DESIGN AND ANALYSIS OF A SMALL-SCALE COST-EFFECTIVE CNC MILLING MACHINE

BY

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THESIS

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ABSTRACT

This thesis aims to explore the theories and techniques behind procedures of developing a high precision cost-effective mini CNC milling machine. This newly designed machine tool can be widely used in electrical and medical industry for making small parts and engraving small features. Various structures were explored and compared during the design stage. Different commercial products were carefully selected and purchased from the Chinese market. PMAC from Delta Tau was used as the motion controller. Different setup and configuration issues using PMAC were explored. A newly designed motion controller using Arduino and TI MSP430 was also tested and implemented as a replacement of PMAC to reduce cost. Fabricated prototype machine was calibrated and tested under various self-testing procedures to meet industrial standard. Comprehensive cost analysis and profit estimation was conducted after completion of the machine tool prototype.

ACKNOWLEDGEMENTS

I would like to express sincere appreciation to my advisor, Professors Placid M. Ferreira for his consistent guidance and support throughout the whole period of my Master's study. My special thanks also go to all my research colleagues whom I worked with, in particular Alaa Aokaily, who offered great help to me to overcome many technical hurdles. And finally, thanks to my wife, Yingjing Xiao for her endless support, love, and inspiration.

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CHAPTER 1

Introduction

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.

The traditional design philosophy of machine tools is multifunctionality and highest precision possible. For example, a shank with spindle together with tailstock can be added onto a standard three axis vertical milling machine to become a multifunctional drilling-milling-turning machine, meaning the machine tool is designed to be used for multiple instead of single purposes. However, with the dramatic increase of industry varieties and the growing demand of miniature products, these general purpose machine tools are not efficient, either in terms of machine time or cost, in manufacturing products with special sizes and precision requirements. Generally speaking, the volume of machine tool is normally three orders of magnitude larger than the volume of the object to be machined. When the object volume is below 10^6 mm^3, the typical equipment of existing process (Figure 1.1) is no longer valid. Therefore, for small objects with volume below 10^6 mm^3, large volume machine tools are usually the only choice.

In order to be able to machine small objects with volume below 10^6 mm^3 while remaining a constant relative accuracy, the precision and resolution of machines should be improved. At this level, machine tools always require high precision components and need to be fabricated with extreme precision. This will significantly increase the cost of producing such machine tools. Therefore, current industry practice tends to downsize the machine tool used to produce small volume objects, i.e. small machine for small products.

There are several advantages of using small machines to produce small sized objects. With a smaller machine size, space is saved. The energy required to operate the machine is reduced as well. It now requires less material and components to make the machine, hence bringing down the cost greatly. The weight of moving component also comes down so that during operation, the vibration and noise, as well as pollution to the environment, are markedly reduced. As the machine becomes denser and lighter, it becomes more portable. The layout of the manufacturing plant can be more flexible. The productivity and manufacturing speed also increases due to possible faster operation.

1.1 Market Research

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. Figure 1.2 is a typical CNC engraving machine made by a Chinese manufacturing company in Changsha. It is claimed to achieve a resolution of 30 µm and repeatability better than 30 µm. The interpretation and interpolation is done using a CNC control package software called Mach3. The machine only costs 500 USD, including everything required to run the machine except a PC. This type of machine is very popular in China. However, because of its low stiffness and controller robustness, it can only machine soft material such as PVC, woods and soft aluminum. Moreover, the precision and repeatability are too low to address the requirements of micro-manufacturing.

While most of the manufacturing activities have shifted to developing countries such as China and Brazil, the traditional machine tool manufacturing companies in western countries are all challenged to use their core competencies in a manner that produces highly differentiated and recognizable products. They are focused on innovative designs, and using high precision components to make high quality machine tools. The costs of these machine tools are much higher than the "Made-in-China" machines. A small company called "CNC MASTERS" in California is selling a small scale CNC milling machine called CNC Baron Milling Machine (Figure 1.3) for 6,575USD. This machine claims to have 0.001'' (25.4µm) resolution and 0.00025'' (6.35µm) repeatability, which is significantly better than "Made-in-China" machines. It also combines the interpolator and the driver into a control unit and integrates the unit onto the machine body, making the control much easier than "Made-in-China" machines. A similar product called "PCNC 770 CNC MILL" sold by its competitor company "TORMACH" has relatively similar machine size and structure (Figure 1.4). The price is slightly higher (6,850USD) while all specifications are about the same. Both companies have many accessories available to upgrade the machine such as 4^{th} rotational axis, coolant kit, and machine stands.

The demand of small scale machine tools has increased significantly during the last decade. TORMACH was founded only 10 years ago in 2002. CNC MASTERS has been in the industry a bit longer since the 1990s. Both companies have experienced significant growth in the last few years. Before the 1990s, good small CNC machines were not available for inventors, R&D professionals, or small manufacturers because the mysterious mask of CNC technology has not been revealed to the general public and the size of the workpiece required to machine using CNC are huge compared to the size now. As modern development in electrical and medical industry boosts demand for smaller parts, inventors, small/boutique manufacturers, garage entrepreneurs, product developers, hobbyists and educators all start to look for a personalized CNC machine system which is useful, affordable, configurable, and portable. Maturing technology and significant drop in computer prices have also made that possible. This is when small machine tool builders come into play. Right now TORMACH is the leading company to provide these small but fully functional CNC machine tools. However, there's still huge room in the market, both in the US and in China. US customers are looking for more affordable machine tools while Chinese customers are looking for better quality products. Therefore, a carefully designed machine tool using China-made components can meet both price and quality requests, hence serving both US and Chinese customers' needs.

