in the manufacturing environment should be well aware of what is possible with sophisticated, computer controlled, machine tools.

The design engineer, for example, must possess enough knowledge of CNC to perfect dimensioning and tolerancing techniques for workpieces to be machined on CNC machines. Manufacturing engineers direct and coordinate the processes for making things from the beginning to the end. The tool engineer must understand CNC in order to design fixtures and cutting tools for use with CNC machines. Quality control people should understand the CNC machine tools used within their company in order to plan quality control and statistical process control accordingly. Production control personnel should be abreast of their company's CNC technology in order to make realistic production schedules. Managers, foremen, and team leaders should understand CNC well enough to communicate intelligently with fellow workers.

It goes without saying that CNC programmers, setup people, operators, and others working directly with the CNC equipment must have an extremely good understanding of this technology. To a large extend, the computer has revolutionized manufacturing technology. Industries are finding that the new manufacturing technology demands well-trained personnel [6].

2.3. ADVANTAGES OF CNC

CNC opens up new possibilities and advantages not offered by the older NC machines:

- Reduction of hardware necessary to add machine functions

- CNC programs can be written, stored, and executed directly at the CNC machine
- Any part of an entered CNC program can be played back and displayed at will
- Many different CNC programs can be stored in the MCU (Machine Control Unit)
- Several CNC machines could be linked together to a main computer
- The programs written via a main computer can be downloaded to any machine in the network. This is called Direct Numerical Control (DNC)
- Several DNC systems can be networked into a larger distributive system [6].

2.4. FINANCIAL REWARDS OF CNC

The manufacturing community turns to CNC technology for the following benefits:

- savings on direct labor
- savings in operator training costs (versus experienced machinists)
- savings in savings shop supervisory costs
- savings due to tighter, more predictable scheduling
- savings in real estate (since fewer CNC machines are needed)
- savings in power consumption (minimum of motor idle time, machine tool) while using a CNC
- savings from improved cost estimating and pricing
- savings due to elimination of costly jig: their design, manufacture and storage
- savings in special tooling design, manufacture and documentation
- reduced inspection time due to CNC's ability to produce better quality parts [6].

2.5. MODERN MACHINE TOOL CONTROLS - THE HEART OF CNC

The most basic function of any CNC machine is automatic, precise, and consistent motion control. Rather than applying completely mechanical devices to cause motion as is required on most conventional machine tools, CNC machines allow motion control in a revolutionary manner. All forms of CNC equipment have two or more directions of motion, called axes. These axes can be precisely and automatically positioned along their lengths of travel. The two most common axis types are linear (driven along a straight path) and rotary (driven along a circular path). Instead of causing motion by turning cranks and handwheels, as is required on conventional machine tools, CNC machines allow motions to be commanded through programmed commands. Generally speaking, the motion type (rapid, linear, and circular), the axes to move, the amount of motion and the motion rate (feedrate) are programmable with almost all CNC machine tools [6].

Accurate positioning is accomplished by the operator counting the number of revolutions made on the handwheel plus the graduations on the dial. The drive motor is rotated a corresponding amount, which in turn drives the ball screw, causing linear motion of the axis.

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

Though a rather crude analogy, the same basic linear motion can be found on a common table vise. As you rotate the vise crank, you rotate a lead screw that, in turn, drives the movable jaw on the vise. By comparison, a linear axis on a CNC machine tool is extremely precise. The number of revolutions of the axis drive motor precisely controls the amount of linear motion along the axis [6].

2.6. HOW AXIS MOTION IS COMMANDED - UNDERSTANDING COORDINATE SYSTEMS

The two most popular coordinate systems used with CNC machines are the rectangular coordinate system and the polar coordinate system. By far, the most popular of these two is the rectangular coordinate system, and we'll use it for all discussions made during this presentation.

Let's relate the coordinate system to the CNC axis motion. Each linear axis of a CNC machine's rectangular coordinate system is broken into increments of measurement. In the inch mode, the smallest increment is usually 0.0001 inch. In the metric mode, the smallest increment is 0.001 millimeter. (By the way, for rotary axes the increment is 0.001 degrees). Each axis within the CNC machine's coordinate system must start somewhere. For CNC purposes, this origin point is commonly called the program zero point (also called work zero, part zero, and program origin) [6].

The program zero point establishes the point of reference for motion commands in a CNC program. This allows the programmer to specify movements from a common location. If program zero is chosen wisely, usually coordinates needed for the program can be taken directly from the print.

With this technique, if the programmer wishes the tool to be sent to a position one inch to the right of the program zero point, X1.0 is commanded. If the programmer wishes the tool to move to a position one inch above the program zero point, Y1.0 is commanded. The control will automatically determine how many times to rotate each axis drive motor and ball screw to make the axis reach the commanded destination point. This lets the programmer command axis motion in a very logical manner [6].

With the examples given so far, all points happened to be up and to the right of the program zero point. This area up and to the right of the program zero point is called a quadrant (in this case, quadrant number one). It is not uncommon on CNC machines that end points needed within the program fall in other quadrants. When this happens, at least one of the coordinates must be specified as minus [6].

2.7. TELLING THE MACHINE WHAT TO DO - THE CNC PROGRAM

Almost all current CNC controls use a word address format for programming. (The only exceptions to this are certain conversational controls.) By word address format, we mean that the CNC program is made up of sentence-like commands. Each command is made up of CNC words. Each CNC word has a letter address and a numerical value. The letter address (X, Y, Z, etc.) tells the control the kind of word and the numerical value tells the control the value of the word. Used like words and sentences in the English language, words in a CNC command tell the CNC machine what it is we wish to do at the present time [6].

A CNC programmer must be able to visualize the machining operations that are to be performed during the execution of the program. Then, in step by step order, the programmer will give a set of commands that makes the machine behave accordingly.Without visualization ability, the programmer will not be able to develop the movements in the program correctly. An experienced programmer should be able to easily visualize any machining operation taking place [6].

Each instruction given within a CNC program is made up of one command. A CNC command is made up of CNC words. The CNC machine will execute a CNC program explicitly. If there is a mistake in the program, the CNC machine will not behave correctly.

Program example:

O0001 (Program number)
N005 G54 G90 S1200 M03 (Select coordinate system, absolute mode, and turn spindle on clockwise at 1200 RPM)
N010 G00 X-.25 Y-.25 (Rapid to X-.25 Y-.25 location)
N015 G43 H01 Z.1 M08 (Instate tool length compensation, rapid in Z to clearance position above surface to drill, turn on coolant)
N020 G01 Z-.25 F10. (Feed into the part Z-.25 at 10 inches per minute)
N025 Y3.25 (Feed tool to Y3.25 location)

N030 X4.25 (Feed tool to X4.25 location)
N035 Y-.25 (Feed tool to Y-.25 location)
N040 X-.25 (Feed tool to X-.25 location)
N045 G00 Z.1 M09 (Rapid out of part to Z.1, turn off coolant)
N050 G91 G28 Z0 (Return to reference position in Z)
N055 M30 (End of program command) [6]

While the words and commands in this program probably do not make much sense, but the important thing is the sequential order by which the CNC program will be executed. The control will first read, interpret and execute the very first command in the program. Only then it will go on to the next command. Read, interpret, execute and then on to the next command. The control will continue to execute the program in sequential order for the balance of the program [6].

CHAPTER 3

LITERATURE REVIEW

Kobeloglu and Cetinkaya mentioned that most of the machine tools, which have a radical effect on the growth of manufacturing worldwide, can be controlled by computers. This controlling method is called CNC (Computer Numerical Control). The CNC machine tools are the machines that are used for successful design and manufacturing processes in a wide range of sectors. The CNC milling, CNC turning, and CNC drilling machines are the examples of CNC machine tools [7].

Newman et al stated that the first NC (numerical control) machine was developed in the 1950s and CNC machines play a vital role in production today. According to Swamidass and Winch, CNC machines can now be used to produce a colossal range of geometrically complex components, from micro- to multi-meter sized parts, from different materials such as wood, aluminium and titanium alloys, etc. CNC machines are the major contributors to the production capacity of the enterprises in the field of manufacturing. Al-Kindi and Zughaer revealed in their study that CNC machines are now being consumed in more than 70% of factories across the USA and the UK, and are currently considered as the heart of machining workshops [8-10].

Yea et al. Stated in their study that today’s product designer is being asked to develop high quality, innovative products at an ever increasing pace. Design is a purposeful process involving creative thinking and problem solving. Design and knowledge have a very strong connection: recollection and application of knowledge can be considered as a straightforward and practical design process. According to Xu and Newman, the goal of the next generation of CNC machines is to be portable, interoperable, and adaptable [11,12].

Peng Zhao et al. explained that the traditional interface closure CNC system makes functional expansion and architecture alteration impossible. It cannot meet the developing demand of modern technology toward openness, flexibility, and intelligence [13].

Haridy et al. evolved in their study that the Computer Numerical Control (CNC) involves machines controlled by electronic systems designed to accept numerical data and other instructions, usually in a coded form. CNC machines are more productive than conventional equipment and consequently produce parts at less cost and higher accuracy even when the higher investment is considered [14].

According to the research of Haridy et al., over the last 50 years, computer numerical control (CNC) technology has been one of the major developments in manufacturing. This led to a conspicuous impact in manufacturing processes. The implementation of numerical control has been developed from simple automatic positioning machines controlled by instruction on punched tape or floppy disk to computerized numerical control in which a micro-computer is used to perform all the numerical control tasks [14].

Haridy et al. also elaboraed in their study that the rapid advancement in NC machine technology has been accelerated by dramatic increases in machine programming and computational control. These advances have provided the manufacturing industry with a new and greater degree of freedom in designing and manufacturing different industrial products. Due to this new freedom, along with other related enhancements, significant changes in manufacturing methodologies have been adopted such as the use of computer aided manufacturing and flexible manufacturing systems. The part program for a product manufactured by CNC machines is a very important stage in the manufacturing process. Therefore, many techniques have been developed to generate CNC part programs, for example using developed software and computer aided design/manufacturing (CAD/CAM) systems [14].

Gordon and Hillery, in their study; In order to conduct machining tests on a composite material, a low cost, high-speed cutting machine was built using linear motors. The rotary drive motors and ballscrews were used to achieve table motion. Kim and Kim designed and manufactured the prototype of an inexpensive CNC lathe machine to facilitate the CNC education in Korea. The machining system was developed using a three-axis CNC milling/drilling machine, a microprocessor, system software, and an automatically programmed tools (APT) processor. Tseng et al. stated that a small scale construction and fundamental features with simple software format make the CNC system a versatile educational tool [15-17].

Zhang et al., introduce a self-made 5-axis machine tool which is applicable to complex 3D micro-milling and also a CNC system that can implement G-code is researched. Many countries have developed a lot of 3-axis micromilling machine tools. However research of 5-axis micro-milling machine tools was still less which can be applicable to the complex 3D micro-milling. For this, we developed a 5-axis micro-milling machine. In the research we constructed a precise 5-axis micromilling machine tool of compact size and low cost (less than 1/10 of the cost of precise milling machines on the market), which was available for machining complex 3D meso-parts [18].

Nae and Andrei mentioned in their work that the CNC milling machine is basically a computer guided machine tool, which can be used to create complex shape parts demanded by latest technology. A milling machine can be very complicated and can have up to 9 axes. CNC milling machine is able to support translational or rotational movements and therefore it can create very complex parts with an improved surface finish [19].

According to BU Ping et al., CNC simulation will improve the efficiency of CNC machine tools and ensure the correction of NC code. It is difficult to promote the application of simulation algorithm to specific machine tools. A general description of CNC machine tools kinematic chain is proposed in this paper. NC code can be checked by workpiece coordinate system simulation effectively; hence a general conversion algorithm from machine coordinate system to workpiece is discussed. In recent years, the multi-axis CNC machine tools are widely used in machining molds and complex parts since they have many advantages. It can complete complex surface machining, and several working procedures can be done in a single clamping with it. Generally speaking, the multi-axis CNC machine tools contain one or more rotary axes; the movement is much more complex [20].

Hanoi explained that nowadays CNC machines include several types: 2-axis CNC machine, 3-axis CNC machine, 4-axis CNC machine, 5-axis machine, etc. The number of the axis of a CNC machine implies the number of degree of freedom that the controller of the machine can be simultaneously interpolated. If the axis number increases, the machining efficiency, effectiveness and accuracy will increase; however, it requires more complex techniques in control programming process. Five-axis CNC milling machine has been proven to be the most efficient tool for fabricating products of complex geometry which may include numerous free form surfaces. The products are widely used in several high technology industries such as the aerospace industry, the automotive industry, the shipbuilding industry, etc. Using 5-axis CNC systems integrated with CAMs, end-to-end component design and manufacturing is highly automated [21].

According to Xia and Ge, it is well known that CNC machining of sculptured surfaces using flat-end cutting tools and 5-axis machines offers the benefits of higher material removal rates, better accessibility, and reduced number of set-ups. The quality of the machined surface is determined by geometric factors as well as kinematic, dynamic, and thermal properties of the machine tool. A vast amount of researeh has been done in the area of 5-axis tool path planning in order to achieve the competing goals of higher accuracy for manufactured surface and reduced machining time. Presents an approach to 5-axis CNC tool path generation for sculptured surface machining with a flat-end cutter. Rational Bezier and B-spline motions are used to plan cutter motions so that an exact representation of the effective cutting shape can be obtained. The exact representation leads to an accurate computation of the scallop curve generated by two adjacent tool paths. Two examples are given to show how this result can be used to accurately plan and verify tool paths for 5-axis CNC milling of sculptured surfaces. [22].

Huo et al. explained that the advantages over the conventional ultraprecision machines may include: small footprint and energy-efficient; ease of localized environmental control and thus low operational costs; Mobility. Advantages over micro/meso machines commonly adopted in micro factories can be summarized as: A better machining envelope for covering a full spectrum of micro-machining applications; Higher static and dynamic stiffness, hence rendering better machining accuracy and surface quality; Key machine components with high performance and matured technologies available; Easy to integrate with other subsystems, including components/tools handling system, condition monitoring, micro tooling, and FTS, etc. Therefore, a 5-axis ultraprecision micro milling machine with a small footprint is desirable to fill the gap for the demanding need of manufacturing 3D complex micro mechanical precision parts with nanometer surface finish [23].

Rklundy et al. mentioned that the trend towards productivity improvement while the components to be machined are becoming more complex is leading to the extended application of five-axis machining, higher spindle speeds and, consequently, higher feed rates, which are all difficult to handle with existing CNC technology [24].

According to Rauch et al., the manufacturing area has benefitted from various progresses over the last decades: the equipment has become faster, smarter and safer to face today’s global challenges. However, CNC programming is somehow still based on dated practices and habits. This mostly comes from the use of ISO 6983 data standard, as known as G-codes [25].

Lee & Bang stated that the currently used language named G-code only has data of operations of machine tools and it focuses its description to tool centre motions. Hence, many data for machining departments, such as tool and workpiece list, job list, and operators’ manual, are also required [26].

Xu, X.W., et al stated that, as the automation progresses in the manufacturing plants, the number of specialized products increase rapidly. Furthermore, there is an increased need for engineers trained in CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing) for process design and operation. This development necessitates detaill and systematic education in CAD/CAM and educational numerical control machine tools. Nassehi et al. explained that the programming of multi-axis mahines has become increasingly complex to the point where computer aided process planning (CAPP) and computer aided manufacturing (CAM) software packages are required to achieve any functionality beyond very simple machining tasks. The performance of Computer aided design (CAD)/(CAM)/CNC chain can have a significant effect on the competitiveness of the manufacturing enterprises, comprising CNC machines. Kim and Kim, in theirstudy mentioned that the different components of the CAD/CAM/CNC chain can exchange information with one another regardless of their native standards [16, 27, 28].

According to Pandian and Pandian, workshop or laboratory education in CAD/CAM software and CNC machine programming and operation is very important in order to teach mechanical, manufacturing, and production engineering students at the undergraduate level. However, in many engineering educational institutions the CAD/CAM and Manufacturing Technology Laboratories and workshops are equipped mainly with large commercial CNCmachines, which are quite expensive andare overdesigned, considering the pedagogical needs of undergraduate students. They demand costly annual maintenance or any sudden breakdown and are time-consuming, as they are difficult to operate [29].

Yusof et al. mentioned in their study that today, with the use of computer technologies and communication technologies in the manufacturing industries, manual and semi-automatic methods are largely being replaced by Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) to implement concurrent engineering. Widespread CADCAM systems will reduce human interaction and the result, should be increased production, reduced costs and better quality of product. CNC machines now, utilize a variety of cutting technologies such as multi turrets and multi spindles in various axial configurations increasing the level of complexity compared to the machines of the previous decade [30].

Schmitz and Ziegert explained in their study that the post-process testing includes those tests which are performed after machining has been completed. The most popular post-process inspection tool is the coordinate measuring machine (CMM). Other post-process methods used to evaluate a CNC machine tool's contouring accuracy involve the use of either master parts or well-defined contours. One example of this technique is the use of standard part paths, such as the part program corresponding to the National Aerospace Standard test part 979 (NAS979), to machine a master part. This part can then be measured to evaluate flatness, squareness, parallelism, roundness, etc. A similar, but somewhat more efficient method has been termed master part tracing [33].

CHAPTER 4

DESIGN AND PROTOTYPE

4.1. DESIGN OF THE MACHINE

In this stage, the machine will be design to the desire design. The initial design will be drafting or sketching then when the design is approved, then step to the next stage of design which is draw the design using the software SolidWorks. Finally, come out with the complete drawing.

Before start the sketching, there are some criteria that must be decided. Firstly, decide the length of travel. The length of travel is the length of X, Y, and Z axis move from one point to the other point. The X axis move left - right, Y axis move front - back, Z axis move up - down. The travel length that have been decided is X axis 140 cm, Y axis 62 cm and Z axis 50 cm.

The basic model of 5-axis desktop CNC milling machine design was made using SolidWorks CAD programme. Figure 4.1 shows the basic 3D drawing of the desktop CNC machine and Table 4.1 shows the names of all the parts numbered in figure 4.1.

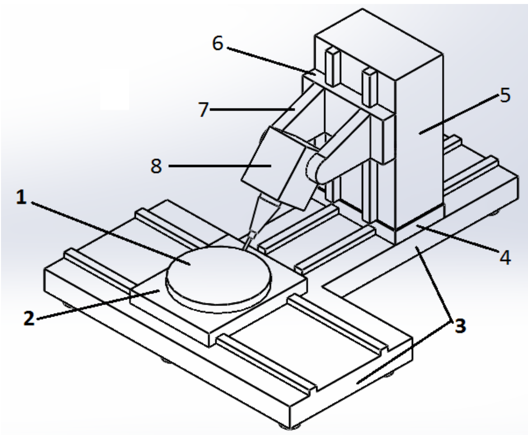


Figure 4.1. 3D drawing of 5-axis desktop CNC machine.

Table 4.1. Names of the machine´s parts.

Number	Name
1	Rotary Table (C-axis)
2	Table Saddle (X-axis)
3	Bed
4	Column Saddle (Y-axis)
5	Column
6	Swivel Head (Z-axis)
7	Yoke
8	Swivel Spindle Head (A-axis)

The selected CNC machine for this study is comprised of three linear axes (X, Y, and Z), and one rotary and swivel axis (C and A respectively). Figure 4.2 points out all the five axes of the desktop CNC milling machine.

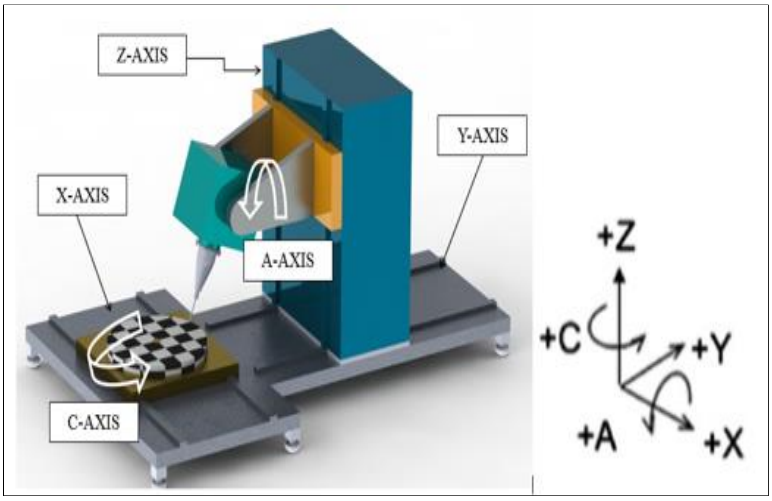


Figure 4.2. 3D CAD model showing all the fives axes.

The figure 4.3 shows the final model of the desired 5-axis desktop CNC milling machine and the figure 4.4 shows the different views of the machine´s model. Whereas, the Figure 4.5 shows the position of the spindle exactly at 180 degrees.