1.2 General Research Objectives

The general objective of this research is to develop a mini CNC machine prototype up to industrially acceptable precision and repeatability with a very limited budget (2,000USD). This research will address all the required procedures for developing a commercial product in a machine tool company, from the early design stage to the subsequent packaging and marketing stage. Various new methods and products is discussed and used to either reduce cost or improve performance.

To accomplish these objectives, this research is divided into a number of tasks. The research tasks can be summarized as follows:

(1) Market analysis. Determine the current market status of small scale machine tools and predict the market potential of the new small scale CNC machine.

(2) Machine design. Various structure designs will be compared and analyzed to come up with an optimal structure for the machine. Critical components required such as motor and linear guides will be carefully compared and selected.

(3) Machine fabrication. All the body parts will be machined and the components will be purchased through various suppliers. Machine will be assembled inside the lab.

(4) Controller setup and configuration. Delta Tau's UMAC will be configured as motion controller for the prototype machine to perform various tuning and testing tasks. A self-designed servo controller will be fabricated and tested on this machine.

(5) Machine test and calibration. The finished prototype machine will be tested using circular testing method.

(6) Total machine cost will be analyzed and a comprehensive business plan will be generated.

The outline of this thesis will generally follow the task orders described above.

1.3 Summary

In summary, this chapter gives an overview of the motivation and procedure of developing a cost-effective mini CNC machine. The current market is lack of an affordable small-scale high precision machine tool system that can be used for small volume production. The machine described 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 machines.

1.4 Figures and Tables

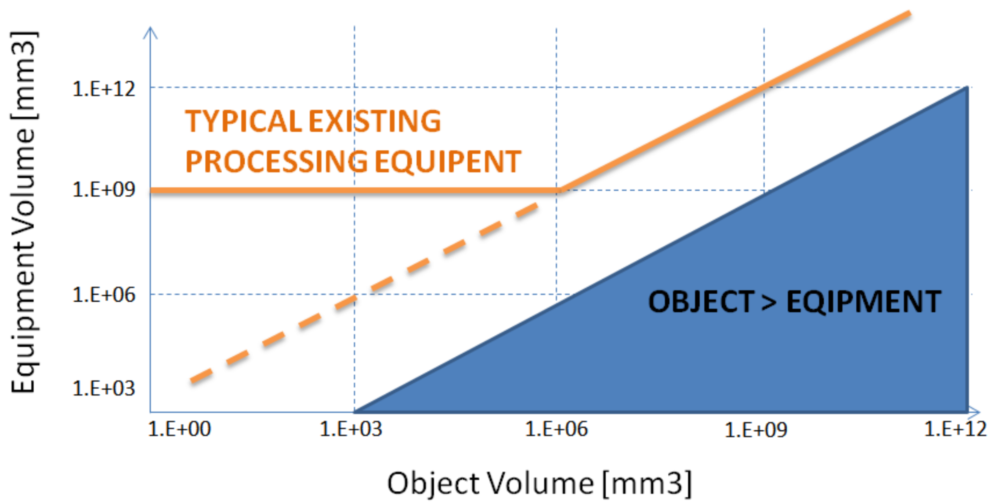


FIGURE 1.1 Relationship between workpiece and equipment size [12]

FIGURE 1.2 Mini CNC Engraving Machine Made in China

FIGURE 1.3 CNC Baron® Milling Machine

FIGURE 1.4 TORMACH PCNC 770 Milling Machine

CHAPTER 2

Literature Review

The first numerical control (NC) milling machine was conceived by Mr. John T. Parsons around 1940s-1950s [14]. Parsons worked to attach servomotors to the x and y axis of a manual operated machine tool to control them with a computer that read punch cards to give it positioning instructions. The reason for devising such a system was to machine complex shapes like arcs that can be made into airfoils for airplanes. This was not a trivial task to attempt with a manual milling machine, so the NC milling machine was born.

Today's modern machinery is CNC (Computer Numeric Control) milling machines and lathes. A microprocessor in each machine reads the G-Code program that the user creates and performs the programmed operations. Personal computers are used to design the parts and are also used to write programs by either manual typing of G-Code or using CAM (Computer Aided Manufacturing) software that outputs G-Code from the users input of cutters and tool path.

In this chapter, some literature relevant to CNC concepts and general design and control of CNC machine will be reviewed. The numerical control aspect are the focus in this review.

2.1 CNC concepts

An important advance in the philosophy of NC machine tools was the shift toward the use of computers instead of proprietary controller units in the NC system of the early 1970s. This gave rise to the computer numerical control (CNC). CNC is a self-contained NC system for a single machine tool including a dedicated minicomputer controlled by stored instructions to perform some or all of the basic NC functions [1]. It has become widely used for manufacturing systems mainly because of its flexibility and less investment required.

Replacing conventional NC hardware with software as as much possible and simplifying the remaining hardware is one of the objectives of CNC systems. While most interpretation and interpolation functions can be replaced by proper software, the remaining hardware must contain at least servo amplifiers, transducer circuits, and interface components, as shown in figure 2.1.

The software portion of a CNC system must consist at least of three major programs: a part program, a service program, and a control program [11]. The part program contains the geometry description of the part being produced and the cutting conditions such as spindle speed and feedrate. Computer Aided Manufacturing (CAM) software can be used to generate this part program. The service program is used to check, edit, and correct the part program. It usually has a user interface that allows the user to operate the machine easily. The control program accepts the part program as input data and produces signals to drive the axes of motion. It performs interpolation, feedrate control, acceleration and deceleration, and position counters showing the current axes position [11].