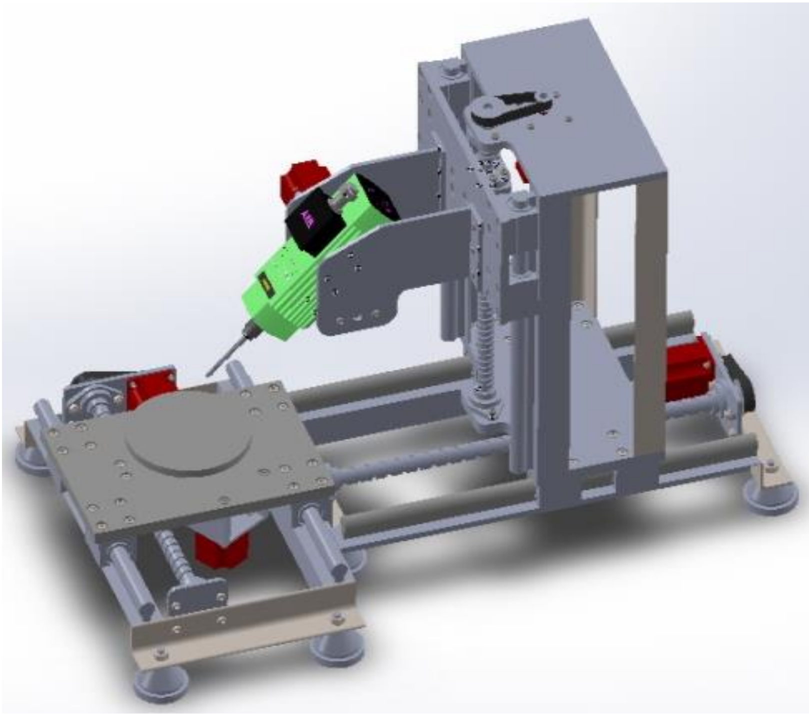


Figure 4.3. Detailed 3D CAD model of desktop CNC milling machine.

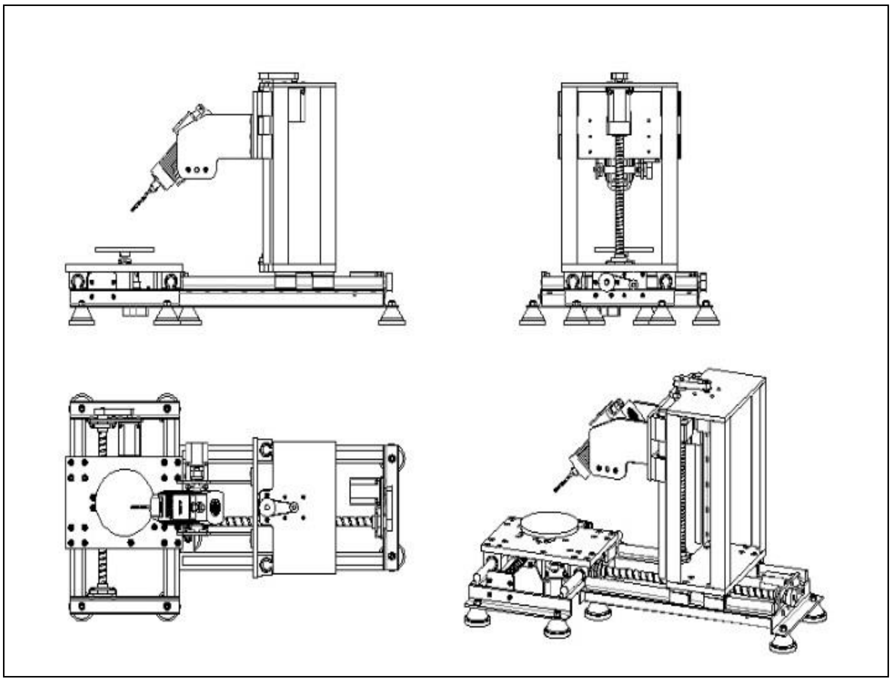


Figure 4.4. Front, Top, Side, and Isometric view of the machine.

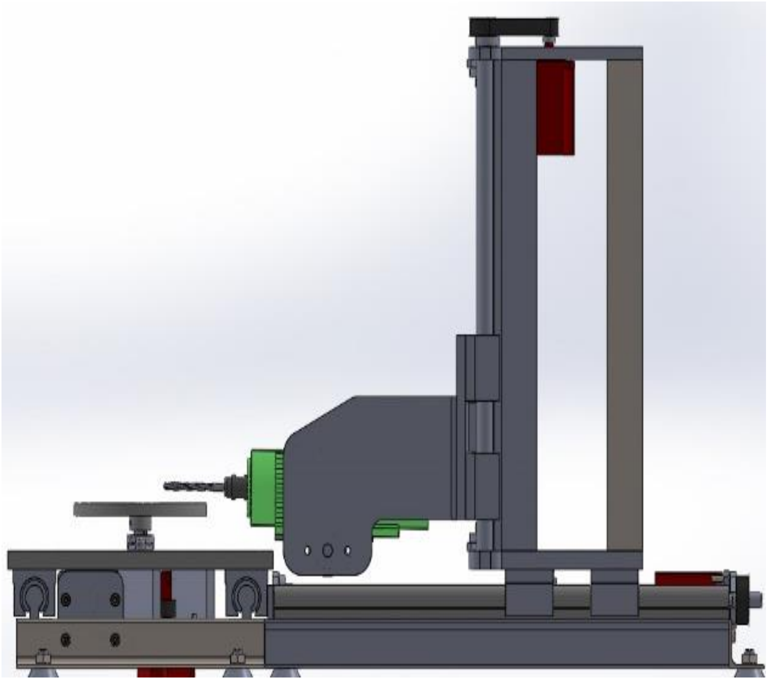


Figure 4.5. Sideview of the machine.

4.2. MAKE-UP OF THE MACHINE

The frame of the machine was built up by 6 mm thick mild steel sheet and supported by using mild steel 50 x 50 hollow box section and 60 x 60 L shape profiles. The thickness of the L-profile was 6 mm (millimeters), where as the thickness of hollow box section was aboout 3 mm.Totally, 3 meters of L-profile and about 4 meters of hollow box section was used. The linear guide rails and the linear bearings were used for the movement of the table on all the linear axes. The screw rods made up of stainless steel were used to assist the motion on all three linear axes.

The stepper motors were connected parallel to the screw rods with the help of timimg belts and timing pulleys. The diameter of the motor´s shaft was 8 mm, where as the diameter of the ball screw was reduced from 16 mm to 12 mm. The timing pulley which was smaller in size was mounted on the motor´s shaft while the larger pulley was inserted in the ball screw with the and the twere attached. In order to operate the machine at high speeds, the ball bearings with their housings were attached at both ends of the ball screws. The main purpose of ball bearings is to reduce the rotational friction and support the radial and axial loads. The structure of the machine was supported by eights wivel feets..

The spindle motor, carrying the cutting tool was mounted on the A axis of the machine. The spindle is able to swivel 360 degrees around the axis. The main purpose of the A axis is to machine complicated parts from the sides. Figure 4.6 shows the detailed 3D model of the designed machines, pointing out the parts with numbers, as mentioned in the parts list (Table 4.2).Table 4.2 shows the list of names and quantity of all the necessary euipments for constructing the prototype of desktop 5-axis CNC milling machine. The motion on both A and C axes was also delivered with the help of timing belt and timing pulleys. In the case of A and C axes, the linear shafts were used instead of the screw rods. The shafts were rigidly joined with rotary table and spindle motor to successfully and efficiently deliver the motoin. The ball bearing with its housing was used on both sides of the shaft and the thrust ball bearing was used on C axis to keep the rotary table on the axis.

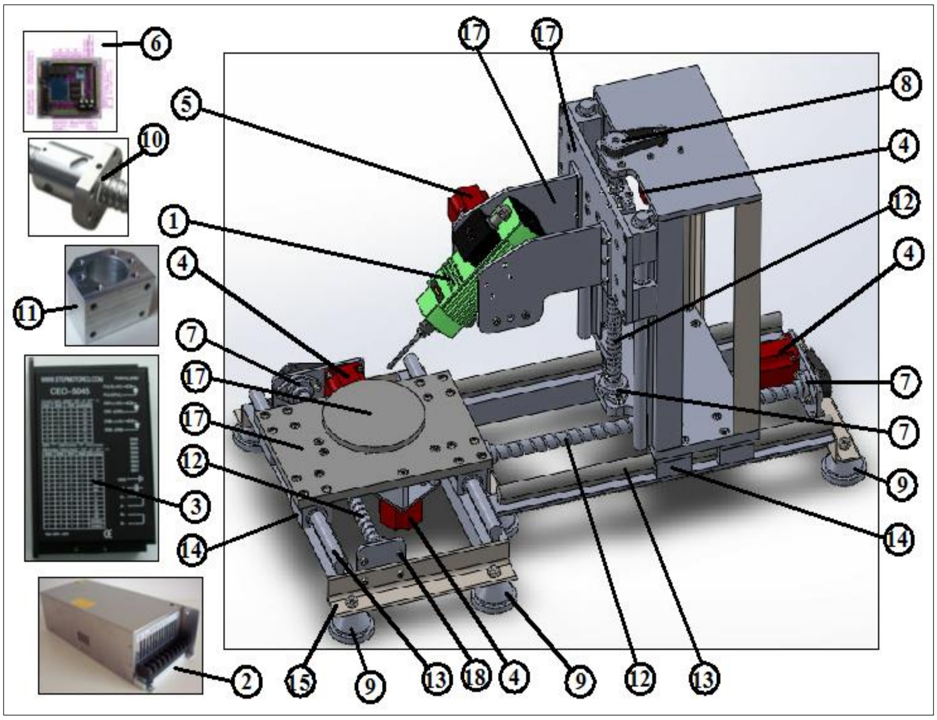


Figure 4.6. 5-axis milling machine with all the required equipments.

Table 4.1. List of equipments′ names and quantity.

S. No.	Equipment Name	Quantity
1	Spindle Motor	1
2	Power Supply	1
3	Motor Driver	5
4	Thrust Ball Bearing	1
5	Stepper Motor 3Nm	5
6	5-Axis CNC Control Card	1
7	Bearing	10
8	Machine Feet	10
9	Ball Screw Nut	3
10	Nut Housing	3
11	Ball Screw	2m
12	Linear Shaft	3m
13	Ball Bearing & Bearing Holder	12
14	Spindle Motor Inverter	1
15	Timing Belts and Pulleys	5
16	Linear Shaft	1m
17	L Profie	3m
18	Hollow Box Section	4m
19	Fasteners	A.R.

The two axes (X and C) of the 5-axis desktop CNC milling machine were constructed and assembled first and shown in figure 4.7.

Figure 4.7. Two axes of the constructed machine.

After constructing the linear X axis and rotary C axis, rest of the three axes (Y, Z, A) were constructed. Figure 4.8 and fiure 4.9 shows the full and final shape of the constructed 5-axis desktop CNC milling machine.

Figure 4.8. Front view of the fully constructed 5-axis CNC machine.

Figure 4.9. Back view of the full constructed 5-axis CNC machine.

Figure 4.10. shows the long table or platform rather than the round shaped one attached with this small-scale 5-axis CNC milling machine. The purpose of faciliating this machine with two different tables (round & rectangle) is to make it machine any kind of small workpiece with several shapes and sizes.

Figure 4.10. Long platform of 5-axis CNC machine.

CHAPTER 5

CONTROL METHODOLOGY

5.1. CONTROLLING METHOD

The stepper motors were used to deliver the motion with the help of timing belt drives on all the five axes. A CNC milling machine which uses stepper motors is easier to be built and accessible even for home made applications. The stepper motors have the great advantage of not needing a feedback from the process while providing high precision and repeatability [16]. The ball screws and screw nut was used on all three linear axes (X, Y, and Z). The electronic 5-axis ontrol card was taking the command from the computer and sending it to the stepper motors through step motor drivers. The signal which was coming from the computer, basically guiding the direction of motion of the desired stepper motor. The interface, five stepper motor drivers, power supply, and inverter were connected with the control card and developed a control unit. The flow chart and control unit connection mechanism are shown in Figures 5.1 and 5.2.

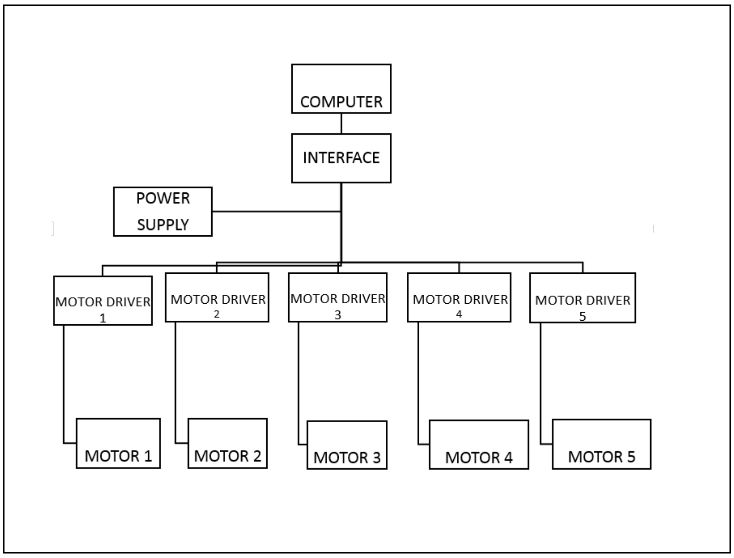


Figure 5.1. Control unit flow chart.

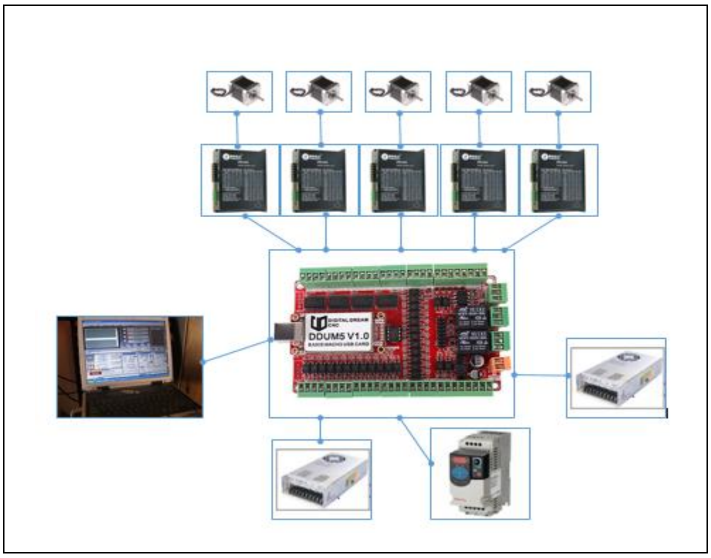


Figure 5.2. Control unit connection mechanism.

Figure 5.3 shows the wiring and connections between the motors, drivers, interface, power supply, spindle motor and its interface.

Figure 5.3. Wiring and connections.

5.1.1. Stepper Motor

Five stepper motors with same specifications were used. The specifications of the used stepper motors is given in Table 5.1.

Table 5.2. Stepper motor specifications.

Step Angle	1.8°
NEMA	24
Ampere	3.0 A
Inductanse	3.0 mH
Resistance	0.9 ohms
Holding Torque	3 Nm
Phase Number	2
Weight	1.1 Kg
Length	80 mm
Number of wires	8

The signals from the amplifiers are given to the stepper motors to produce movements in the all the directions (X, Y, Z, A, C). The number of pulses per second determines the actual speed of rotation. The current of the signal issued by the microprocessor must be sufficiently amplified before it is fed to the stepping motors which actuate the axis of motion. The drive module must be capable of supplying the output without distorting the switching sequence required to run the stepping motor. The stepper motor shaft is coupled to a screw rod that is connected to the work slide through a nut. The rotation of the stepper motor shaft results in linear motion of the slide.

The pulse rate determines the cutting velocity. The stepping motors used for this system are the two-phase type. The common terminals of the stepper motor are fed with a 36 V supply for all the axes´s motors. The variable resistance may be used to get the correct drop across the corresponding terminals. The microprocessor chip acts as a buffer while double inverting the logic levels supplied to it from the microprocessor. The main drive corresponds to the motor that drives the spindle. The Figure 5.4. shows the stepper motors used in this study, while the figure 5.5. shows the 2-dimensional view of the motor along with the dimensions and wiring connection mechanism.

Figure 5.4. Stepper motors.

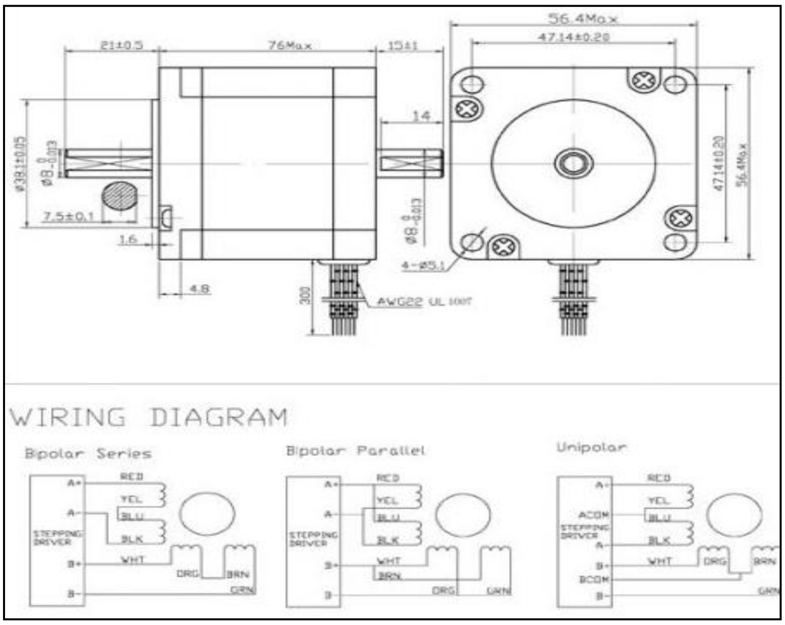


Figure 5.5. Stepper motor dimensions and wiring diagram.

The open-loop control means that there is no feedback and uses stepping motors for driving the leadscrew. A stepping motor is a device whose output shaft rotates through a fixed angle in response to an input pulse. The accuracy of the system depends on the motor's ability to step through the exact number. The frequency of the stepping motor depends on the load torque. The higher the load torque, lower would be the frequency. Excessive load torque may occur in motors due to the cutting forces in machine tools. Hence, this system is more suitable for cases where the tool force does not exist. The stepping motor is driven by a series of electrical pulses and each pulse causes the motor to rotate a fraction of one revolution.

Closed-loop NC systems are appropriate when there is a force resisting the movement of the tool/workpiece. The encoder consists of a light source, a photo detector, and a disk containing a series of slots. The encoder is connected to the leadscrew. As the screw turns, the slots cause the light to be seen by the photo detector as a series of flash which are converted into an equivalent series of electrical pulses which are then used to characterize the position and the speed. The equations remain essentially the same as open-loop except that the angle between the slots in the disk is the step angle. Both the input to the control loop and the feedback signals are a sequence of pulses. In this study, a open-loop system was used for the machining.

5.1.2. Driver Card

Five driver cards (one for each motor) were used. The task of the drive control circuit is to control the information between the computer and the driver circuit. By controlling the driver circuit according to the computer´s command, which runs the engine or steps of motor, direction of rotation is transmitted to the driver circuit. The communication is done via control program of the control circuit and the parallel port (LPT). Figure 5.6. shows the stepper motors´ drivers and Table 5.1 shows the characteristics of the motors´ drivers used in this study.

Figure 5.6. Stepper motor drivers.

Table 5.3. Motor driver characteristics.

DC power input type	12V~36VDC , AC power input : 23V~24V
Output current	0.3A-2.0A
Mircostepping	1(1.8º)、1/2、1/4、1/8、1/16、1/32、1/64、1/128
Pulse/rev	200,400,800,1600,3200,6400,12800,25600
Dimensions	96mm×60mm×24.5mm
Weight	<200g.
Working environment	Temperature-15～80℃

5.1.3. Control Card (Interface)

The five axis control card was used to connect all the motor drivers. The job of the control card is to take the signal in the form of codes, from the computer and then send it to the motor driver. Figure 5.7. shows the picture of 5-axis control card.

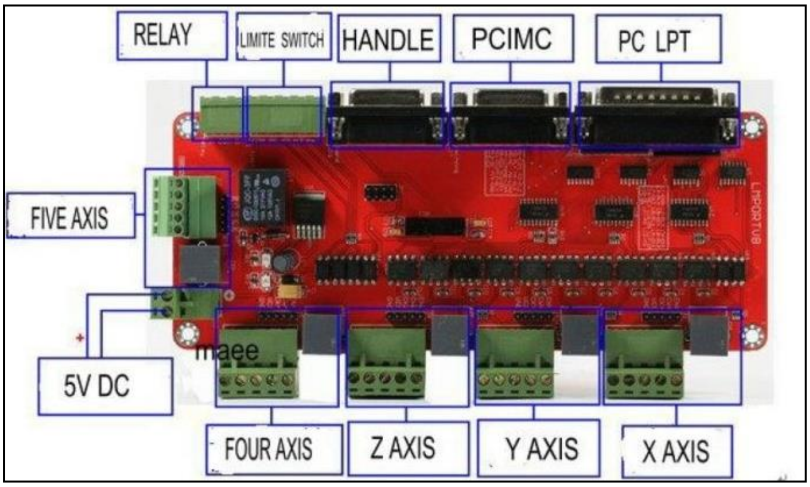


Figure 5.7. 5-axis control card (Interface).

5.1.4. Spindle Motor

In this study, Hertz brand (HMA42C) Spindle Motor was used. The spindle has a power of 0.75 KW and a speed range of 50 to 18000 rpm (revolutions per minute). The speed of the spindle was controlled manually. Figure 5.8 shows the picture, figure 5.9 shows the 2D view and the dimensions, and table 5.2 shows the charcteristics of the spindle motor used in this study.

Figure 5.8. Spindle motor.