Most closed-loop CNC systems include both velocity and position control loops. The velocity feedback is usually provided by a tachometer and the position feedback is usually provided by an encoder or resolver. CNC software can also retrieve velocity feedback from encoder by differentiating the input signal [11].

The computer output in CNC systems can be transmitted either as a sequence of reference pulses or as a binary word. If the reference pulse sequence is generated, each pulse generates a motion of 1 BLU of axis travel. The number of pulses represents position and the pulse frequency represents axis velocity. In an open-loop system, these pulses are the control signal of a stepper motor. In a closed-loop system, these pulses can be fed as a reference signal [11].

2.2 Design consideration of CNC machine tools

CNC machine tools must be better designed and constructed, and must be more accurate than conventional machine tools. It is necessary to minimize all non-cutting machine time, by fast tool changing methods, and minimize idle motions by increasing the rapid traverse velocities to make the use of the machine tool more efficient.

Digital control techniques and computers have undoubtedly contributed to better accuracy and higher productivity. However, it should be noted that it is the combined characteristics of the electric control as well as the mechanical design of the machine tool itself that determine the final accuracy and productivity of the CNC machine tool system.

High productivity and accuracy might be contradictory [11]. Because high productivity requires higher feed, speed and depth of cut, which increases the heat and cutting forces in the system. This will lead to higher deflections, thermal deformations and vibration of the machine, which results in accuracy deterioration. Therefore, to achieve high operating bandwidth while maintaining relatively high accuracy, the structure of CNC machine tool must be more rigid and stiff than its conventional counterpart.

To achieve better stiffness and rigidity of structure, several factors should be considered in the design. The first concern is the material. Conventional machine tools are made of cast iron. However, the structures of CNC machines are usually all-steel-welded, constructed to achieve greater strength and rigidity for a given weight. In addition, better accuracy is obtained in CNC machines by using low-friction moving parts, avoiding lost motions and isolating thermal sources. Regular sliding guides have higher static friction than the sliding friction. The force used to overcome the static friction grows too large when the guide starts to move. Due to inertia of the slide the position goes beyond the controlled position, adding overshoot and phase lag to the system response, and affects the accuracy and surface finish of the part. This can be avoided by using slides and leadscrews in which the static friction is lower than the sliding friction [11]. For example, rolling type parts such as ball-bearing leadscrew and recirculating linear slides, as shown in figure 2.2, can be used. Detailed discussion of selecting these components will be included in chapter 4.

Generally speaking, the entire machine component must use rigid and strong material. The spindle should have high strength, sustain a high temperature and be supported by large bearing. The clamp system should be strong enough to hold work piece when the machine faces a moveable part during the manufacturing process. In addition, clamping system should be efficiently moved, fast in clamping or unclamping the work piece with fast movement during the process. The choosing of cutting tools is important in order to make sure it will not break when cutting the work piece.

2.3 Summary

In conclusion, this chapter mainly summarizes some key concepts of computer numerical control and design considerations of CNC machine tools mentioned in literature. These concepts are implemented in the whole design process in this project. Several components are chosen based on the reasons discussed in section 2.2. The servo controller architecture developed in the final stage exactly follows the concepts of CNC software described in section 2.1. The literature provides clear background knowledge and guidance for the development of a small scale CNC machine tool.

2.4 Figures and Tables

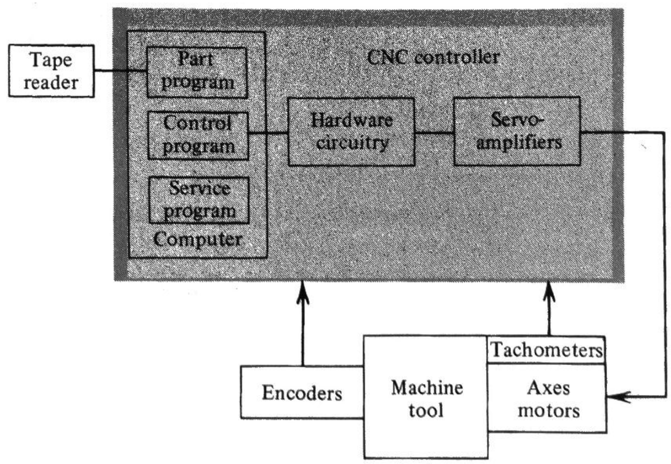


Figure 2.1 Schematic diagram of a CNC system [11]

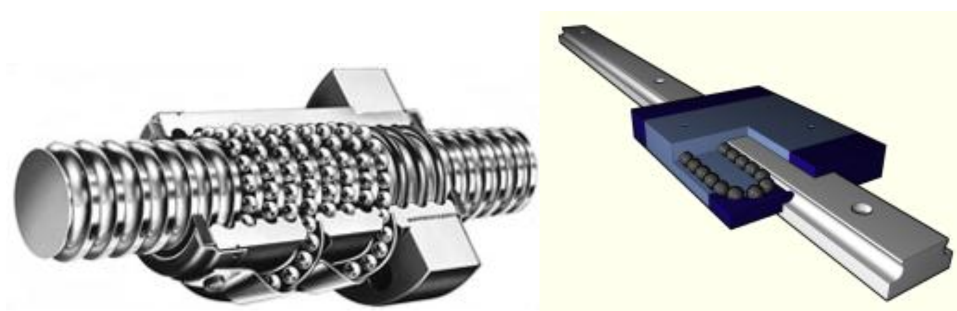


Figure 2.2 Ball-bearing leadscrew and recirculating linear slides [13]

CHAPTER 3

Structure Design and Analysis

Machine structure is the “backbone” of the machine tool. It integrates all machine components into a complete system. The machine structure is crucial to the performance of the machine tools since it is directly affecting the static and dynamic stiffness, as well as the damping response of the machine tool. A carefully designed structure can provide high stiffness, result in higher operation bandwidth and more precise operation. A small-scale machine tool generally requires even higher stiffness than the ordinary large-scale machine tool since it is usually operated at higher speeds. There are several other issues related to the machine structure such as symmetry, connectivity and errors. In this chapter, some most common structures used on machine tools will be compared and analyzed.

The desired structure should achieve high stiffness and a workspace of at least 50*50*40 mm^3. The accuracy of the prototype should achieve at least 50µm and the repeatability should be within 10µm. To achieve higher efficiency, the maximum machine speed should be as fast as possible. Hence a large operation bandwidth is desired (0-10Hz). Last but not least, the cost of the whole structure frame should be controlled under 500 USD to give more room for selecting electrical components.

3.1 Structure Comparison

The two most common machine structures in the industry are open frame structures and closed frame structures, as shown in Figure 3.1 and Figure 3.2. Generally speaking, the closed frame structure provides a strong ridged structure loop, symmetry, and good thermal stability, which provides better stiffness than the open frame structures generally used for easy access to the work zone, with the same order-of-magnitude in size. Closed frame structures typically are used in large precision machines such as CMMs. The work pieces to be machined or measured are generally large and heavy. Therefore it is much easier to move the tool with respect to a fixed work piece. This structure consumes more material, hence is more expensive to build.

Open frame machine tool structure is also called a C or G structure. This structure is very commonly seen in small machines. Although the structure is asymmetrical, which leads to undesirable thermal gradients and bending moments, it’s an ideal structure for small machines. The work pieces are usually small and light so the material removal rate is much smaller than those big work pieces made by the big machine, so the error caused by thermal effects is not a significant issue. A critical part of the structure is cantilevered, which leads to Abbe errors [17], but this can be compensated by spring loading in the opposite direction or pre-compensating bending in design. The material required to construct this structure is also less than the close flame structure and hence much cheaper to make. After evaluating the pros and cons of both structures, the author decides to use an open frame structure for this small scare machine.

There are many different variations on an open frame structure. Generally they can be grouped into two categories distinguished by the tool orientation, i.e. vertical tool position and horizontal tool position, as shown in Figure 3.3 and in Figure 3.1.

In the horizontal configuration, the work piece is fixed on vertical XY plane, which requires the work piece to be light and compact. The Abbe error on XY plane is not significant because the weight of work piece is very small and can be neglected. Spindle is mounted horizontally to ensure maximum stiffness along Z axis. This is the ideal structure for micro-manufacturing machine tools. However, the length scale of the work pieces to be machined is designed to be between 10mm and 70mm. The weight effect of the work piece with this length scale cannot be ignored, for it creates challenge to fix the work piece onto the vertical XY plane. Due to this crucial situation, the machine is designed to have typical vertical tool position open frame structure. However, a bold attempt was made in design stage by introducing a moving Z axis which flexibly transfers a vertical milling type machine into a lathe type machine.

3.2 Structural Analysis

Based on previous discussions, the typical open-frame vertical milling structure is chosen to be the support structure of this mini CNC machine. The most important part on this structure is the vertical support for z axis. This support frame can be viewed as a cantilever beam and the resonant mode of the whole machine is dominated by this support frame. In this session, a draft CAD model is first created using Solidworks and static and modal analysis is conducted using Solidworks Simulation package. To perform FEA analysis, the material and the geometry should be clearly defined first.

LY12, a hard aluminum alloy is chosen for fabricating the prototype machine's frame. This is the one of the most commonly available aluminum alloy materials in the Chinese market. A summary of its basic mechanical properties is listed below.

The price of LY12 aluminum alloy only costs about 4.5 USD per kg and it comes with a wide range of cross-section purchased as a raw material. Stainless steel is another option. But since it is more expensive, heavier, and harder to machine, it is not worthwhile to use this material for making just one machine. Therefore, LY12 aluminum alloy is the most affordable and ideal material to prototype machines in early design stage.

Figure 3.4 shows one structure designed to fix Z stage and support XY stage. The total height of the structure without motor is 407mm. The width of the support frame is 150mm. The whole structure is constructed by 1.5mm thickness LY12 aluminum plates and connected by M6 screws. The height of the structure allows around 40mm free motion on Z axis from top position to working table. A mode test is done on this structure using Solidworks Simulation package. The least four mode shapes and their frequencies are shown in figure 3.5, assuming the base surface is fixed.

From the modal analysis, the smallest modal frequency is determined to be 396Hz. The machine operating frequency should be limited well below this frequency to avoid resonance. Spindle rotation creates the highest frequencies during normal CNC operation. Using equation 3.1 we can determine the maximum allowable spindle speed during normal operation.

$$V = \frac{f*60}{n} \tag{3.1}$$

In the equation above, V is the spindle speed in RPM, f is the modal frequency in Hz, n is the flute number of the tool. Therefore, if we use a 4 flute end mill during operation, the theoretical maximum spindle speed is 5940 RPM to avoid structure resonance.