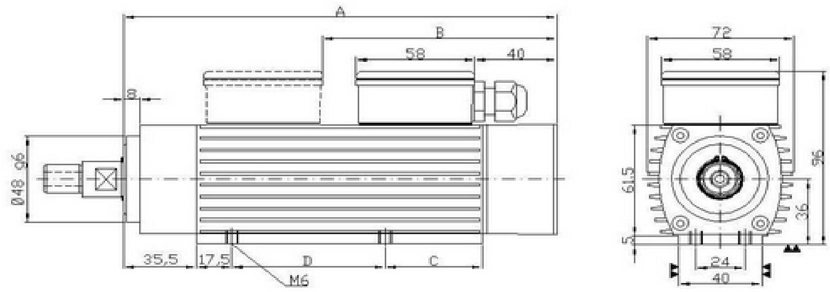


Figure 5.9. Spindle motor dimensions.

Table 5.4. Spindle motor characteristics.

Type	HMA42C
Serial	04-13
Power	0.75 KW
Energy	1.00 Hp
Frequency	300 Hz
Rotational Speed	18000 rpm
Current	3.70/2.10 A
Voltage	220 V
Weight	2.9 Kg
Angle	CosΦ 0.71
Collet Type	ER 16

5.1.5. Spindle Motor Inveter

0.75 KW 4M AC inverter was used. Inverter means frequency converter. The Inverter is used to either increase or decrease the speed of the spindle motor. Figure 5.10 shows the picture of spindle motor inverter which was used in this study.

Figure 5.10. Spindle motor inverter.

5.1.6. Collet

In this study, ER16 collets were used. A set of collets used is shown in figures 5.11 and 5.12.

Figure 5.11. ER16 collet set.

Figure 5.12. ER16 collets.

5.1.7. Power Supply

In this study, a 36 volts NES-350 power supply was used. Figure 5.13 shows the picture and table 5.4 shows the characteristics of the power supply used to control the 5-axis CNC machine.

Figure 5.23. Power supply.

Table 5.5. Power supply characteristics.

Series	NES-350
Supply Type	Enclosed
Total Power	349.2 W
Number of Outputs	1 Output
Form Factor	Internal
Fan	Yes
Input	180~264, 90~132 VAC
Output 1	36 VDC
Output	9.7 A
Operating Temperature	-20 to 60 °C
Length	8.46 in.
Width	4.52 in.
Heigh	1.97 in.
Safety	EN, UL
Input Range	254 to 370 VDC
Voltage	36 V
Current	10 A
R & N	240 mV**0**
Efficiency	88%

5.1.8. CAD Programme

In order to automatically generate the G and M codes using CAM programme, the desired shape of the workpiece is need to be modelled first in any of the CAD programmes (i.e. SolidWorks, Pro Engineer, CATIA, etc). Figure 5.14 shows the example of a gear modelled in Pro Engineer programme.

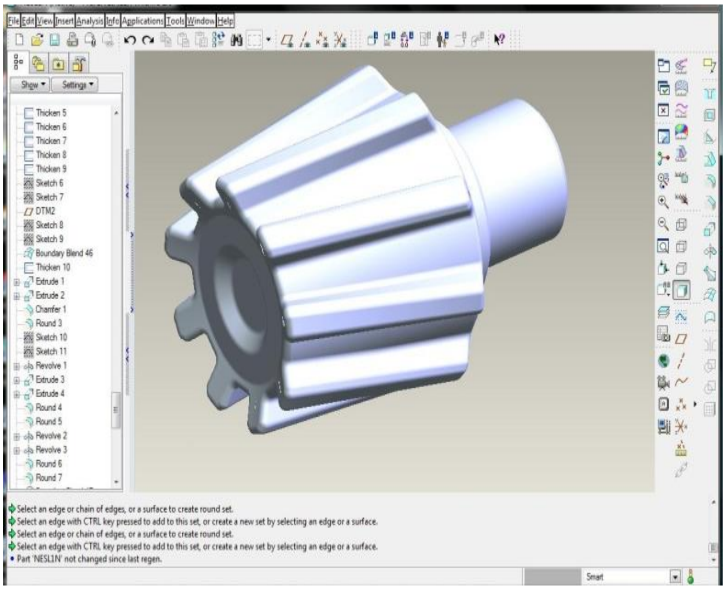


Figure 5.34. Gear shape modelled in Pro Engineer [34].

5.1.9. CAM Programme

To generate the G and M codes for manufacturing the desired part any of the CAM programmes (Mastercam, SolidCAM, Catia CAM, etc) can be used. Planning for writing a CNC program is very important. The first step to be taken before writing any CNC program is to thoroughly study the part drawing. The drawing indicates what the part looks like, its material, precision, surface finish, material treatment (if any), and many other requirements. Important factors in the decision to utilize CNC operations in the part's manufacture include the quantity of parts to be machined, the part quality, the tooling costs, the holding device design and manufacturing and the cost running the CNC machine.

Based on the requirements of the part drawing a method of manufacturing has to be written. Among other things it includes the order and the ways of machining the part. Ordinarily it is the programmer's responsibility to develop the order of operations (operation sheets), which later will be used in writing the program. Next step is to decide on a CNC machine to be used. The programmer selects a machine based on its ability to optimize the cutting operations required to manufacture the part. Availability as well as the capacity of the CNC machine must be considered. It is the programmer's job to decide how the part is to be held during machining.

Acting on a sketch or a formal drawing, the setup person carries out the task of securing the part to the table of the CNC machine. It is important that the part does not move or become disengaged from the machine table during the machining process. The programmer continues with the job of deciding on the machining sequence and the tooling needed. In general, machining should proceed in the following order:

- rough turning
- rough boring
- drilling & tapping
- finish turning
- finish boring
- finish reaming

The cutting sequence, together with the required cutting tools, is documented. The holding devices and the cutting tools must be available at the time the job is scheduled to run. Based on the material of the part, tooling, finish requirements, the programmer decides on cutting parameters: spindle speed and feed rate. These values he uses later when he writes the program.

After all the planning is completed the programmer is ready to write the program. Based on the decisions he made while planning the job the programmer establishes:

- programming origins in relations to the machine origins for X, Y, Z coordinates
- mode of programming: absolute or incremental
- units of programming (inch or metric)
- tool change position

After finishing writing the program the programmer will transfer the program, together with the setup instructions, to the machine. A person (setup man) who is responsible for setting up and, sometimes, for the operation of the machine, will act upon the instructions of the programmer and set up the job. He will:

- load the program into the control
- set the tools
- set the holding device
- get tool offsets
- prove-out the program
- do partial inspection
- adjust cutting parameters
- report any problems to the programmer

The programmer will actively participate in debugging the program for any discrepancy and make the required adjustments needed for the job to run trouble free. A completed program is ready for production only if it is capable of producing quality parts in the time projected.

5.1.10. Control Programme

To operate this CNC machine automatically, Mach3 control programme was used. The G and M codes which were obtained from MasterCAM programme were uploded in Mach3 programme, then with the help of this programme the signals were sent to the stepper motor through the control card and the stepper motor driver, and the workpiece was machined in to the required shape. Mach3 is an economical and easy to operate control programme with many advanced features. The Mach3 programme main window is shown in Figure 5.15:

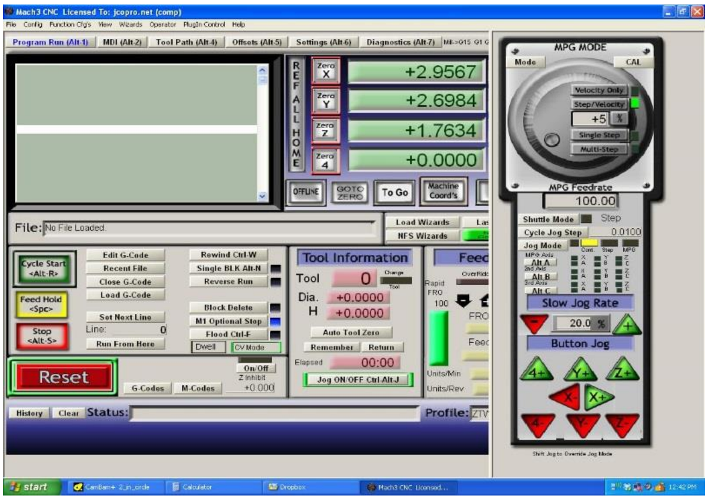


Figure 5.15. Mach3 programme main window [36].

- Mach3 turns a typical computer into a CNC machine controller.
- It is very rich in features and provides a great value to those needing a CNC control package.
- Mach3 works on most Windows PC2's to control the motion of motors (stepper & servo) by processing G-Code. While comprising many advanced features, it is the most intutive CNC control software available.
- Mach3 is customizable and has been used for many applications with numerous types of hardware.

Here are some of the basic features and functions provided by Mach3;

- Converts a standard PC to a fully featured,6 axis CNC controller
- Allows direct import of DXF,BMP,JPG,and HPGL files through LazyCam
- Visual G code display
- Generates G code via LazyCam or Wizards
- Fully customizable interface
- Customizable M-Codes and Macros using VBscript
- Spindle Speed control
- Multiple relay control

- Manual pulse generation
- Touch screen ability
- Full screen eligibity [36]

Figure 5.16 shows the offsets window in the Mach3 control program.

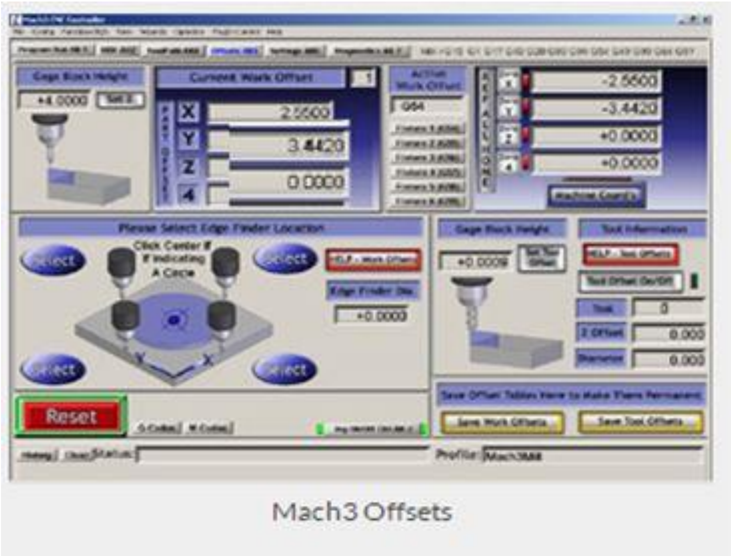
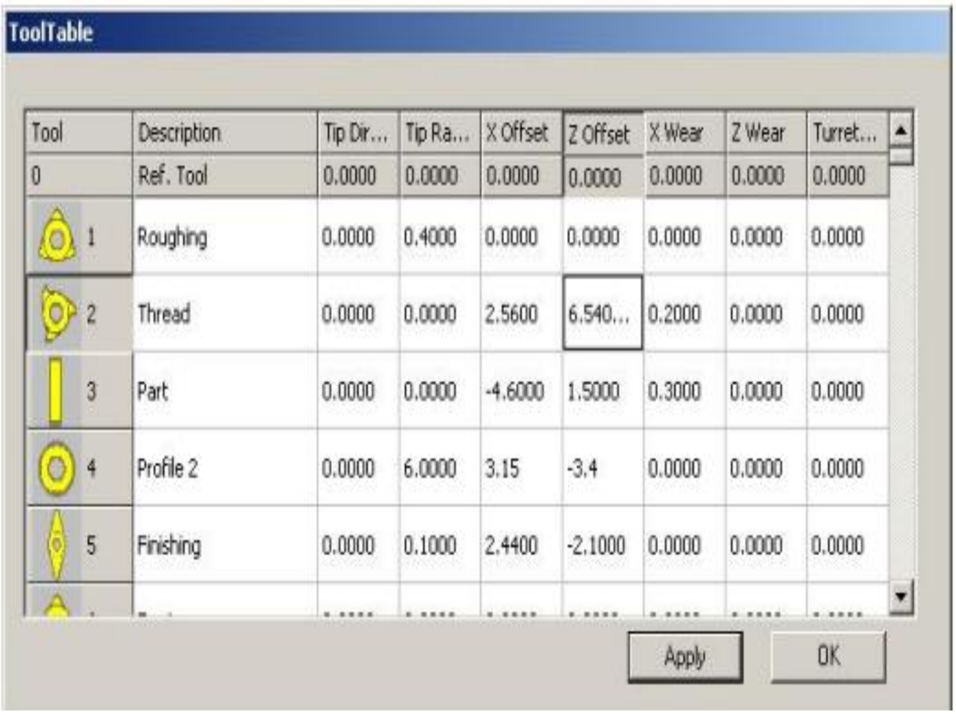


Figure 5.46. Mach3 offsets window [36].

Mach3 has successfully been used to control the following types of equipment:

- Lathes
- Mills
- Routers
- Lasers
- Plasma
- Engravers
- Gear cutting

Figure 5.17 shows the table in Mach3 program which can be used for the selection of suitable cutting tool during the machining process.



ToolTable

Tool	Description	Tip Dir...	Tip Ra...	X Offset	Z Offset	X Wear	Z Wear	Turret...
0	Ref. Tool	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	Roughing	0.0000	0.4000	0.0000	0.0000	0.0000	0.0000	0.0000
2	Thread	0.0000	0.0000	2.5600	6.540...	0.2000	0.0000	0.0000
3	Part	0.0000	0.0000	-4.6000	1.5000	0.3000	0.0000	0.0000
4	Profile 2	0.0000	6.0000	3.15	-3.4	0.0000	0.0000	0.0000
5	Finishing	0.0000	0.1000	2.4400	-2.1000	0.0000	0.0000	0.0000

Apply OK

Figure 5.17. Tool table [36].

It should be noted that milling and turning operations are totally different from each other. Figure 5.18 shows the difference between the milling and turning operations.

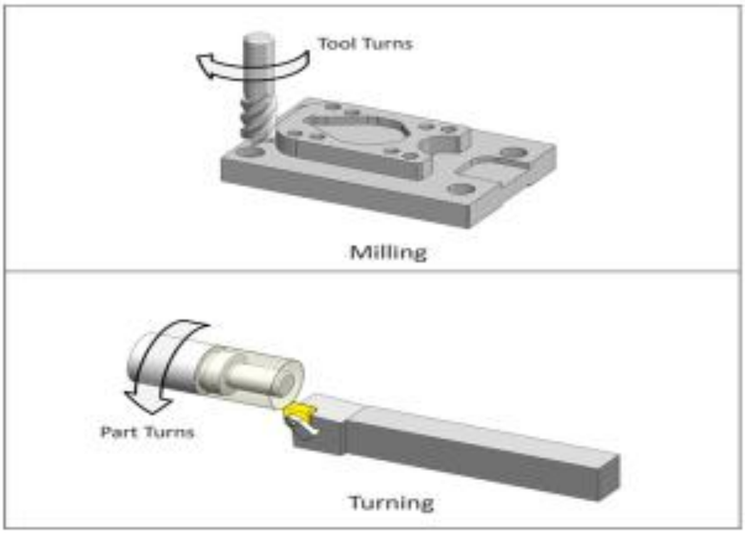


Figure 5.18. Difference in operations [36].

The desired machining operaion can be selected and performed using Mach3 program. The machine which is designed and constructed in this study is able to do all the operations shown in the figure 5.19.

Figure 5.19. Selection of operations window [36].

CHAPTER 6

RESULTS AND DISCUSSION

6.1. MOTOR TURNING

First of all, it was very important to make the arrangements and settings of steps per unit, step pulse and Dir pulse for the motors of all the five axes. The Figure 6.1. shows the x-axis motor movement profile and also the other arrangements in Mach3 programme.

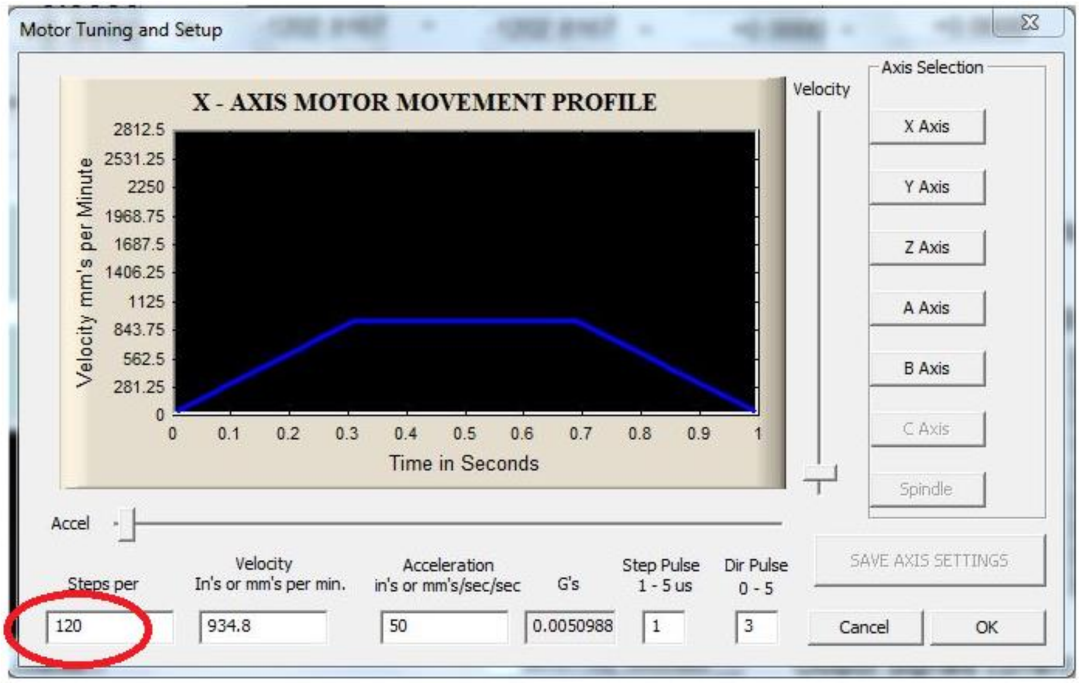


Figure 6.1. Arrangement of x-axis motion in Mach3 programme.

The steps per unit number is essential to set because it controls the motion of stepper motor and also tells that how much distance that axis has travelled. For example, figure 6.1, figure 6.2, and figure 6.3. show the steps per figure of 120, which means if 10 mm value is entered in Mach3 programme then machine will almost travel same distance.

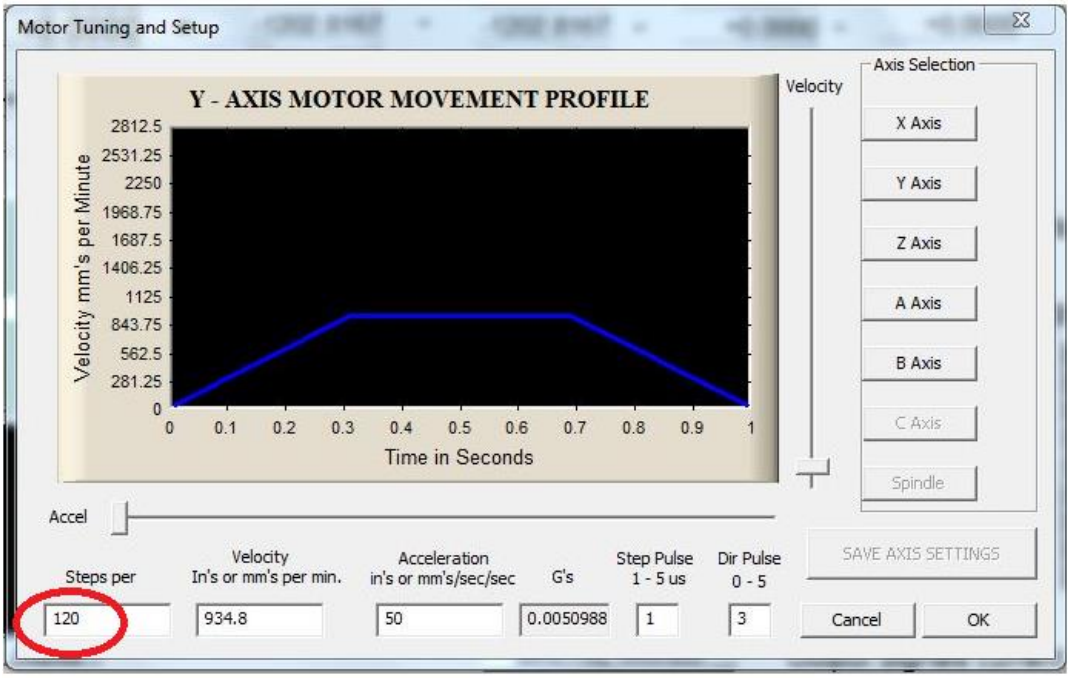


Figure 6.2. Arrangement of y-axis motion in Mach3 programme.

The ‘steps per unit’ part is very difficult because it is very hard to meet the same results. It means if Mach3 screen shows 10 mm distance then it will be very tough job to measure that whether the machine´s axis has really travelled that much distance or not, beacuse there is also a factor of accuracy. For any machine, it is impossible to achive a accuracy of 100%, beacuse the issue of backlash.