A novel structure has also been created in the design stage as shown in figure 3.5. This structure involves using a flexible hinge on Z axis which allows Z axis to rotate 90 degrees about Y axis to transform the vertical milling into a Lathe type structure. In traditional multi-purpose machine, all axes are fixed and there is an additional motor mounted on the lathe chuck to perform lathe function. By using this structure, we only need to use one spindle to do both milling and lathe, and the cost of the machine is reduced. The control of the axis is also simplified because four-axis controller board is not required. However, due to an additional degree of freedom to the structure, the position precision and alignment of the Z axis during movement becomes a huge issue. Therefore, additional alignment feature should be marked onto the machine body to ensure Z axis is sitting at the desired position after transformation. Figure 3.6 (a) shows Z axis at the vertical position; (b) shows Z axis at the horizontal position.

Due to complexity of the structure and failure to find a suitable off-the-shelf chuck that can be fixed into the spindle shank, the flexible Z axis design was not taken into the fabrication stage.

The structure shown in figure 3.4 is used for prototype. When the final product goes into mass production, the fabrication process using metal plate requires more labor force and introduces more error sources. The ideal manufacturing process to machine parts like this should be die casting. Casting significantly reduces the costs when going into mass production and creates identical parts which reduce error. Therefore, a new frame structure desired to manufacture by casting is designed as shown in figure 3.7.

In this structure, the contact surfaces with axes are purposely designed with allowances so a grinding process can be used on these surfaces to ensure good contact between axes module. All the angles are curved for better casting performance. Grey cast ion is commonly used for such structure. A modal test is done on this structure and the first two modes are shown in figure 3.8.

The mode frequency for this structure are lower than the prototype structure, which means the spindle speed should be further limited. More analysis and optimization need to be done on this structure to achieve higher mode frequency in the future.

3.3 Summary

In conclusion, this chapter compares different structures used in traditional machine tools. Pros and cons of different structures are discussed and the most suitable structure for a mini-CNC machine is chosen. This is open-frame vertical tool structure. After this decision, three detailed designs are created and analyzed, one for prototype, one novel attempt, and one for mass production. Modal analysis is performed on two designs to obtain resonant frequencies of the structure. With this information, the maximum spindle speed can be determined.

3.4 Figures and Tables

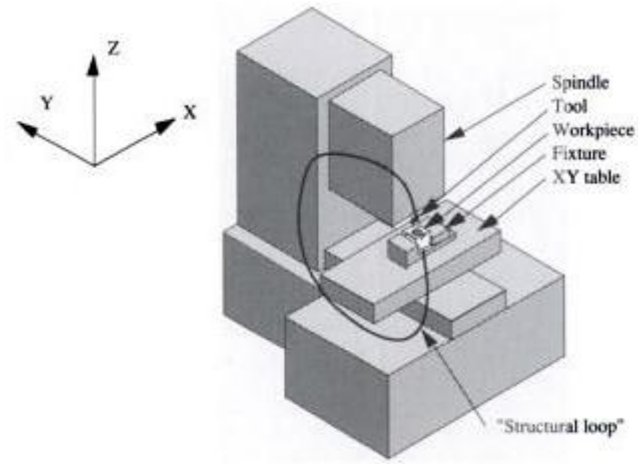


FIGURE 3.1 Open frame machine tool structure vertical tool position [17]

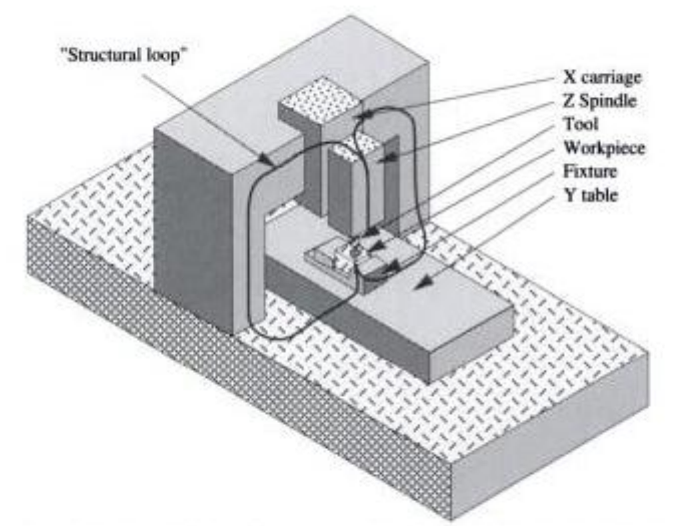


FIGURE 3.2 Close frame machine tool structure vertical tool position [17]

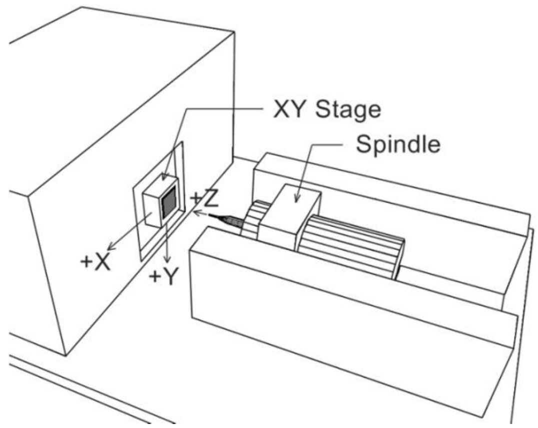


FIGURE 3.3 Horizontal tool position open frame structure

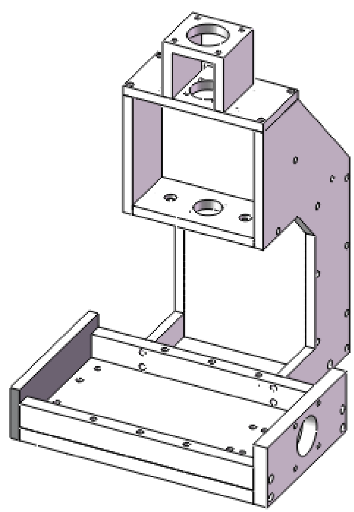
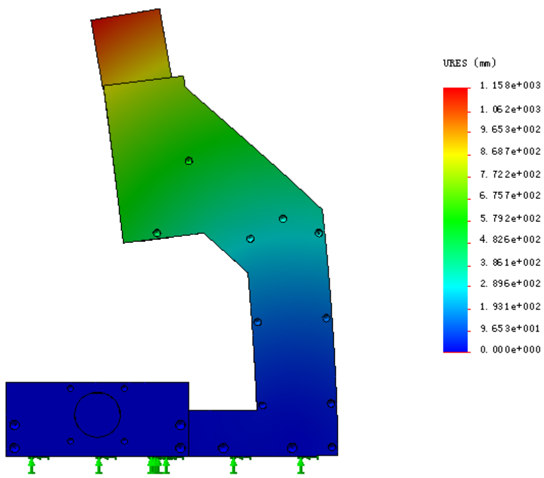
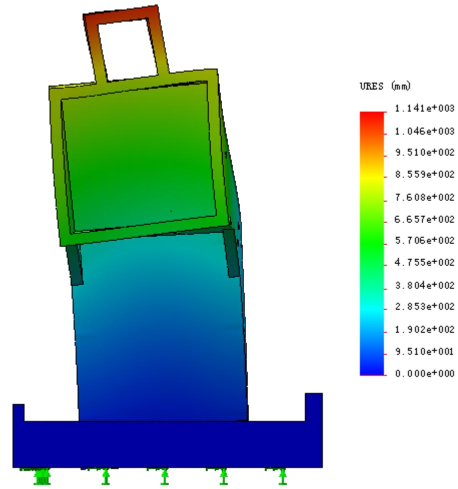


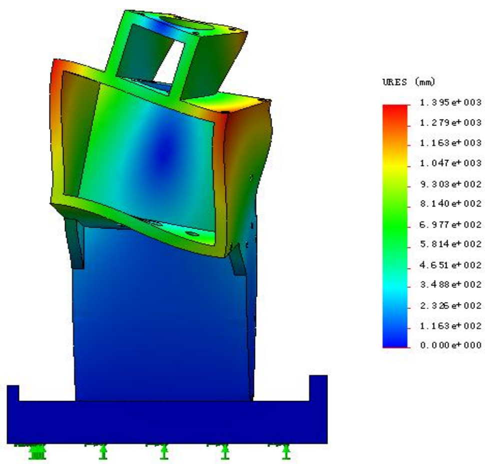
Figure 3.4 Design of open-frame support structure for mini-CNC prototype