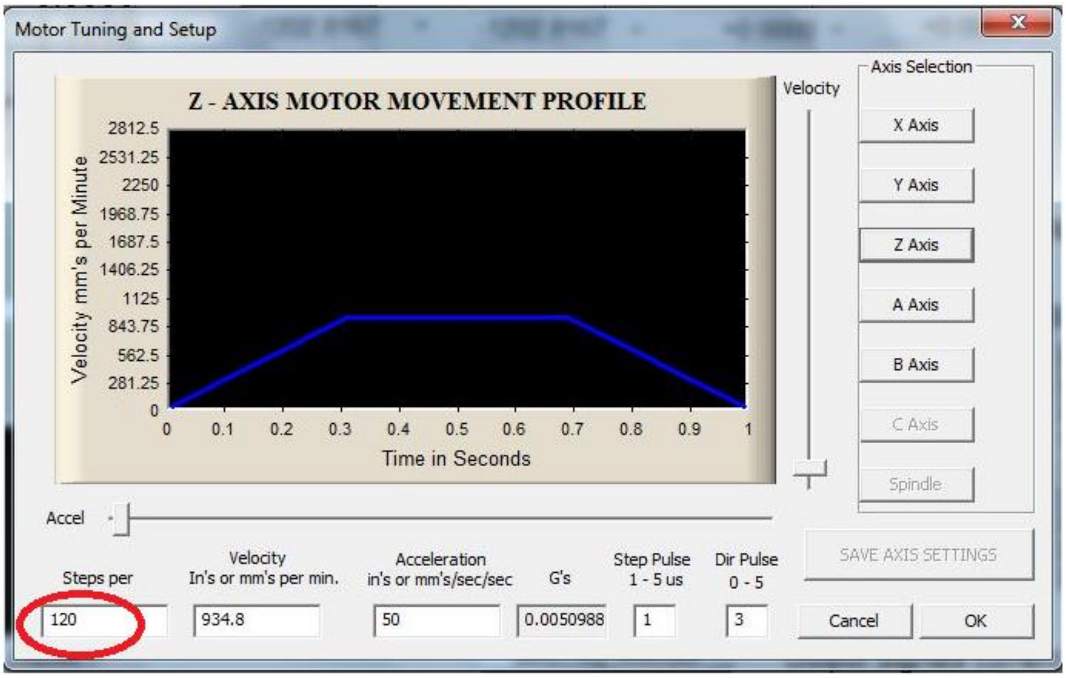


Figure 6.3. Arrangement of z-axis motion in Mach3 programme.

The figures 6.4. and 6.5. show the steps per unit number and other settings of A and B axes. For the A and B axes, the normal shaft was used instead of the screw rod to deliver the motion.

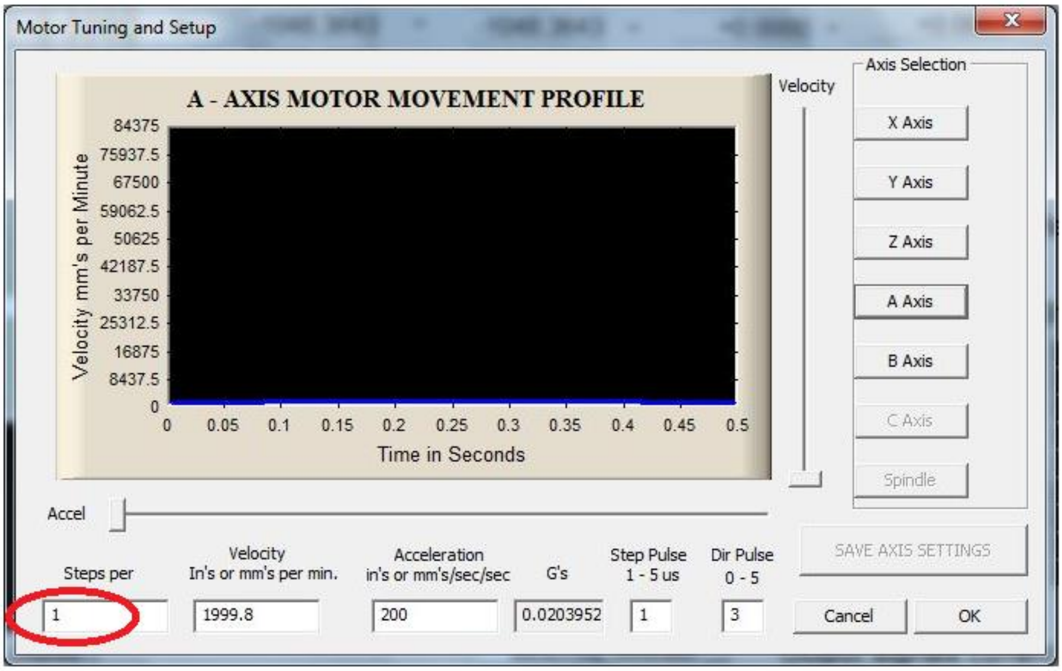


Figure 6.4. Arrangement of a-axis motion in Mach3 programme.

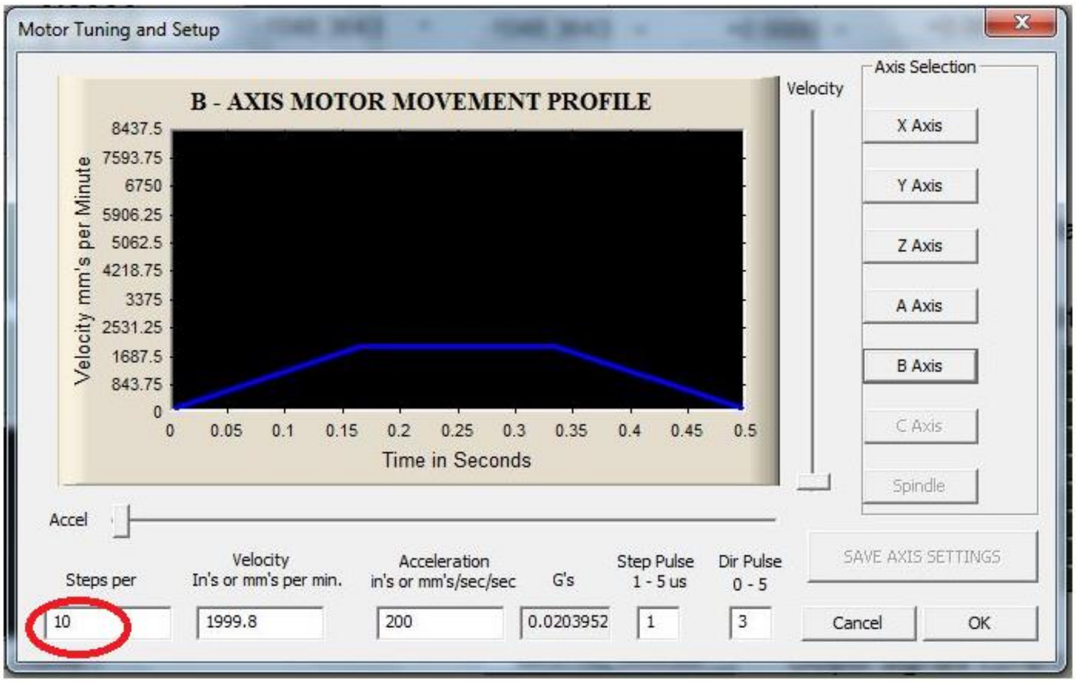


Figure 6.5. Arrangement of b-axis motion in Mach3 programme.

6.1.1. Calculating The Steps Per Unit

The number of steps Mach3 should send for one unit of movement depends on the mechanical drive (e.g. pitch of ballscrew, gearing between the motor and the screw), the properties of the stepper motor and the micro-stepping.

6.1.2. Calculating Mechanical Drive

First of all, the number of revolutions of the motor shaft (motor revs per unit) to move the axis by one unit need to be calculated. Then the raw pitch of the screw need to find out.

Inch screws may be specified in threads per inch (tpi). The pitch is 1/tpi (For this study, the pitch of an 8 tpi single start screw is 1/8 = 0.125")

If the screw is multiple start multiply the raw pitch by the number of starts to get the effective pitch. The effective screw pitch is therefore the distance the axis moves for one revolution of the screw. Now you can calculate the screw revs per unit;

$$\text{screw revs per unit} = 1/\text{effective screw pitch}$$

If the screw is directly driven from the motor then this is the motor revs per unit, also If the motor has a belt drive with N_m teeth on the motor gear and N_s teeth on the screw gear then:

$$\text{motor revs per unit} = \text{screw revs per unit} \times N_s / N_m$$

For this study, suppose our 8 tpi (teeth per inch) screw is connected to the motor with a toothed belt with a 48 tooth pulley on the screw and an 16 tooth pulley on the motor then the motor shaft pitch would be 8 x 48/16 = 24. As a metric example, suppose a two start screw has 5 millimetres between thread crests (i.e. effective pitch is 10 millimetres) and it is connected to the motor with 24 tooth pulley on the motor shaft and a 48 tooth pulley on the screw. So the screw revs per unit = 0.1 and motor revs per unit would be 0.1 x 48/ 24 = 0.2

After that, the pitch of the belt teeth need to be known. Belts are available in metric and imperial pitches with 5 or 8 millimetres common metric pitches and 0.375" (3/8") common for inch belts and for chain. This is best done by measuring the total distance spanning 50 or even 100 gaps between teeth. For all drives this would be the tooth pitch. If the number of teeth on the pulley on the primary shaft which drives the rack/belt is N_s then;

$$\text{shaft revs per unit} = 1/(\text{tooth pitch} \times N_s)$$

and also,

$$\text{motor revs per unit} = \text{shaft revs per unit} \times N_s/N_m$$

It is to be noted that for rotary axes (e.g. rotary tables or dividing heads) the unit is the degree.

6.1.3. Calculating Motor Steps Per Revolution

The basic resolution of all modern stepper motors is 200 steps per revolution (i.e. 1.8^o per step). The encoder resolution is usually quoted in CPR (cycles per revolution) Because the output is actually two quadrature signals the effective resolution will be four time this value. It would be expected to have a CPR in the range of about 125 to 2000 corresponding to 500 to 8000 steps per revolution.

6.1.4. Calculating Mach3 Steps Per Motor Revolution

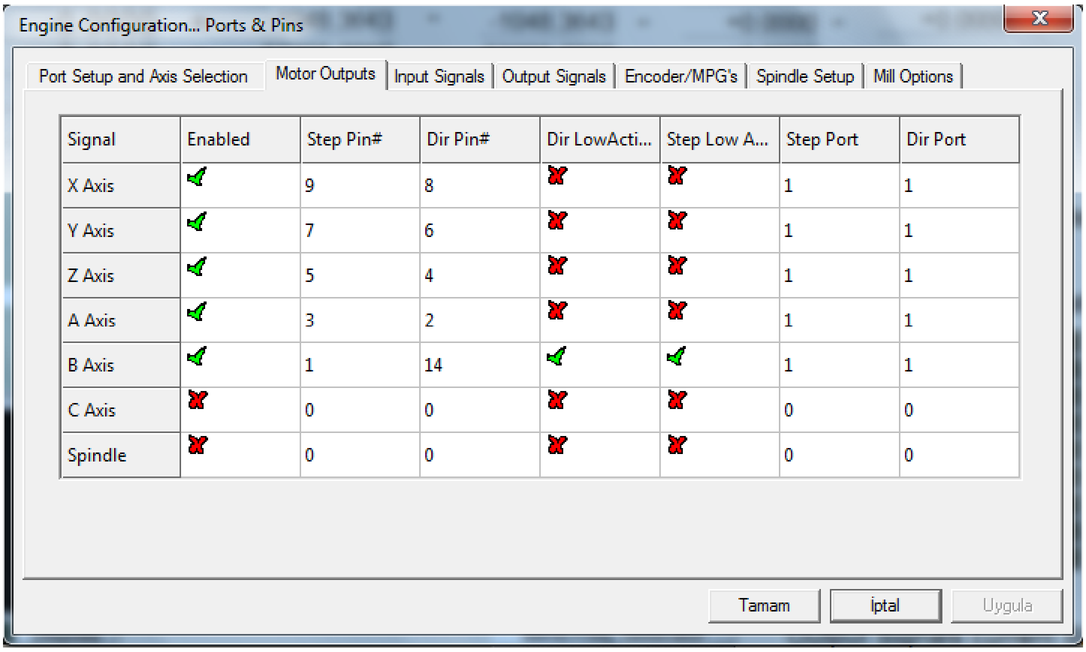
Some micro-stepping drives have a fixed number of micro-steps (typically 10) while others can be configured. In this case, 10will be be a good compromise value to choose. This means that Mach3 will need to send 2000 pulses per revolution for a stepper axis drive.

6.1.5. Mach3 Steps Per Unit

Finally steps per unit can be calculated by using the equation shown below:

Mach3 steps per unit = Mach3 steps per rev x Motor revs per unit

The pins and ports arrangement is also very important for all the axes of the machine to work. Figure 6.6. shows the setting of pins and ports which were done according to the motor driver interface.



Signal	Enabled	Step Pin#	Dir Pin#	Dir LowActi...	Step Low A...	Step Port	Dir Port
X Axis	✓	9	8	✗	✗	1	1
Y Axis	✓	7	6	✗	✗	1	1
Z Axis	✓	5	4	✗	✗	1	1
A Axis	✓	3	2	✗	✗	1	1
B Axis	✓	1	14	✓	✓	1	1
C Axis	✗	0	0	✗	✗	0	0
Spindle	✗	0	0	✗	✗	0	0

Figure 6.6. Ports and Pins in Mach3 programme.

6.2. ACCURACY TESTS

6.2.1. For X-Axis

In this study, the accuracy of the machine was measured using Standard Deviation method. The Standard Deviation is a measure of how spread out numbers are. The standard deviation is the square root of the Variance.

The variance is defined as, the average of the squared differences from the Mean. Value (X) = Σ (X - mean) 2 / (n-1) are calculated from the formula. The standard deviation is the square root of the variance. Figure 6.7. shows the test part with the reading on the Vernier Callipers for x-axis accuracy test and Table 6.1. shows the Standard deviation calculation of the X-axis.

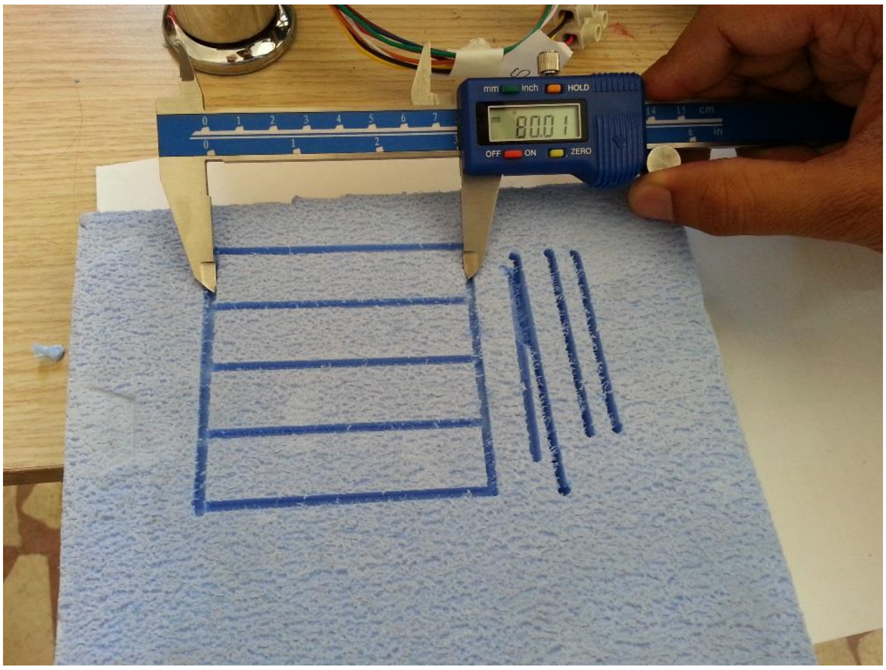


Figure 6.7. X-axis accuracy test.

Table 6.6. Standard deviation calculation of x-axis.

TEST	READING (mm)	(X – Average)	(X – Average)²
X 1	79,95	-0,04	0,0016
X 2	80,02	0,03	0,0009
X 3	79,97	-0,02	0,0004
X 4	80,01	0,02	0,0004
AVERAGE	**79,99**	**TOTAL**	**0,033**

Average = 79.99

Variance = 0.033 / 3 = 0.11

Standard Deviation = √ ¬ ¬ 0.011 = 0.332, Confidence Interval*;

*(Confidence Interval is the range of values that you can be 95% certain contains the true mean of the population)

Confidence interval for the overall average;

Lower limit = (average) - (table value) x (standard deviation)

Upper limit = (average) + (table value) x (standard deviation)

Table value of the t distribution to the small sample size used. t3; 0.05 = 0.841

Lower limit = 79.99 - (0.841) x 0.332 = 79.71

Upper limit = 79.99 + (0.841) x 0.332 = 80.27

Determining the average of the observations must be within the range of the confidence. for µx

calculated 95% confidence interval (79.71, 80.27) is found.

6.2.2. For Y-Axis

Figure 6.8. shows the test part with the reading on the Vernier Callipers for y-axis accuracy test and Table 6.2. shows the Standard deviation calculation of the Y-axis.

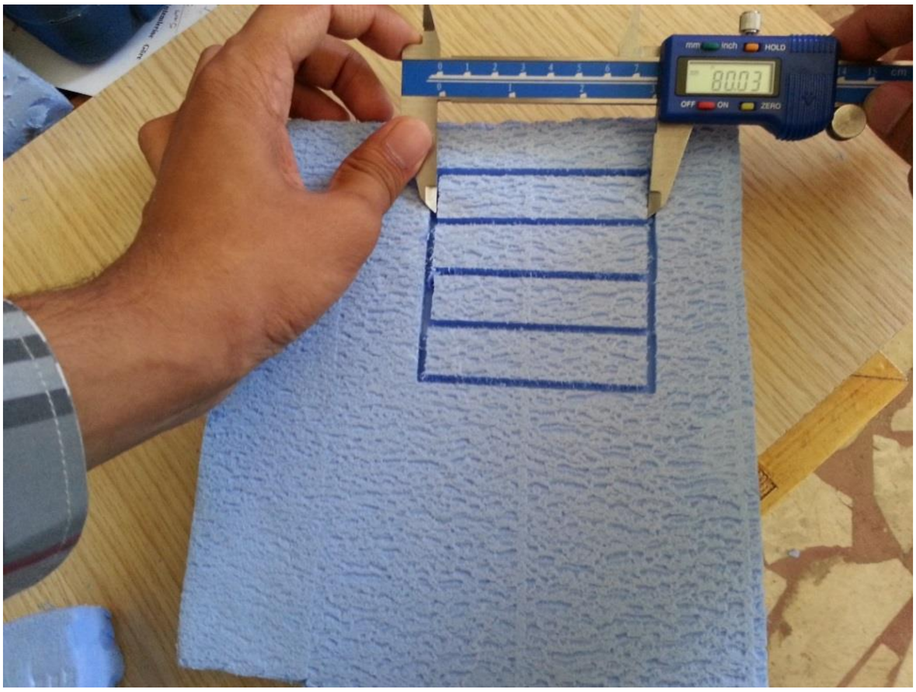


Figure 6.8. Y-axis accuracy test.

Table 6.7. Standard deviation calculation of y-axis.

TEST	READING (mm)	(X – Average)	(X – Average)²
Y 1	80,05	0,04	0,0016
Y 2	79,98	-0,03	0,0009
Y 3	79,97	-0,04	0,0016
Y 4	80.03	0,02	0,0004
AVERAGE	**80,0075**	**TOTAL**	**0,0045**

Average = 80.0025

Variance = 0.0045 / 3 = 0.0015

Standard Deviation = √ ¬ ¬ 0.0015 = 0.387, Confidence Interval*;

*(Confidence Interval is the range of values that you can be 95% certain contains the true mean of the population)

Lower limit = (average) - (table value) x (standard deviation)

Upper limit = (average) + (table value) x (standard deviation)

Table value of the t distribution to the small sample size used. t3; 0.05 = 0.841

Lower limit = 80.0075 - (0.841) x 0.0387 = 79.97

Upper limit = 80.0075 + (0.841) x 0.0387 = 80.04

Determining the average of the observations must be within the range of the confidence. for μy

calculated 95% confidence interval (79.97, 80.04) is found.

6.2.3. For Z-Axis

Figure 6.9. shows the test part with the reading on the Vernier Callipers for z-axis accuracy test and Table 6.3. shows the Standard deviation calculation of the Z-axis.

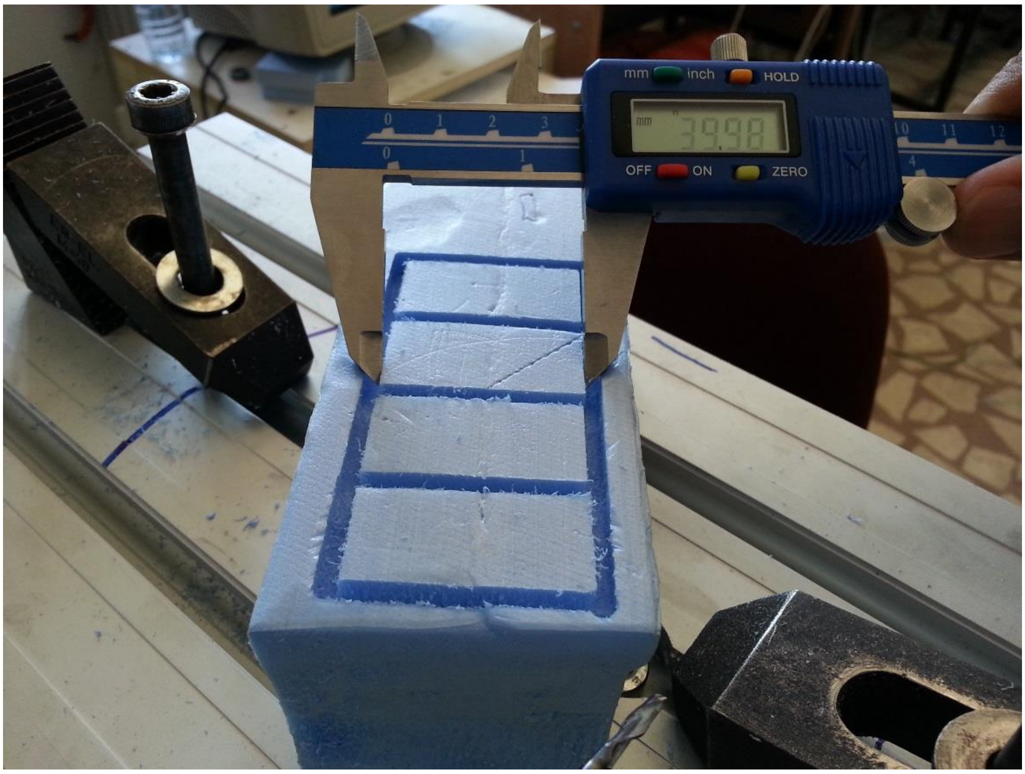


Figure 6.9. Z-axis accuracy test.

Table 6.3. Standard deviation calculation of z-axis.

TEST	READING (mm)	(X – Average)	(X – Average)²
Z 1	39,99	-0,015	0,00023
Z 2	39,98	-0,025	0,00063
Z 3	40,03	0,03	0,00063
Z 4	40.02	0,02	0,00023
AVERAGE	**40,005**	**TOTAL**	**0,0017**

Average = 40.005

Variance = 0.0017 / 3 = 0.00057

Standard Deviation = √ ¬ ¬ 0.00057 = 0.024, Confidence Interval*;

*(Confidence Interval is the range of values that you can be 95% certain contains the true mean of the population)

Lower limit = (average) - (table value) x (standard deviation)

Upper limit = (average) + (table value) x (standard deviation)

Table value of the t distribution to the small sample size used. t3; 0.05 = 0.841

Lower limit = 40.005 - (0.841) x 0.024 = 39.98

Upper limit = 40.005 + (0.841) x 0.024 = 80.02

Determining the average of the observations must be within the range of the confidence. for μy

calculated 95% confidence interval (39.98, 40.03) is found.

6.2.4. For A-Axis

The accuracy of the a-axis was measured manually. A thin and sharp pencil was placed at the zero or starting point of the rotation, equal to the end mill, attached with the spindle motor. The axis was moved from 0 to 180^o several times. The test was started with one tour and then two, three, four, and so on. To make the rough estimate of the precision of the axis, totally ten tours were made continuously. The average deviation of approximately 1^o was observed.

Although this test method is not very accurate method for the sake of performing accuracy and precision tests, but due to unavailability of the suitable measuring device or sensor, this manual method was only the option.

6.2.5. For C (B)-Axis

The accuracy of the c or b-axis was also measured exactly similar to the a-axis. But in this case a end mill with 3 mm diameter was used instead of the pencil. The end mill was used to drill the hole at a certain point, which was considered as a reference point for all the measurements for this axis.

6.3. MACHINNING THE WORKPIECES

The different types of workpieces were machined with different shapes and sizes by using this micro 5-axis CNC milling machine. The G and M codes were written manually. Some of the workpieces machined for this study and their G and M codes are also shown is this chapter.

Figure 6.10. shows the four different pictures of the machined workpiece using this micro 5-axis CNC milling machines. The codes which were written by hand to get this shape of the workpiece in Mach3 programme are also shown in figure 6.11. For this workpiece, actually B and Z axes were mostly used.

Figure 6.10. Workpiece after machining.

```
b0 f50
z 7
b60.0 f50
b0 f50
z10
b60.0 f50
b0 f50
z 9
b 60.0 f50
b0 f50
z 11
b60.0 f50
b0 f50
z12
b60.0 f50
b0 f50
z 13
b 60.0 f50
b0 f50
z 15
b60.0 f50
b0 f50
z10
b60.0 f50
b0 f50
z 17
b 60.0 f50
b0 f50
z 19
b60.0 f50
b0 f50
z20
b60.0 f50
b0 f50
z 21
b 60.0 f50
b0 f50
z 22
b60.0 f50
b0 f50
z 23
b60.0 f50
b0 f50
z 24
b 60.0 f50
b0 f50
z 26
b60.0 f50
b0 f50
z 27
b60.0 f50
b0 f50
x 0 y 0 z 0
```

Figure 6.11. Codes for obtaining the circular shape.

Figure 6.12. shows the machined part using all five axes. This shape was obtained by using a square workpiece of 200 x 200 mm. In this case, the codes were also written manully. Figure 6.13. shows the codes written for acquiring this shape.

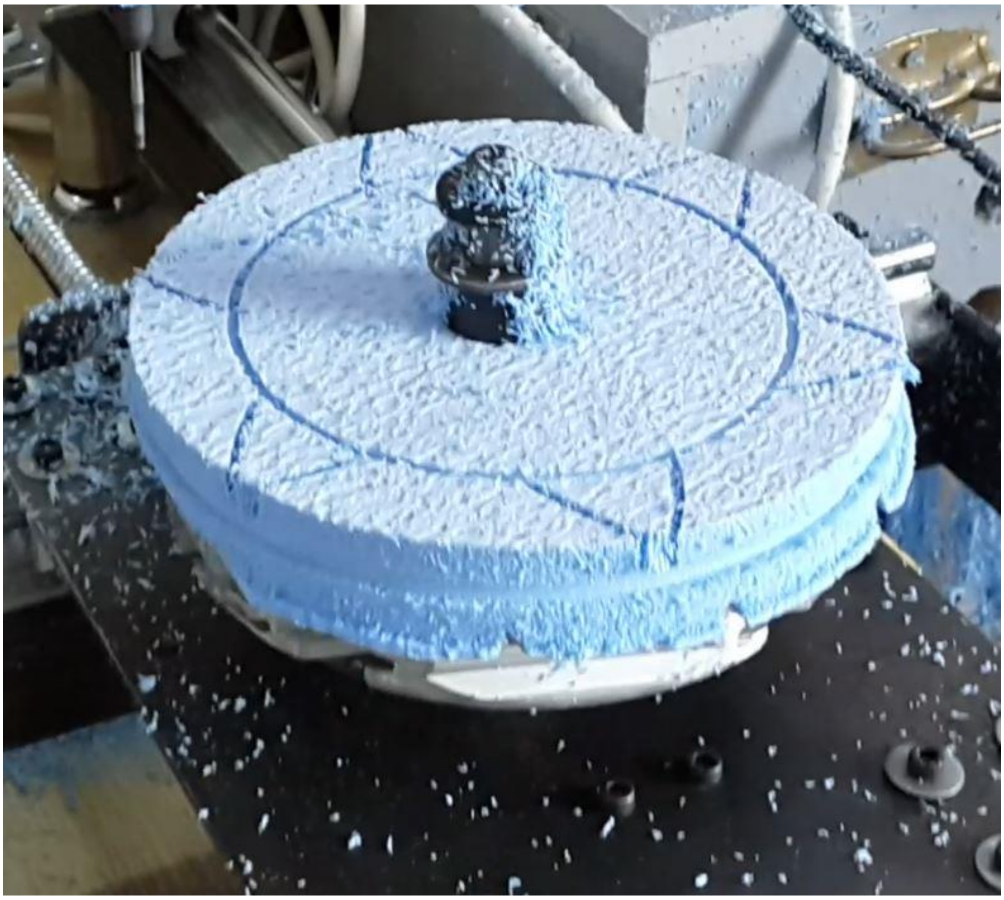


Figure 6.12. Part machined using all five axes.

```
x 80 f200
y 15
z 5
b 60.0 f50
b0 f50
z 7
b60.0 f50
b0 f50
z10
b60.0 f50
b0 f50
z 9
b 60.0 f50
b0 f50
z 11
b60.0 f50
b0 f50
z12
b60.0 f50
b0 f50
z 13
b 60.0 f50
b0 f50
z 15
b60.0 f50
b0 f50
z10
b60.0 f50
b0 f50
z 17
b 60.0 f50
b0 f50
z 19
b60.0 f50
b0 f50
z20
b60.0 f50
b0 f50
z 21
b 60.0 f50
b0 f50
z 22
b60.0 f50
b0 f50
z 23
b60.0 f50
b0 f50
z 24
b 60.0 f50
b0 f50
z 26
b60.0 f50
b0 f50
z 27
b60.0 f50
b0 f50
z 0
x 0
y 0
x 0 z0 y0
a150.0 f100
x 100 f200
y -100
z 235
y -78
b60.0 f50
b0 f50
z 236
b60.0 f50
b0 f50
z 237
b60.0 f50
b0 f50
z 238
b60.0 f50
b0 f50
z 239
y -85
z 0
a0 f50
x 100
z 15
y 15
a30.0 b5.0 f50
a0.0 b10.0 f50
a30.0 b15.0 f50
a0.0 b20.0 f50
a30.0 b25.0 f50
a0.0 b30.0 f50
a30.0 b35.0 f50
a0.0 b40.0 f50
a30.0 b45.0 f50
a0.0 b50.0 f50
a30.0 b55.0 f50
a0.0 b60.0 f50
a30.0 b55.0 f50
a0.0 b50.0 f50
a30.0 b45.0 f50
a0.0 b40.0 f50
a30.0 b35.0 f50
a0.0 b30.0 f50
a30.0 b25.0 f50
a0.0 b20.0 f50
a30.0 b15.0 f50
a0.0 b10.0 f50
a30.0 b5.0 f50
a0.0 b0.0 f50
z -5
x 116 y 43
z 5
b60.0 f50
b0 f50
b60.0 f50
b0 f50
z 0
y 0
x 0
a0
```

Figure 6.13. Codes for using all the axes.

It is to be noted that this 5-axis machine is basically (3+2) axis machine. It means that maximum three axes can work simultaneously, these three axes have to be linear axes (X, Y, and Z). Also other two rotary axes (A and C) can move simultaneously. The table 6.4. shows the major properties of this small-scale 5-axis CNC milling machine.

Table 6.4. General characteristics of the machine.

Travel on X axis	400 mm
Travel on Y axis	620 mm
Travel on Z axis	500 mm
Rotation on A axis	360 degrees
Rotation on C axis	360 degrees
Length of A axis	150 mm
Length of C axis	160 mm (diameter)
Spindle Motor	0.75 KW, 50-18000 rev/min (Inverter Controlled)
Functions and Operations	2 and 3-dimensional small complex and eccentric parts manufacturing, surface machining, cutting, drilling, and milling.
Control Programme	Mach 3
Supporting Files	NC code, DXF, WMF, HPGL, PLT, CMX, JPEG, etc.
Machinable Materials	Wood, Aluminum, Copper, Hard Plastics (polyamide, Castamide, etc..), Plexiglass and other soft materials.
Cooling System	No

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

This study presents a guide to produce a cost-effective, portable, and easy to build and operate 5-axis desktop CNC milling machine, to be used for small-scale industrial applications and educational purposes. This machine is affordable for the Universities´s laboratories and workshops, where 5-axis CNC machine is not availale, as it is much cheaper than commercial 5-axis CNC machines. This machine can also be very effective for learning and teaching purposes, and after some improvements in the design and construction, may also replace large-scale 5-axis CNC machines in technical training institutes or other institutions. The author of this thesis is pleased to mention that the 5-axis desktop CNC milling machine presented in this work is the first five axis machine at the campus of Karabuk University, which has worked successfully and machined several workpieces using all of its fives axes.

The current market is lack of an affordable 5-axis small-scale high precision machine tool system that can be used for small volume production. The machine presented in this thesis will help to solve this problem and serve those who want to make small things but don’t want to spend money on big and heavy machines. This 5-axis machine is also time-saving, because of the fact that some of the parts which are machined using 3-axis micro CNC machines can be machined with ease and also in shorter time.

This machine can be very helpful for small batch manufacturing, especially of complex shapes. It can also be very useful in facilitating the CNC machine education in Turkey as well as many other least developed countries across the globe. The machine designed and constructed in this work is well suitable for the manufacturing of light weight materials (i.e. wood, aluminium, plastivaloire, castermid, etc), as the harder materials produce great vibration in the machine. This work gives the product designers or industrial design engineers a hypothesis for further development and improvement.

7.2. FUTURE RECOMMENDATIONS

- Improved Design. The improvements can be made in the current design, presented in this dissertation or a different type of with better design can be made.

- Noise Test. Noise tests can be performed and recommendations for its control can be given.

- Vibration Test. Vibration tests can also be performed and recommendations for its can be demonstrate.

- Coolant Addition. The coolant can also be added to this type of machines such as cutting oils or water-miscible fluids.

- Distance Control. The distance or gap control can be done during the machining.

- Different CAM Program. Other CAM programs can also be used to generate codes for the desired shape of the workpiece (i.e. CATIA-CAM, TopSolid CAM, etc.)

- Different Control Program. Other control programs can also be used to control these kinds of micro CNC machines (i.e. Mach4, RDNO, etc).

- Post-Processing Test. Postprocessing can also be done after the machining process.

- Performance Test. Performance tests can be performed to check the performance of this or another machine and also the tolerance of the process.

- Accuracy Test. Accuracy tests can be performed to check the accuracy of this or another machine.

- More Axes. The CNC milling machines can have upto 9 axes, so more axes can be added and the new machine with increased axes can be designed and constructed.

REFERENCES

1. Hashim, N., “Design of mini CNC machine”, Bachelor´s Thesis***, University of Malaysia Pahang,*** Malaysia (2012).

2. Jywe, W., Hsu, T.-H. and Liu, C.-H., “Non-bar, an optical calibration system for five-axis CNC machine tools”, ***International Journal of Machine Tools & Manufacture***, 59: 16-23 (2010).

3. Koyun, S. and Erdem, S., “Design and prototype of a bridge type industrial CNC machine”, Bachelor´s Thesis, ***Technical Education Faculty of Karabuk University***, Karabuk (2013).

4. Gun, M., Huseyin, K. and Cetinkaya, K., “Design and manufacturıng of a five-axis cradle CNC”, ***International Symposium on Industrial Design Engineering (ISIDE)***, Karabuk, 6-11 (2014).

5. Internet: The Kneeslider, “Personal Size 5 Axis CNC Milling Machine from PocketNC”, **http://thekneeslider.com/personal-size-5-axis-cnc-milling-machine-from-pocketnc** (2014).

6. Goldenberg, J., “Computer Numerical Control (CNC) Component-Student Manual”, ***Queensborough Community College-NSF Tech ASCEND,*** New York, USA (2003).

7. Kobeloglu, A. and Cetinkaya, K. “Design and the prototype of a desktop CNC lathe to be utilized for educational purposes”, ***Global Journal on Technology***, 1: 0, (2012).

8. Newman, S., Nassehi, A, Xu, X. W., Rosso Jr., R. S. U., Wang, L., Yusof, Y, Ali, L., Liu, R., Zheng, L.Y., Kumar, S., Vichare, P., and Dhokia, V., “Strategic advantages of interoperability for global manufacturing using CNC technology”, ***Robotic and Computer-Integrated Manufacturing***, 24 (6): 699-708 (2008).

9. Swamidass, P. M., and Winch, G. W., “Exploratory study of the adoption of manufacturing technology innovations in the USA and the UK”, ***International Journal of Production Research***, 40 (12): 2677-2703 (2002).

10. Al-Kindi, G. and Zughaer, H., “An approach to ımproved CNC machining using vision-based system”, ***Materials and Manufacturing Processes***, 27 (7): 765-774 (2012).

11. Ye, X., Liu, H., Chen, L., Chen, Z., Pan, X., and Zhang, S., “Reverse innovative design; an integrated product design methodology”, ***Computer-Aided Design***, 40 (7): 812-827 (2008).

12. Xu, X. and Newman, S., "Making CNC machine tools more open interoperable and a review of the technologies", ***Computer in Industry***, 57 (2): 141-152 (2006).

13. Zhao, P., Lou, P. and Wu, M., "Open CNC system design based on multi-agent technology", ***International Conference on Computational Intelligence and Software Engineering (CiSE),*** Wuhan, 1-4 (2010).

14. Haridy, S., Wu, Z. and Shafik, A., "An educational scheme for a CNC drilling machine", ***International Journal of Manufacturing, Materials, and Mechanical Engineering (IJMMME),*** 2 (2): 1-11 (2012).

15. Gordon, S. and Hillery, M., "Development of a high-speed CNC cutting machine using linear motors", ***Journal of Metarials processing Technology***, 166 (3): 321-332 (2005).

16. Kim, J. D. and Kim, M. H., "A study on the design of CNC lathe for education and application", ***International Journal of Production Economics***, 25 (1-3): 169-180 (1991).

17. Tseng, A., Kolluri, S. P. and Radhakrishnan, P., "A CNC machining system for education", ***Journal of Manufacturing Systems***, 8 (3): 207-214 (1989).

18. Zhang, X., Fu, H., Han, Z., and Sun, Y., "5-axis micro-milling machine tool for machining complex 3D meso-scale parts", ***Proceedings of the IEEE, International Conference on Mechatronics and Automation***, Changchun, 9-12 (2009).

19. Nae, I. and Andrei, T., "Designing and building a CNC router using stepper motors", ***Petroleum - Gas University of Ploiesti Bulletin, Technical Series***, 62 (1): 55-62 (2010).

20. Ping, B., Jiangang, L., and Liang, H., "A general motion simulation description of multi-axis CNC machine tools", ***Proceedings of the IEEE, 31st Chinese Control Conference (CCC),*** Hefei, 4486 - 4489 (2012).

21. My, C. A., "Integration of CAM systems into multi-axes computerized numerical control machines", ***Second International Conference on Knowledge and Systems Engineering***, Hanoi, 7-9 (2010).

22. Xia, J. and Ge, Q. J., "An exact representation of effective cutting shapes of 5-axis CNC machining using rational Bezier and B-spline tool motions", ***Proceedings of the IEEE, International Conference on Robotics & Automation (ICRA)***, (1): 342-347 (2001).

23. Huo, D., Cheng, K., and Wardle, F., "Design of a 5-axis ultraprecision micro milling machine UltraMill: Part 1: holistic design approach, design considerations, and specifications", ***International Journal of Advanced Manufacturing Technology***, 47 (9): 867-877 (2010).

24. Rklundy, S., Bjurstamy, P. and Novaky, A. “Compensation of systematic errors in 5-axis high-speed machining”, ***International Journal of Production Research***, 40 (15): 3765-3778 (2002).

25. Rauch, M., Laguionie, R., Hascoet, J., and Xu, W., “Enhancing CNC manufacturing ınteroperability with STEP-NC", ***Journal of Machine Engineering,*** 9 (4): 26-37 (2009).

26. Lee, W and Bang, Y., “Design and implementation of an ISO14649-compliant CNC milling machine”, ***International Journal of Production Research***, 41 (13): 3007-3017 (2003).

27. Xu, X.W., Wang, H., Mao, J., Newman, S. T., Kramer, T. R., Proctor F. M. and Michaloski, J. L., “STEP-Compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration”, ***International Journal of Production Research***, 43 (17): 3703-3743 (2005).

28. Nassehi, A., Newman, S. T., Xu, X. W., Rosso Jr., R. S. U., “Toward interoperable CNC manufacturing”. ***International Journal of Computer Integrated Manufacturing***, 21 (2): 222-230 (2008).

29. Pandian, S. and Pandian, S. R., “A low-cost build-your-own three axis CNC mill prototype”, ***International Journal on Mechanical Engineering and Robotics***, 2 (1): 2321-5747 (2014).

30. Yusof, Y., Newman, S., Nassehi, A. and Case K., “Interoperable CNC system for turning operations case world academy of science”, ***Proceedings of World Academy of Science, Engineering and Technology***, 25: 941-947 (2009).

31. Sherring da Rocha Jr. P. A., Souza, R. D. S. and Tostes, M. E. L., “Prototype cnc machine design”, ***9th IEEE/IAS International Conference on Industry Applications (INDUSCON)***, Sao Paulo, 1-5 (2010).

32. Nae, I. and Andrei, T., “Designing and building a CNC router using stepper motors”, ***Petroleum - Gas University of Ploiesti Bulletin, Technical Series***, 62 (1): 55-62 (2010).

33. Schmitz, T. and Ziegert, J., “Pre-Machining CNC contour validation”, ***Machine Tool Research Center of the University of North Carolina at Charlotte,*** North Carolina (2010).

34. Hasar, N., “Four axis CNC machining desktop design and helical-bevel gear ımplementation”, Master´s Thesis, ***Graduate School of Natural & Applied Sciences of Karabuk University***, Karabuk (2012).

35. Schmitz, T., “Machining virtual test parts”, Master´s Thesis, ***University of Florida,*** Gainesville, FL, (1996).

36. Fenerty, A. and Prentice, J., “Using Mach3 Mill- A user´s guide to installation, configuration and operation”, ***ArtSoft Software Incarporated***, US (2005).

37. Qin, W., “Design and analysis of a small-scale cost-effective CNC milling machine”, Master´s Thesis, ***University of Illinois at Urbana-Champaign,*** Urbana, Illinois (2013).

38. Benhabib, B., “Manufacturing: Design, production, automation, and ıntegration”, ***Marcel Dekker,*** ISBN: 0-8247-4273-7, New York, USA, (2003).

39. Gun, M., Huseyin, K. and Cetinkaya, K., “Design and manufacturıng of a five-axis cradle CNC”, ***International Symposium on Industrial Design Engineering (ISIDE)***, Karabuk, 6-11 (2014).