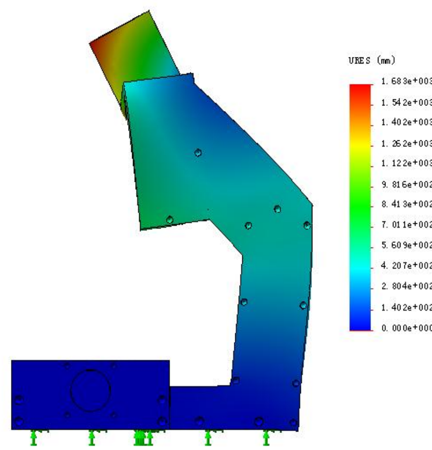
(a) Mode 1: 396.02 Hz



(b) Mode 2: 622.59 Hz

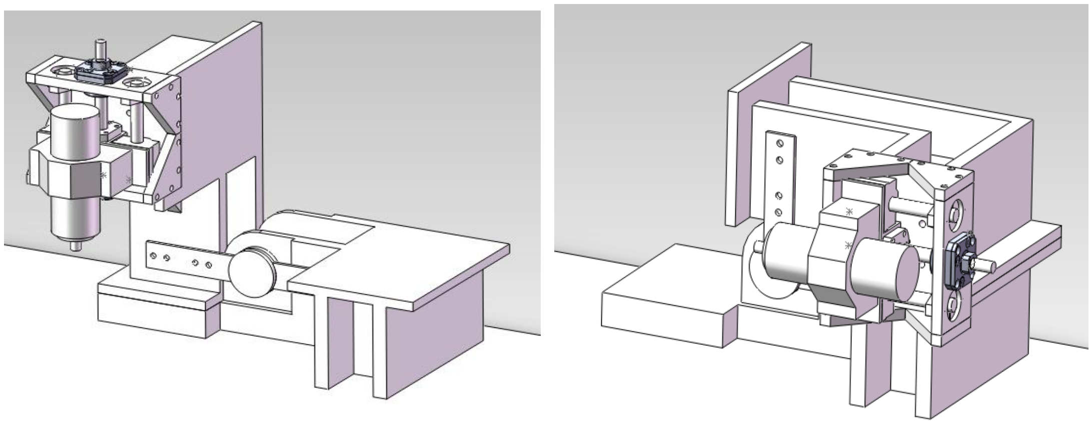


(c) Mode 3: 962.35 Hz



(d) Mode 4: 1134.5 Hz

Figure 3.5 Modal analysis of the design structure



(a) Position 1 (b) Position 2

Figure 3.6 Flexible Z axis design

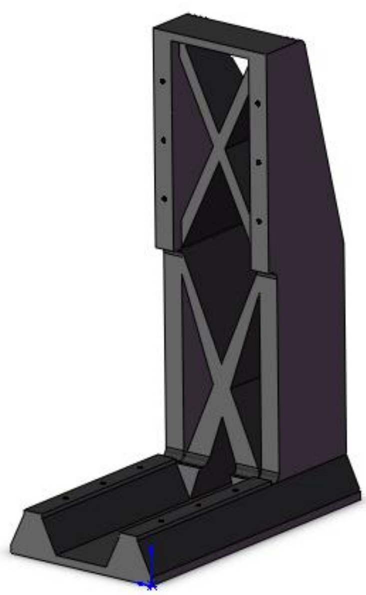
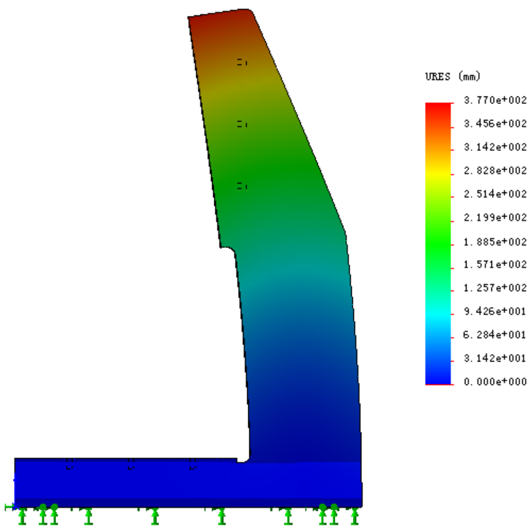
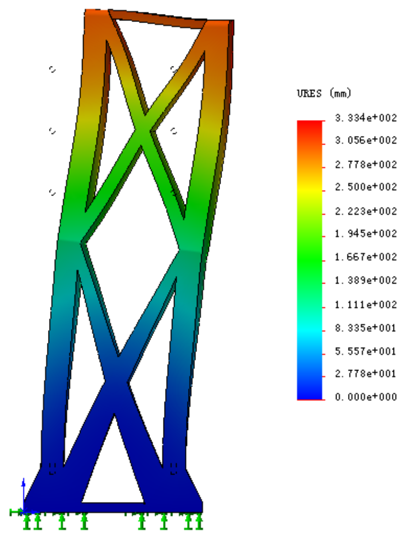


Figure 3.7 Main frame structure made by casting



(a) mode 1: 236.62Hz



(b) mode 2: 282.78Hz

Figure 3.8 Modal analysis result for cast structure

Table 3.1 Mechanical Properties of LY12 Aluminum Alloy [15]

Ultimate Tensile Strength (MPa)	445
Yield Strength (MPa)	400
Density (g/cm^3)	2.78
Elastic Modulus (GPa)	72.4
Poissons Ratio	0.33
Fatigue Strength (MPa)	117
Shear Modulus (GPa)	27.0
Shear Strength (MPa)	296

CHAPTER 4

Machine Fabrication

In this chapter, the detailed fabrication procedure of the prototype mini CNC machine is described, starting with the selection of various off-the-shelf components. The reasons behind the selection of various parts will be discussed. The unit price of all components will be listed and summarized in the cost summary section. Details that require extra attention will be mentioned during the fabrication description.

4.1 Selection of Components

4.1.1 Selection of motors

Selection of motors is carried out first because it is directly related to the driving mechanism as well as control method. Four different motors, steppers, servos, linear, and voice coils will be discussed. Stepper motor and servo motor are rotary motion motors, and linear motor and voice coils are linear motion motors. Each of them has unique strengths and weaknesses which make them suitable in certain applications. For rotary motion motors, a lead screw is always needed to transform rotary motion into linear motion, while for linear motion motors, one is not required.

Figure 4.1 shows a typical linear voice coil motor. The actuating mechanism is similar to a solenoid. These motors consist of two separate parts; the magnetic housing and the coil. Applying a voltage across the terminals of the motor causes the motor to move to one direction. Reversing the polarity of the applied voltage will move the motor to the opposite direction. The generated force is proportional to the current that flows through the motor coil. This force is almost constant in the specified stroke range of the motor. Voice coil motors do not need commutation and using a position sensor, positioning accuracies of less than one micron are achievable. However, due to limit of stroke distance and low force generation during movement, it is not suitable in our application because we require a stroke distance of at least 40mm in each axis and the force required during machining is high. The motor itself is also quite expensive (200USD for a 38mm stroke VCM). We can’t use this type of motors if we only have a 2000USD budget. However, it is widely used as actuator in the current micro machine tools (mMTs) since the precision of the motion is the highest among all four types of motors while the stroke and force required is small.

There are many types of linear motors in the current market. Voice coil is one of them. Figure 4.1 shows a typical linear induction motor model made by Aerotech. In a linear induction motor, the stator of a conventional induction motor is unwrapped and laid out flat and the "rotor" moves past it in a straight line. Linear induction motors have lots of advantages compared to voice coil motor. Although its accuracy is not as good as a voice coil, it still provides good repeatability (less than 1 micron), faster acceleration, high velocity, high force generation, smooth and no cogging movement, and a wide range of stroke models available for selection. It is the linear version of rotary servo motor. However, the main issue for our application is that it is still very expensive. An off-the-shelf model can easily cost 300 USD each and customized length costs even more. Although its capabilities are very good, it cannot be used due to budget constraints.

A stepper motor as shown in figure 4.3 is an electromechanical device which converts electrical pulses into discrete mechanical movements. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation. The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied. Servo motor internally contains a feedback sensor to tell its current position which allows precise control on angular position. The industrial servo motor speed output is proportional to the input current level. They look pretty similar to each other but the control method is completely different.