40. Internet: MDA Precision, “TN5 5-Axis CNC Milling System with Tool Height Setter”, **http://www.mdaprecision.com/5-axis-cnc-mill-50.html** (2014).

41. Internet: ShopBot, “5-Axis PRSalpha CNC”, **http://www.shopbottools.com/ mproducts/5axis.htm** (2006).

42. Internet: HURCO, “Hurco 5-Axis CNC Mills Yield Maximum Profitability”, **http://www.hurco.com/en-gb/machine-tools/machining-CENTRES/5-axisve rtical/Pages/Trunnion-Table.aspx** (2014).

43. Internet: Instructables, “DIY CNC by Instructables”, **http://www. instructables.com/id/DIY-CNC/** (2014).

44. Internet: Norman Noble, Inc., “High-Speed Contour Milling Services”, **http:// mmu.ic.polyu.edu.hk/mu_proj/2003/M6/design.htm** (2014).

45. Internet: HSM WORKS-The CAM solution for SolidWorks, “CNC Handbook”, **http://www.hsmworks.com/docs/cncbook/en/#Ch07_StandardCADViewsC AMViews** (2012).

46. Internet: CNC Cookbook, “5-Axis CNC Benefits”, **http://blog.cnccook book.com/2012/03/25/5-axis-cnc-benefits/** (2012)

47. Internet: Western CNC, “5 Axis CNC Routers”, **http://westerncncinc.com/5-axis-routers/#5_axis_table** (2014).

48. Internet: AJ Grupp, “5 axis CNC Routers”, **http://www.5-axis-cnc.com/**(2011).

APPENDIX A.

CNC MACHINE´S PARTS TECHNICAL DRAWINGS

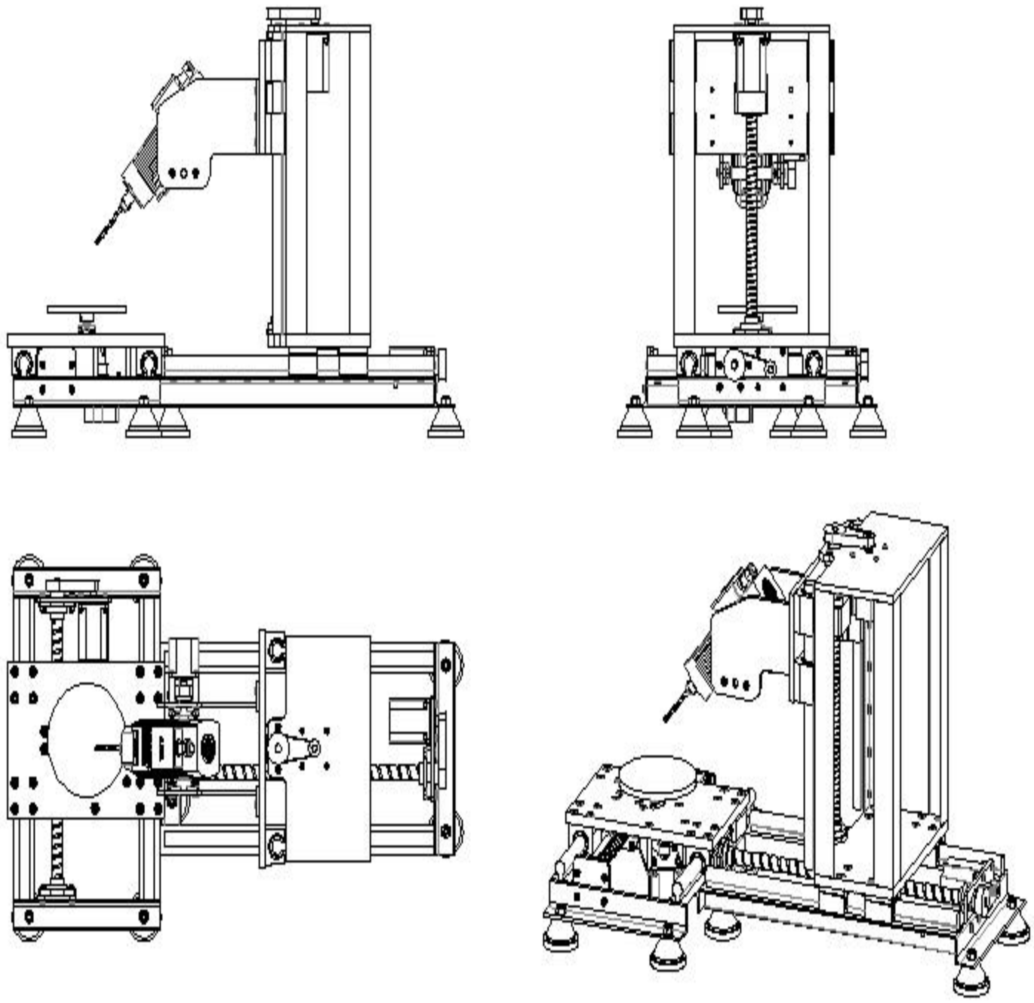


Figure Appendix A.1. Different views of 5-axis desktop CNC milling machine.

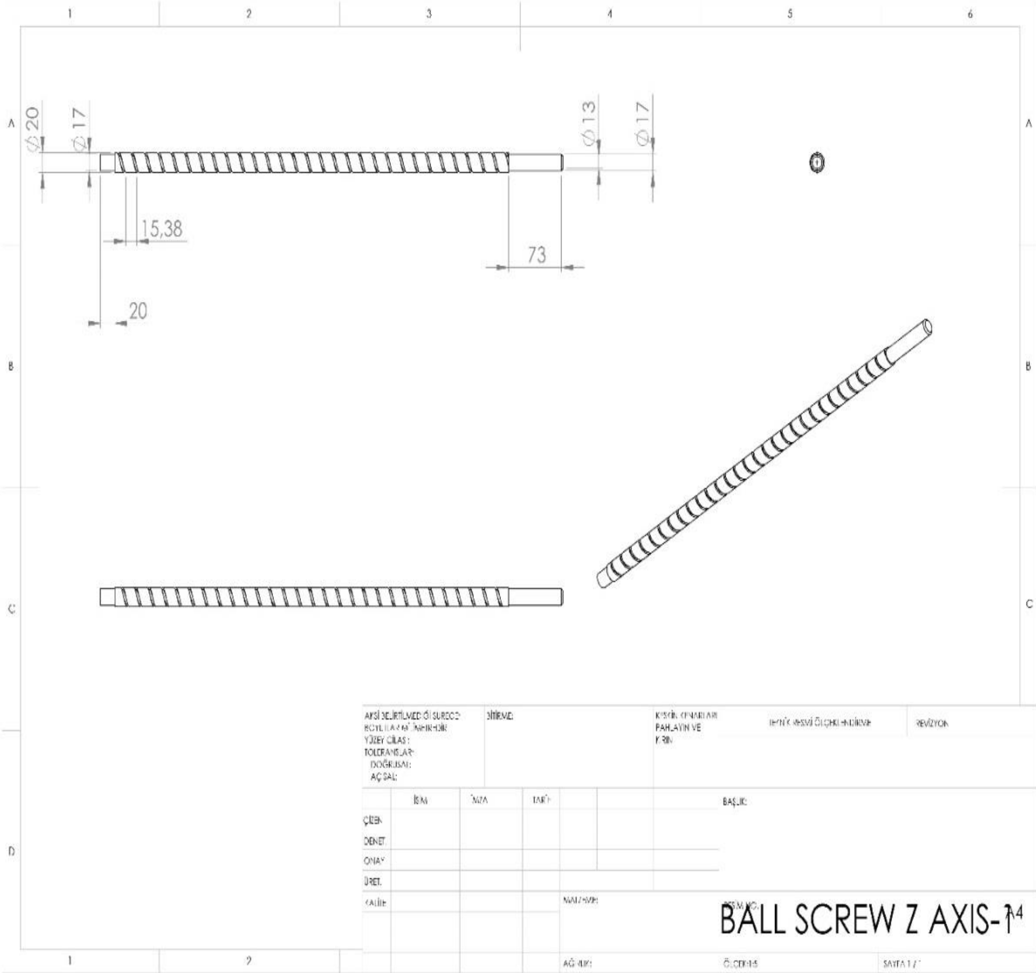


Figure Appendix A.2. Ball screw for z-axis.

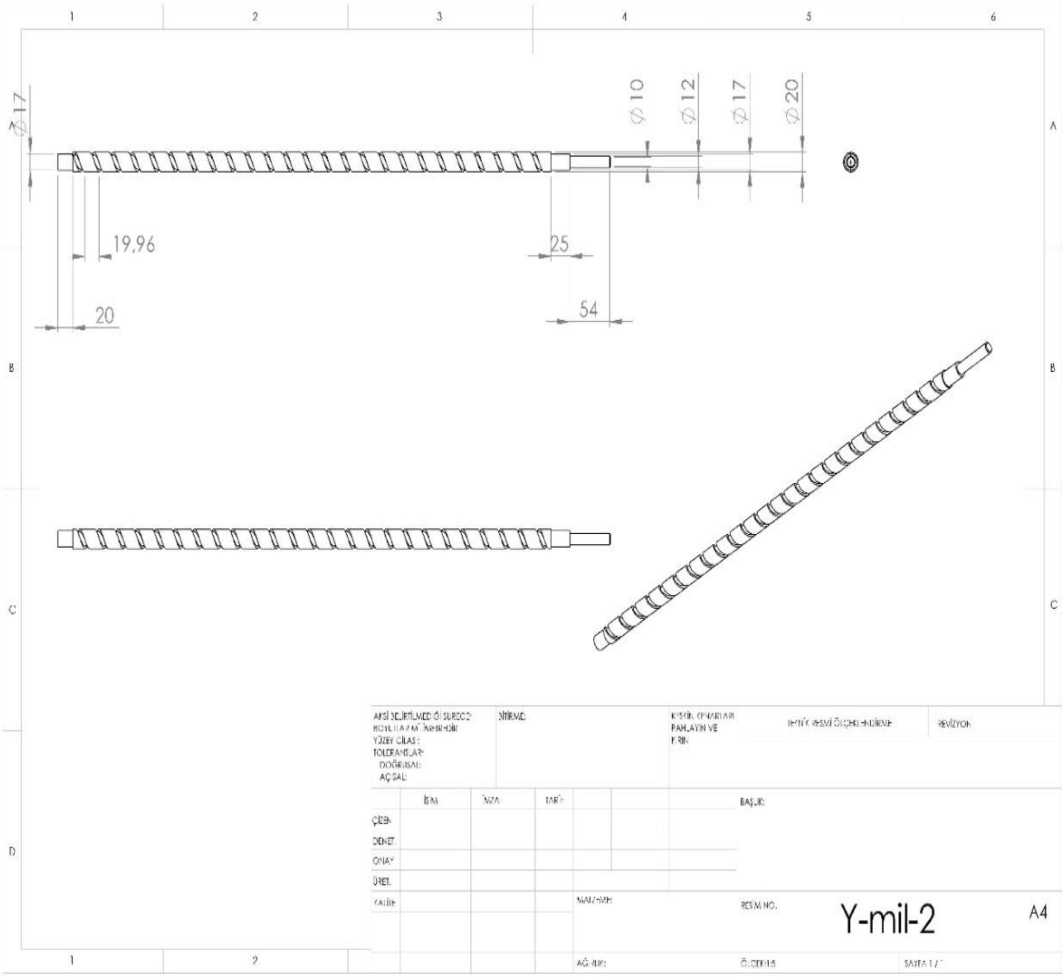


Figure Appendix A.3. Ball screw for y-axis.

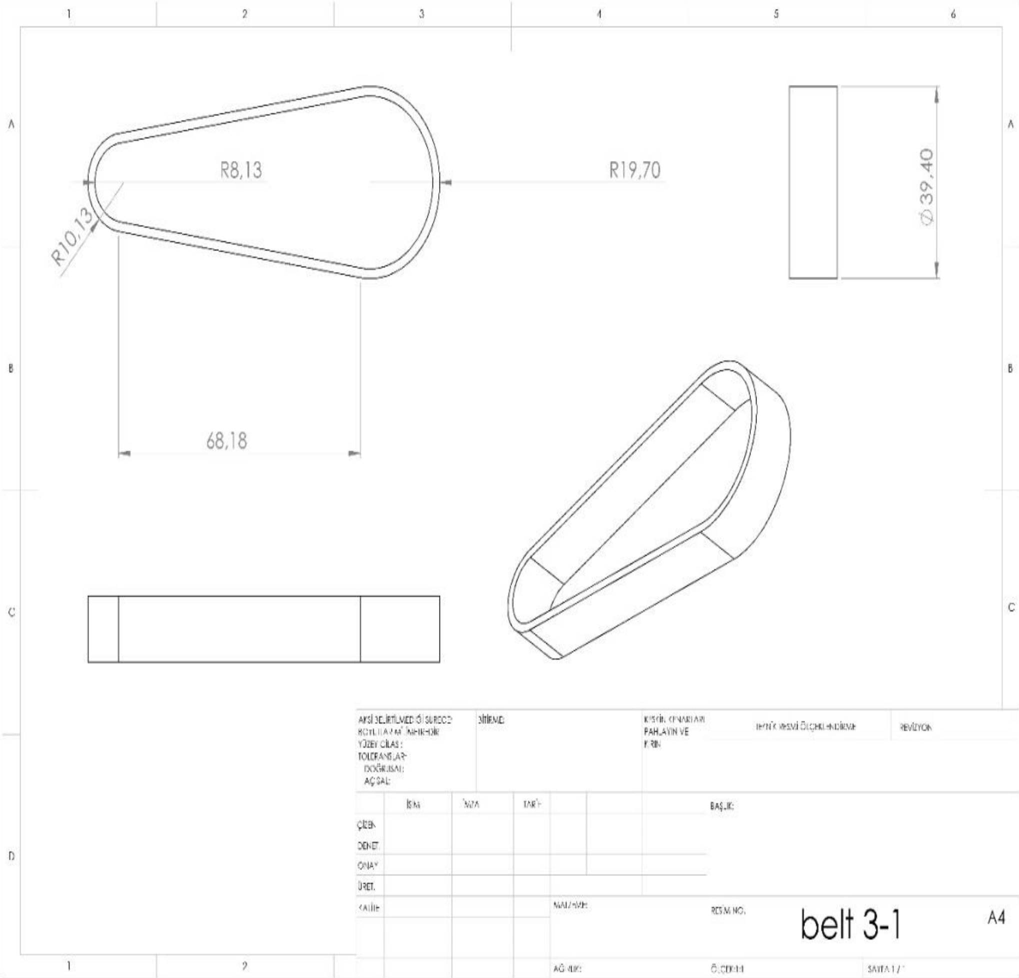


Figure Appendix A.4. Belt for pulleys.

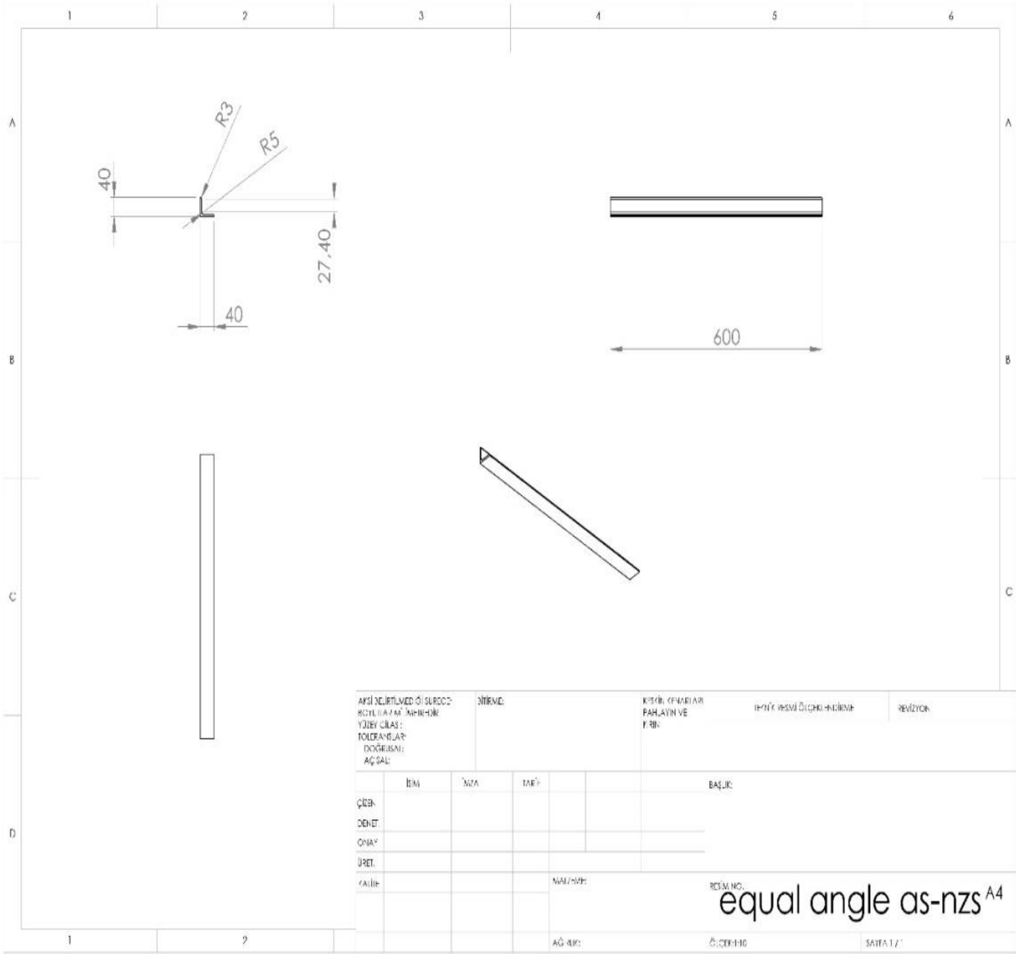


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Figure Appendix A.5. L-profile.

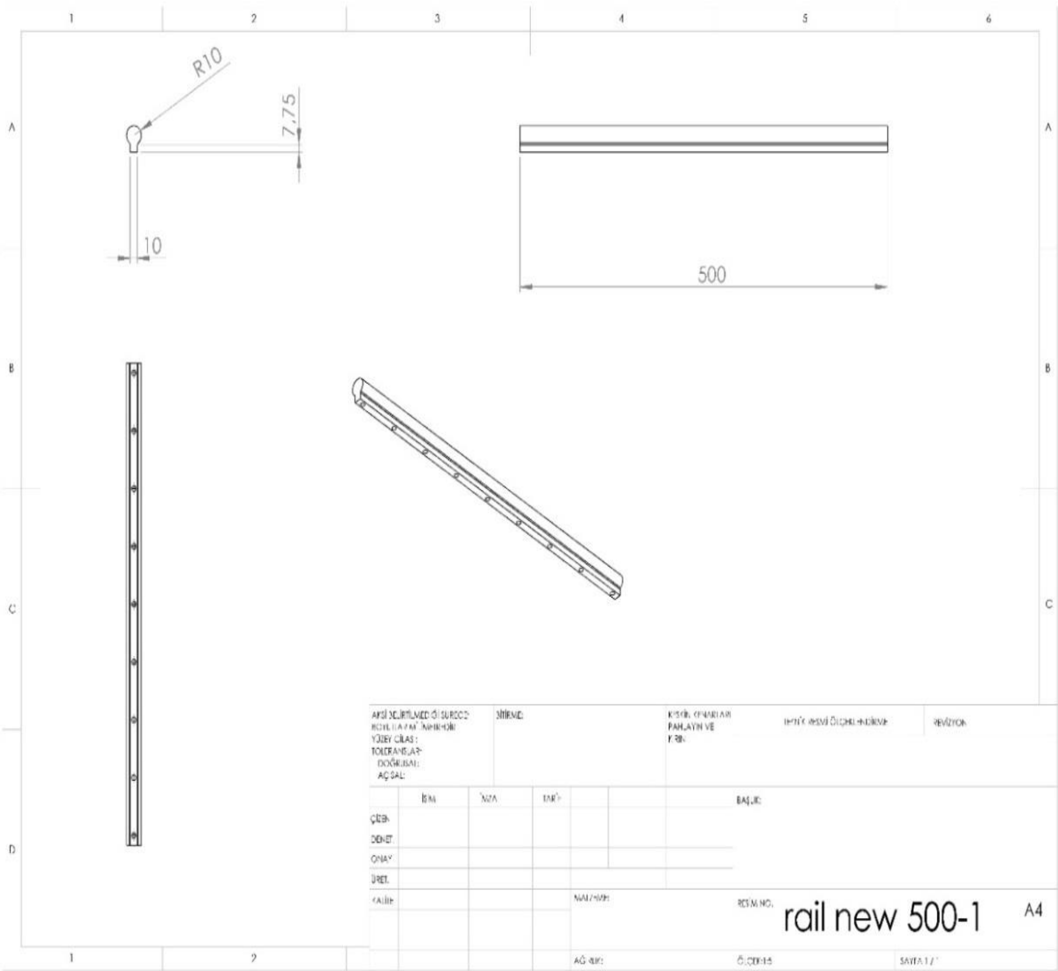

Figure Appendix A.6. Slide rail for x-axis.

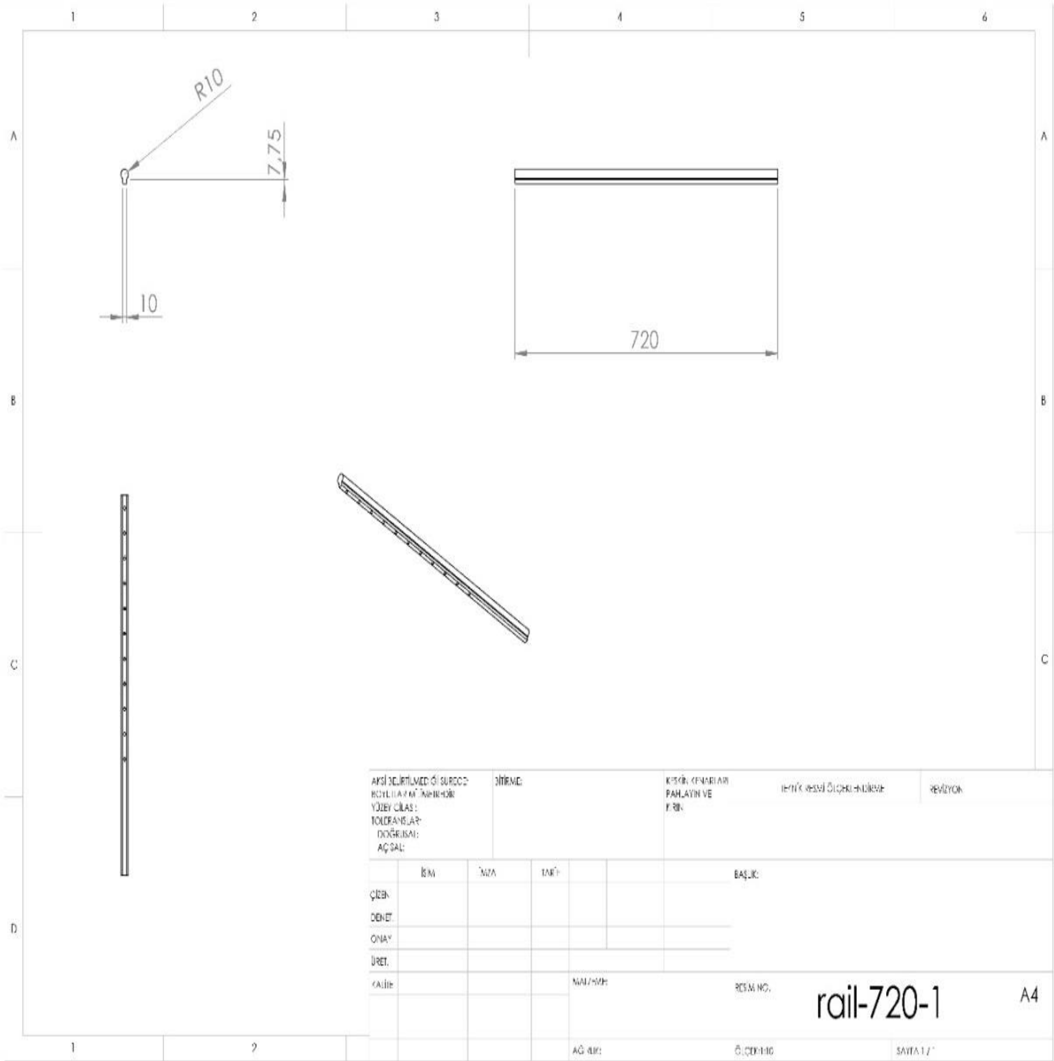

Figure Appendix A.7. Slide rail for y-axis.

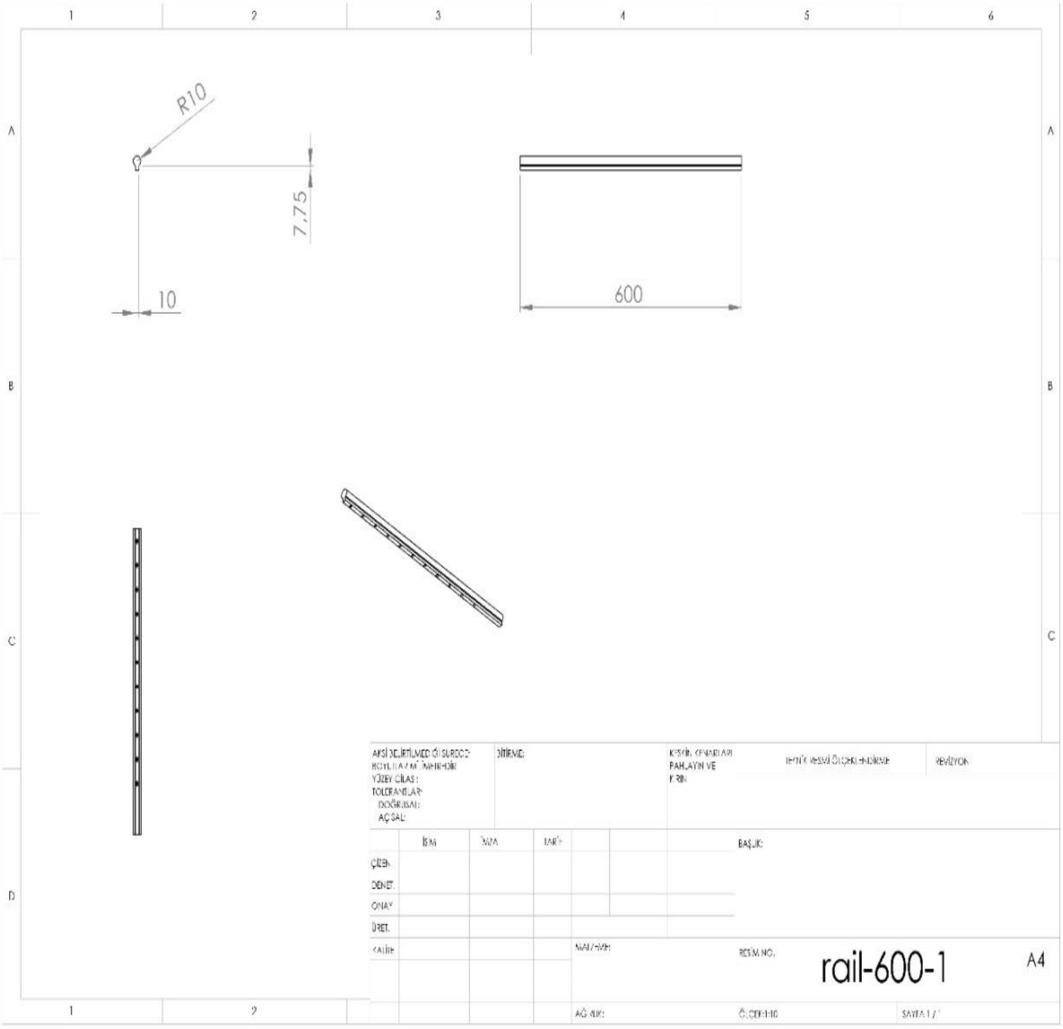

Figure Appendix A.8. Slide rail for z-axis.

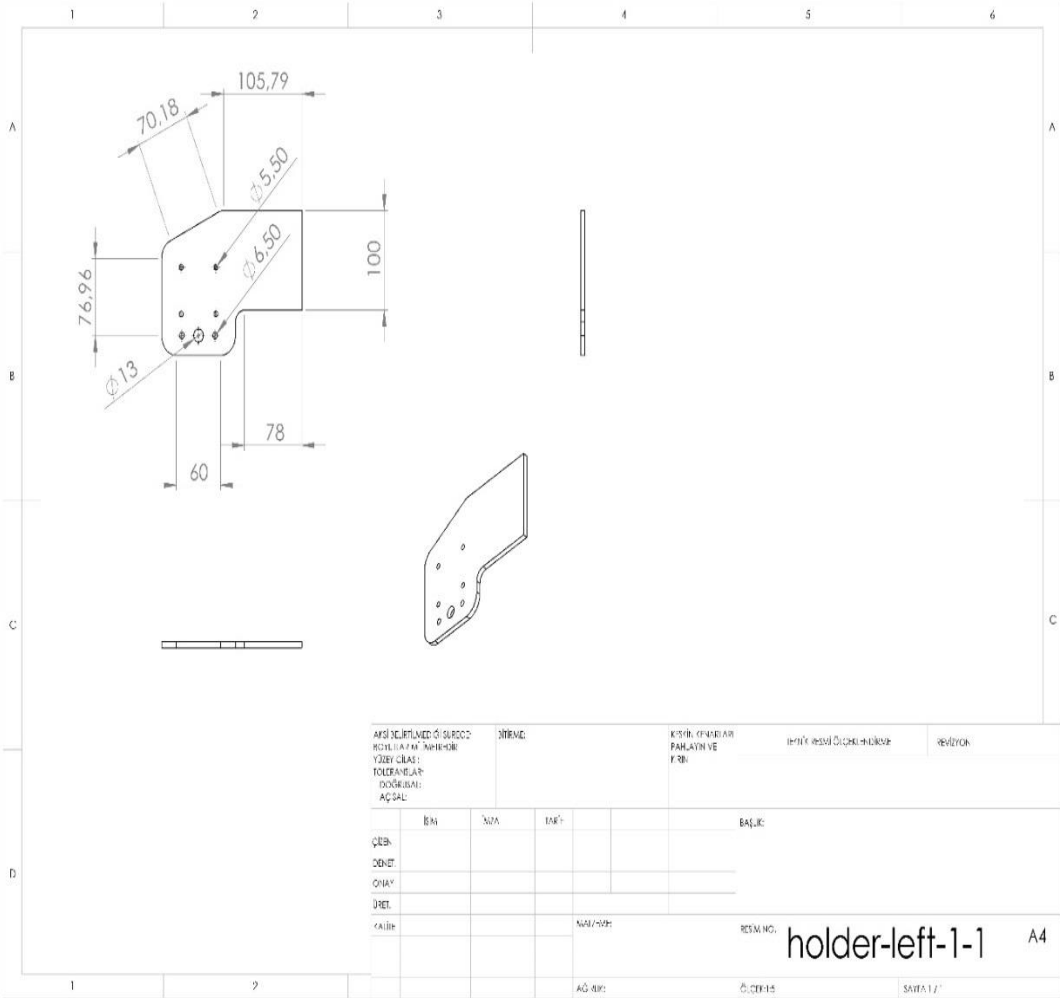

Figure Appendix A.9. Yoke for holding spindle motor.

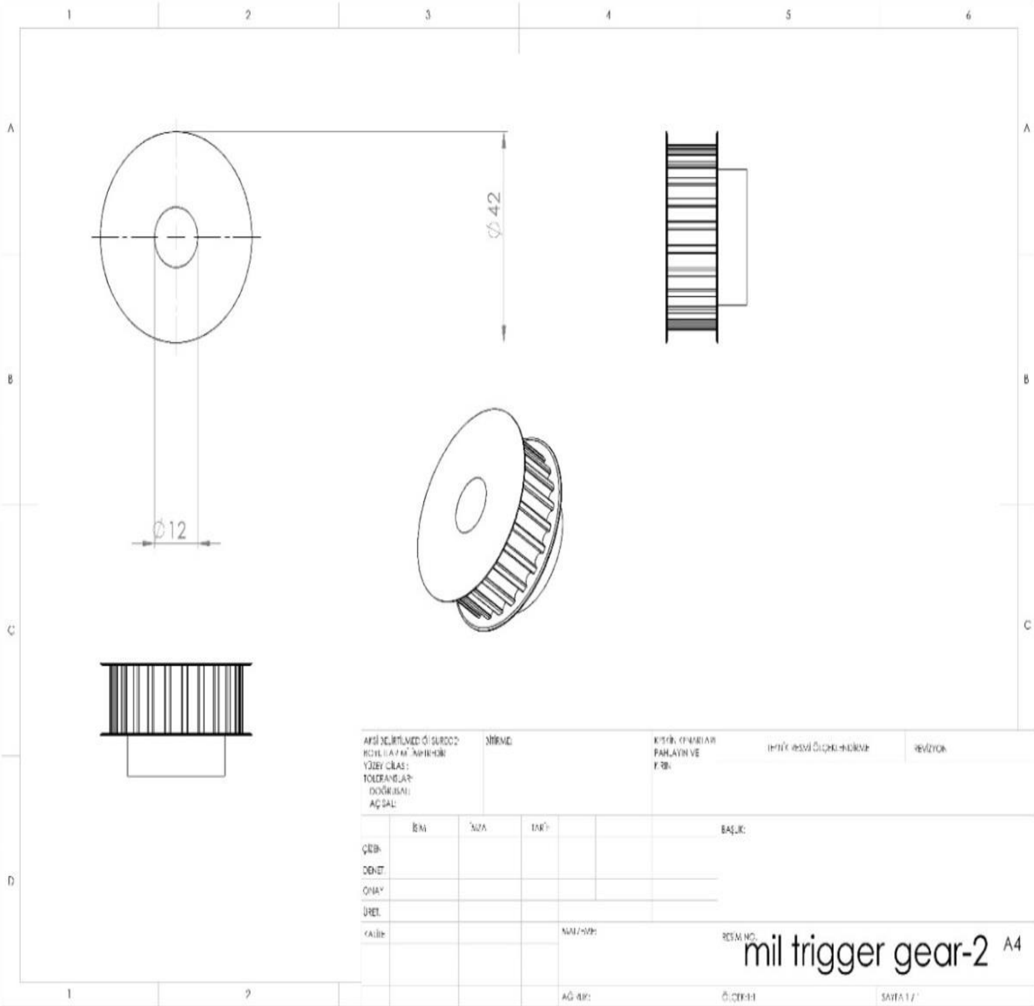

Figure Appendix A.10. Gear connected with screw rod for all axes.

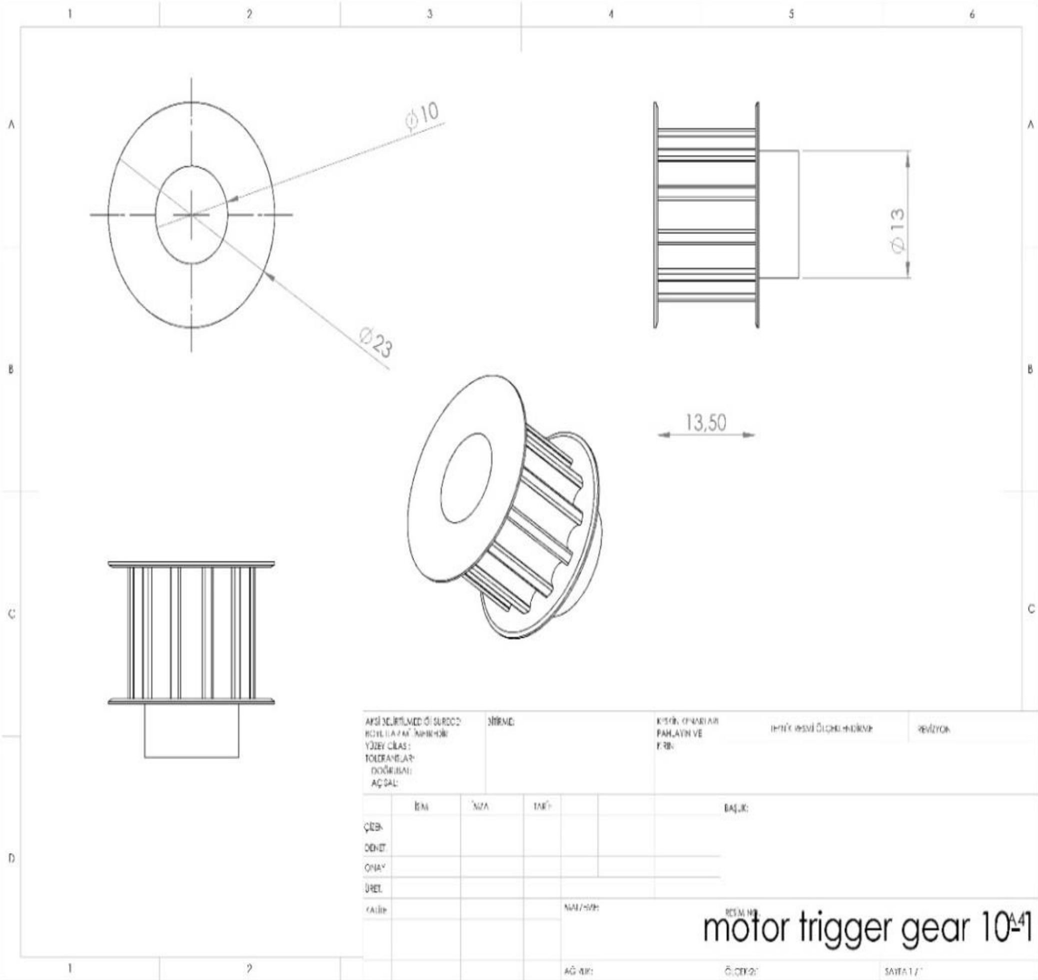

Figure Appendix A.11. Gear connected with stepper motor for all axes.

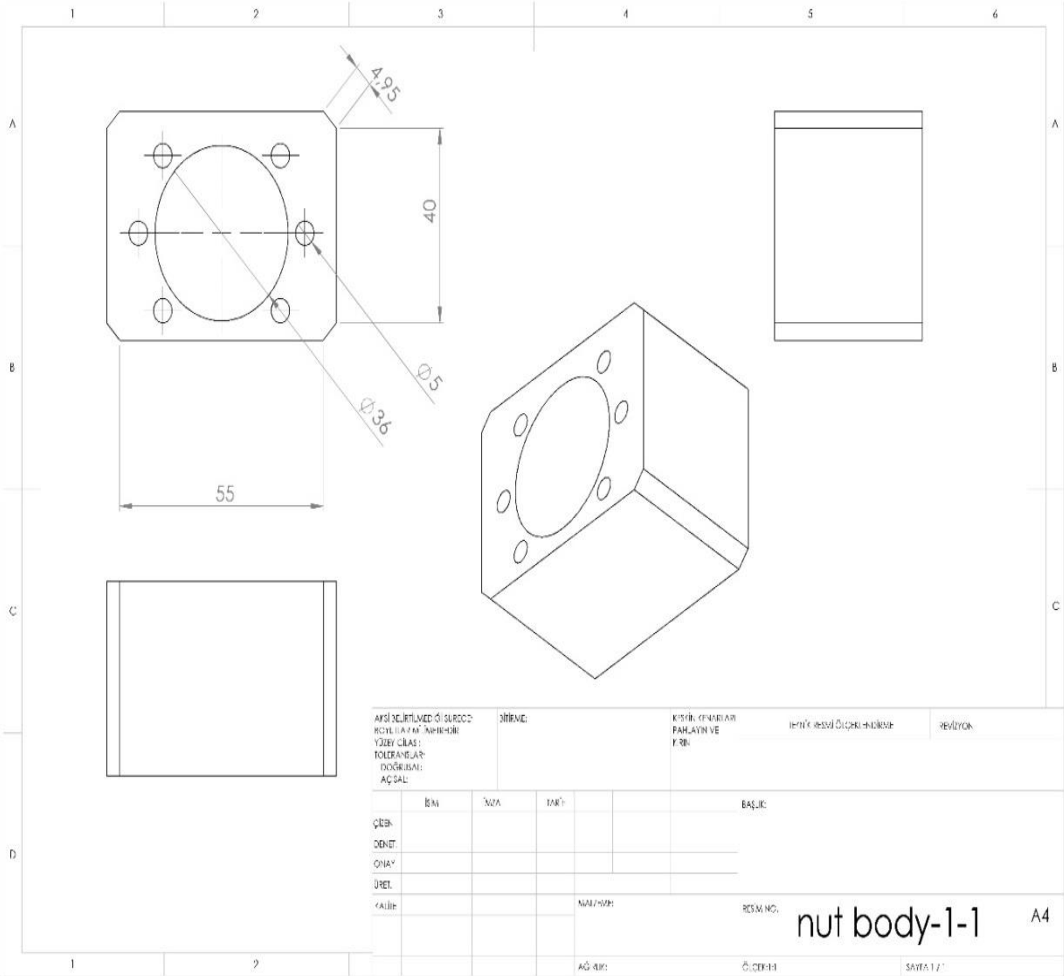

Figure Appendix A.12. Screw rod nut housing for all linear axes.

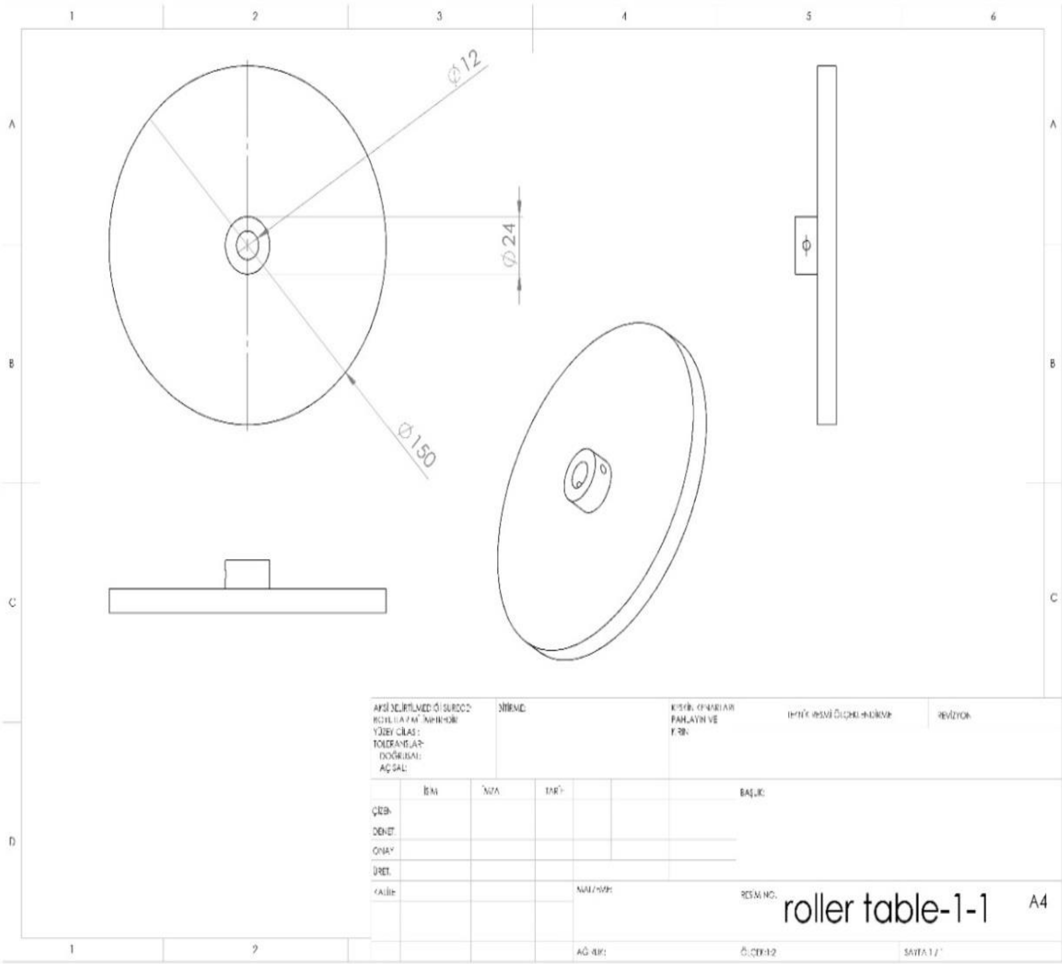

Figure Appendix A.13. Rotary table for c-axis.

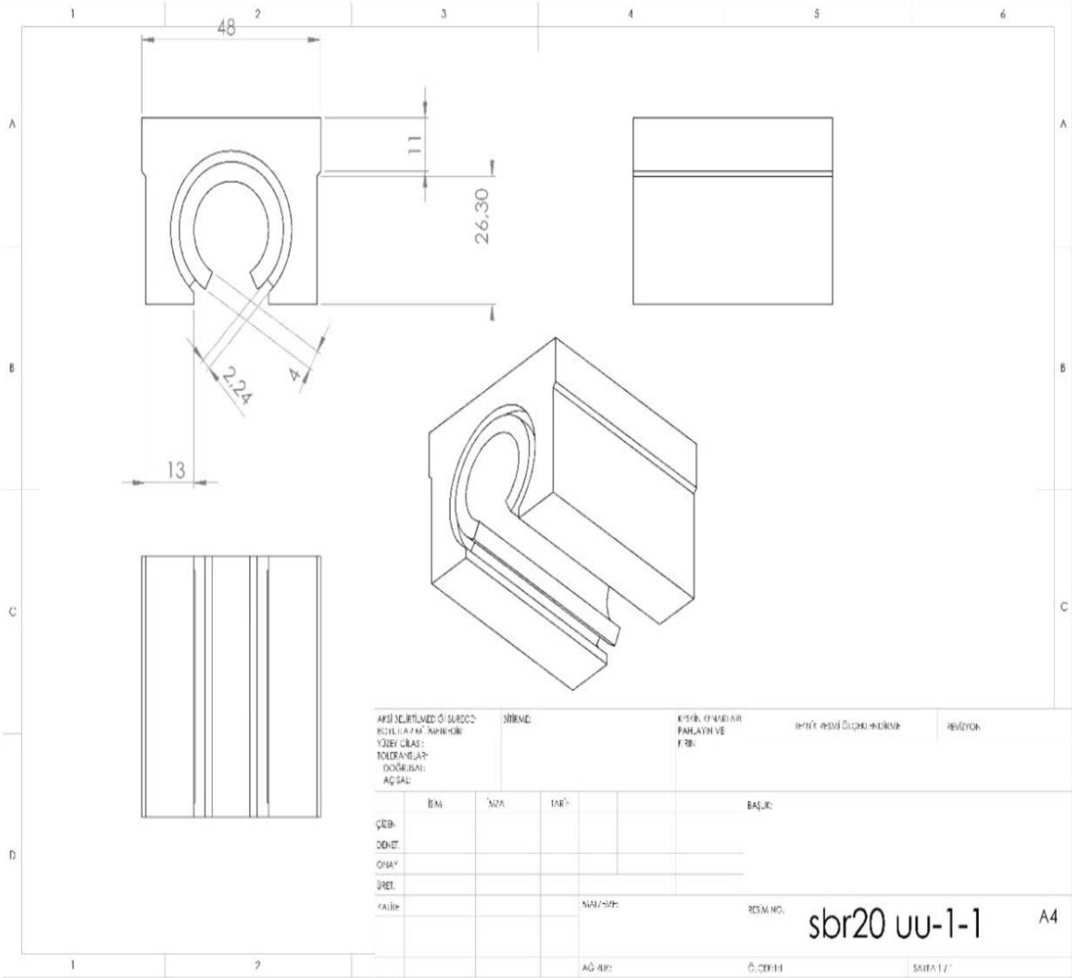

Figure Appendix A.14. Linear slide bearing for all linear axes.

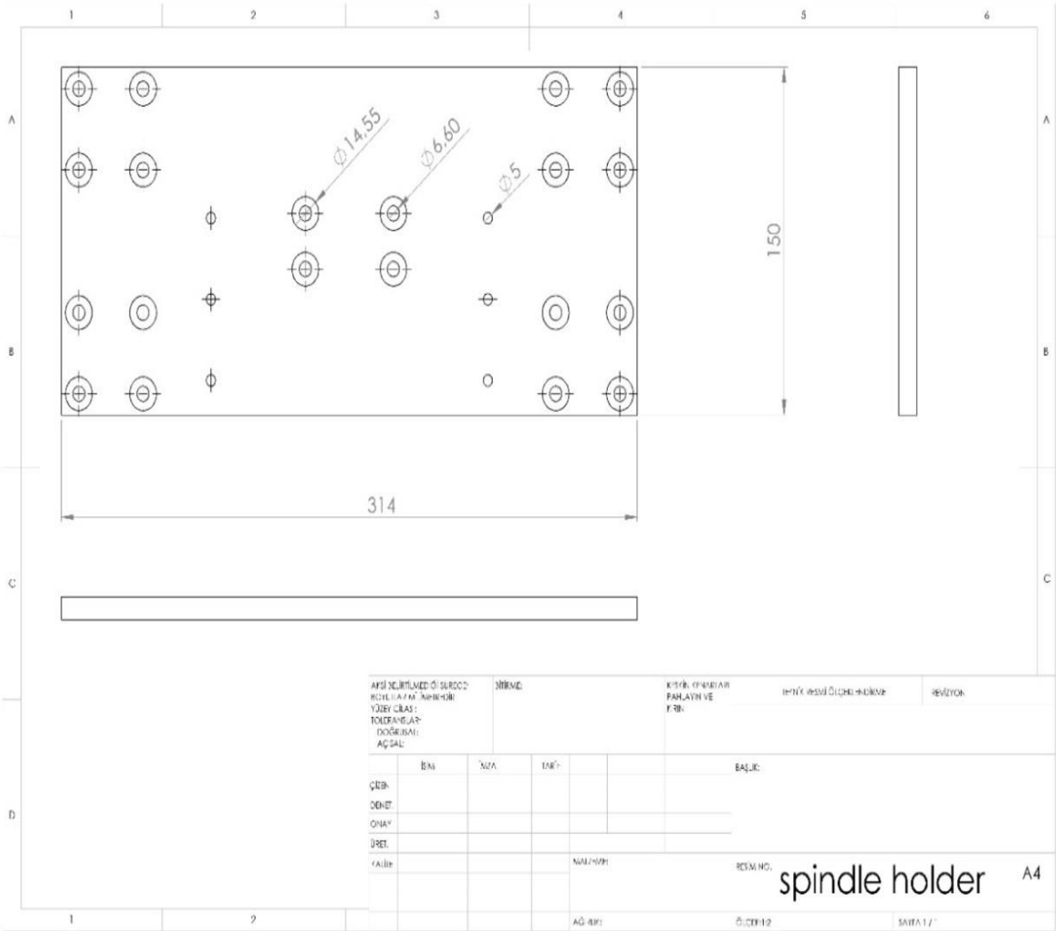

Figure Appendix A.15. Table for z-axis.

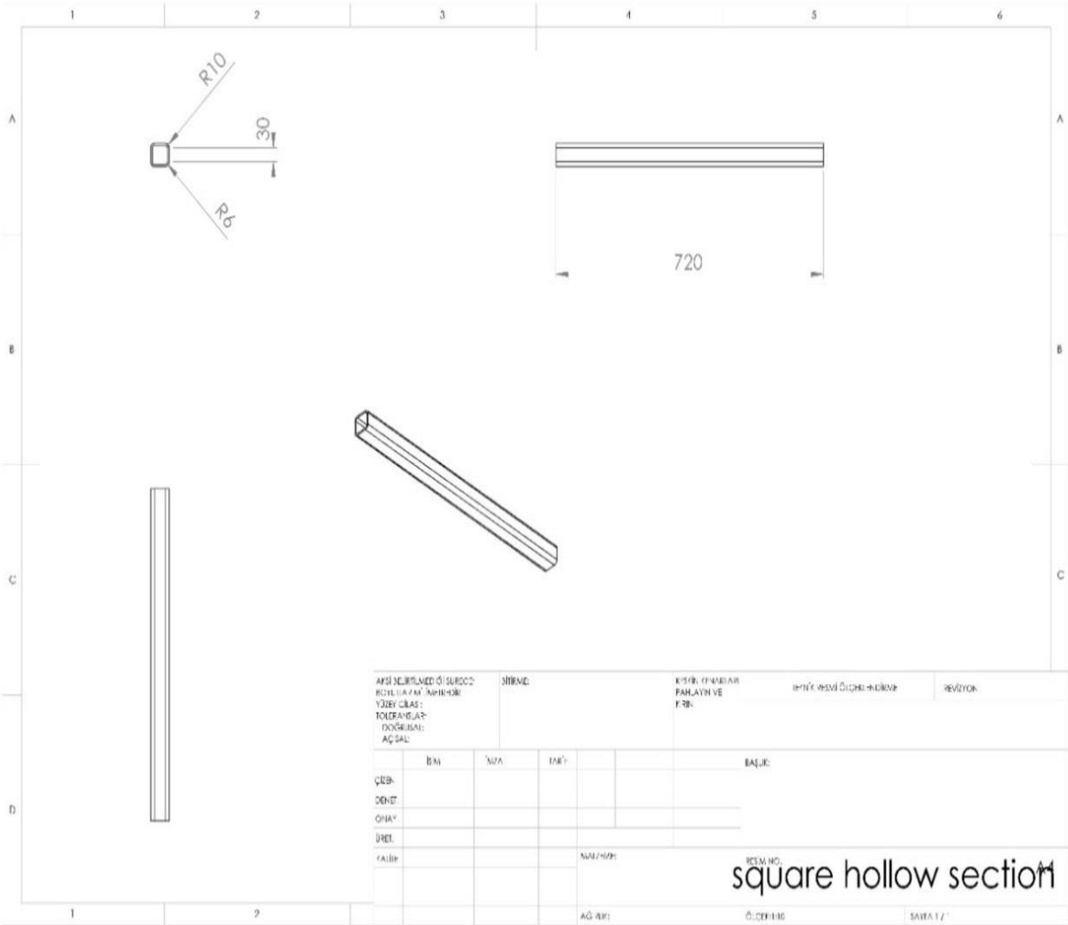

Figure Appendix A.16. Square hollow section for all linear axes.

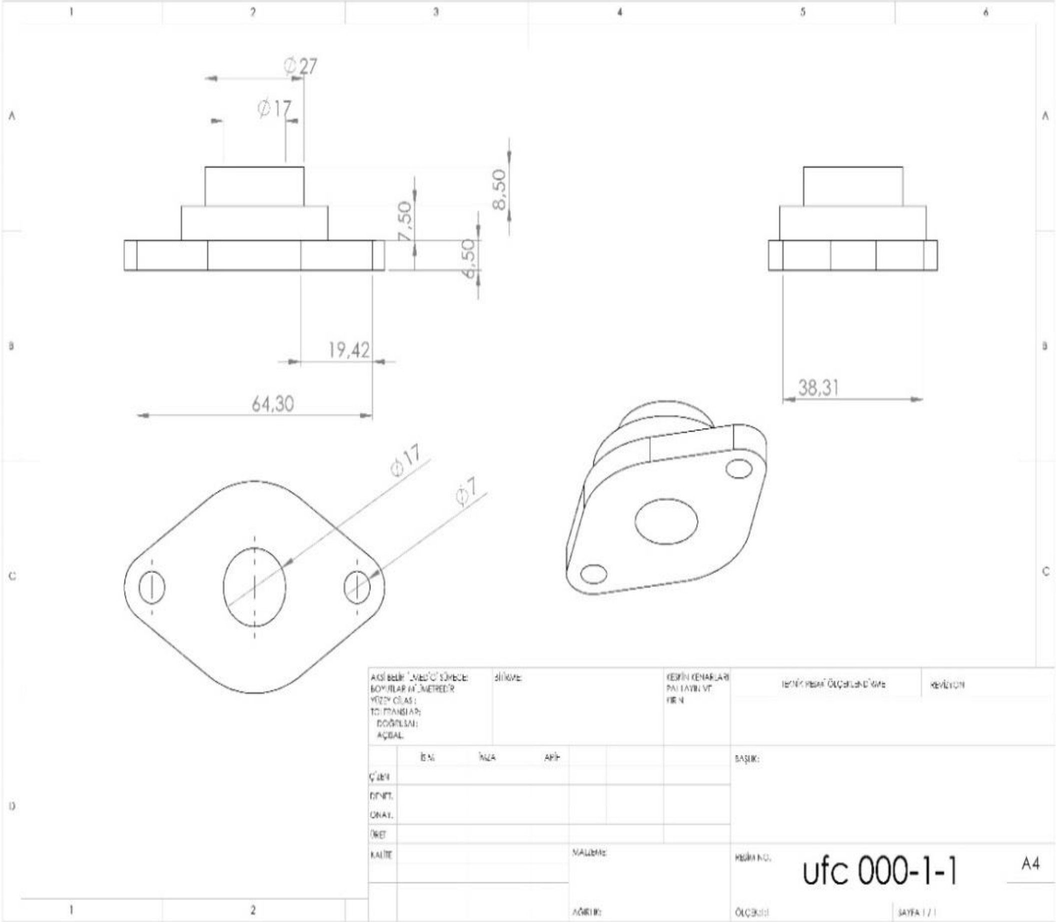

Figure Appendix A.17. Linear bearing for all the five axes.

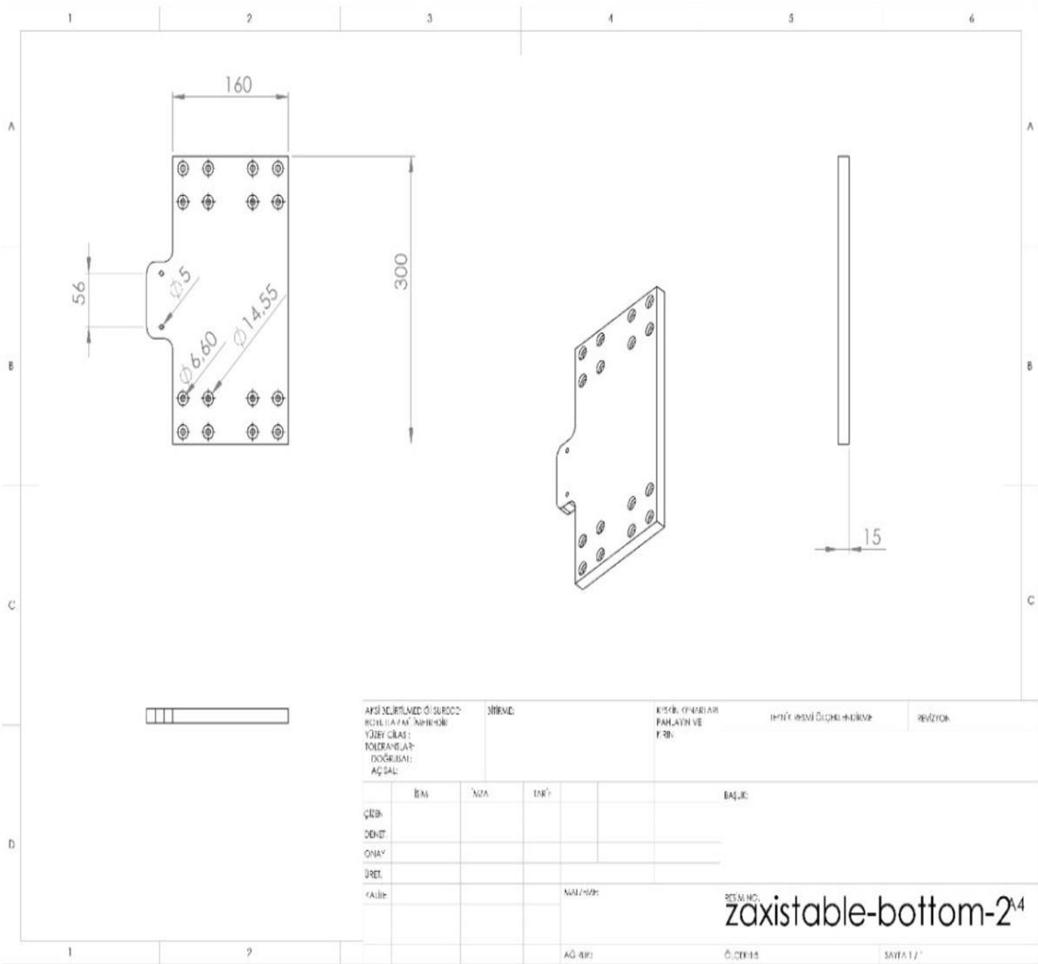

Figure Appendix A.18. Bottom table for z-axis.

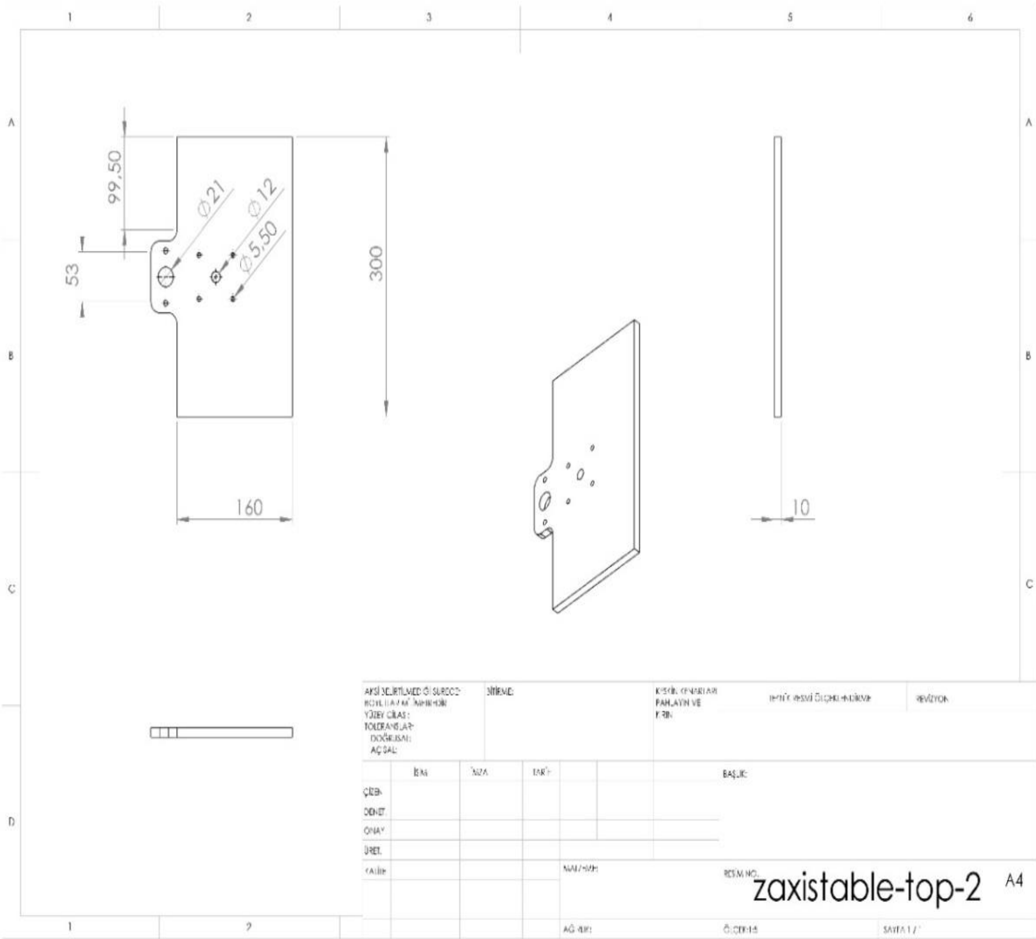

Figure Appendix A.19. Top table for z-axis.

RESUME

My full name is Syed Arslan Hassan NAQVI. I was born on December 1988, in Multan, Pakistan. I also completed my primary and middle education in Multan, Pakistan. I studied four years High School in Abu Dhabi, the capital city of United Arab Emirates (UAE). In 2011, I completed my Bachelor degree in Mechanical Engineering, at the University of Greenwich, in England. In 2012, I joined the department of Manufacting Engineering, at Karabuk University.

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