The basic difference between a traditional stepper and a servo-based system is the type of motor and how it is controlled. Steppers typically use 50 to 100 pole brushless motors while typical servo motors have only 4 to 12 poles. Steppers don't require encoders since they can accurately move between their many poles, whereas servos with few poles require an encoder to keep track of their position. Steppers simply move incrementally using pulses [open loop] while servos read the difference between the motors encoder and the commanded position [closed loop], and adjust the current required to move. Table 4.1 summarizes some key differences between servo motors and steppers.

Steppers are the most affordable actuating solution for machine tools currently. Lots of commercially available small CNC machines including CNC Baron and TORMACH we mentioned in chapter one use stepper motors to drive the axes together with an encoder to tell the current position. The control is still open-loop while the encoder is used just as an evaluation device to make minor adjustments for small position offsets. Despite the price factor, servo motors have better precision, resolution, higher speed and acceleration, and more control techniques can be used. Nowadays the price of servo motors has dropped to almost equivalent to steppers. One can easily get a servo motor together with its amplifier for less than 200USD each from the Chinese market. I choose to use the one as shown in figure 4.4 (DC36.10S1+BLM57180). The cost for each motor drive kit is 187USD.

4.1.2 Selection of linear guides and lead screws

DC servo motors are chosen to be used as actuators from last session. Therefore, we have to use lead screw mechanism to transfer rotary motion into linear motion.

When selecting the lead screw, we want to have the smallest pitch size possible to increase our resolution. The current market has various models and quality levels to choose from. C3 is the most precise level but also the most expensive. C7 is the cheapest and most commonly used level. In level C7, 0802 is the smallest pitch size model. 0802 stands for 8mm diameter and 2mm pitch. We have 0802, 1002, 1004, 1204, 1604, 1605 to choose from. The cheapest one is 1605, but it has the largest pitch and diameter. The machine size will also be affected by using large diameter lead screws. 0802, 1002 offers the smallest pitch size but the price is almost tripled compared with the 1605 model. Among 1004, 1204, and 1604 model, 1004 is the most expensive model. 1204 is only slightly more expensive than 1604 and offers a much smaller diameter. Therefore, 1204 C7 model is selected as the lead screw of our machine. The lead screw contains a preloaded circulating ball nut which eliminates backlash and reduces friction, as shown in figure 4.5.

There are also various types of linear slides to choose from. Figure 4.6 shows the three most common types of linear slides used in machine tools, i.e. cross-roller guide, recirculating ball slides, and rolling bearing slides.

Among three different slides, rolling bearing slides are the cheapest choice. It is compact, lightweight, and provides unlimited range of motion. However, it is the least stiff and has the largest friction one among the three. Recirculating ball slides are more expensive, but have less friction and are stiffer than rolling bearing slides. Cross-roller guides have limited range of motion, but enjoy the highest stiffness and robustness among three different slides, and have the same level of friction as recirculating ball slides. Since we only need limited range of travel in our machine, and higher stiffness allows the machine to operate at much higher bandwidth, so within our budget, cross-roller guide is the best choice.

4.1.3 Selection of feedback sensors

Two types of encoders are compared in this session, rotary encoder and linear encoder, as shown in figure 4.7. Rotary encoders are generally small and attached at the back of motors to sense the angle of rotation. It is cheap, easy to install, and gives unlimited range of travel. But due to the limit in size, the resolution in coding disk is very limited. For example, a 1000 pulse per rotation disk is considered as a relatively high resolution encoder disk. If the lead screw pitch is 4 mm, the resolution of this encoder is given by

$$\frac{pitch}{ppr} = \frac{4}{1000} = 0.004mm \tag{4.1}$$

Also since it is not attached directly on table, some features such as backlash, lead screw wind up, and small vibrations of the table cannot be diagnosed.

Linear encoder is fixed directly onto the end effector so the position of end effector can be directly obtained. Pitch size information is no longer required in resolution calculation. You can directly obtain the resolution information from product specification (i.e. 5 micron or 1 micron) to decide whether this meets your requirements. However, it only has limited travel range, is more expensive than rotary encoder and the installation procedure is more complex.

Since the range of travel on our mini CNC machine is relatively small, we can find small linear encoders within our budget and obtain the position information of the table directly. Therefore, linear encoder with 1 micron resolution is selected as feedback sensor on our machine.

4.1.4 Other essential parts and accessories

The next important component of the machine is the spindle. The desired spindle used on our machine should have less runout error, higher RPM for small tools, and be cheap. Good spindles are very expensive. For example, Westwind air bearing spindle can easily cost 2000USD each. However, there are many DC motors available in Chinese market which can be used as our spindle axis. The kit that was purchased contains one 300W DC motor, 48V power supply, amplifier and the mount bracket, as shown in figure 4.8. The total price for one kit is just 80 USD. The spindle is specified to have 12000RPM and 5 micron runout error. From chapter 3.2 we have calculated our maximum spindle speed. So this spindle can satisfy our requirements.

Figure 4.9 shows the rest of the accessories necessary for fabrication, including lead screw stand, shaft coupler, Z axis shaft and rolling bearing slide, Z axis shaft stand, base mounting leg, and limit switches.

The metal parts required to construct the main structure are arranged by their shapes and thickness in order to determine the cross section and the length of raw material to be purchased. This step can minimize the waste of material by minimizing the area consumed by various pieces of geometries, as shown in figure 4.10.

From figure 4.10, we can see what cross section of the raw material should be chosen and how long it should be cut. Most pieces have regular rectangle geometry so it is easy to cut into shape by using regular cutting machine. However, some pieces, such as 240*16*50 and 50*50*150 in figure 4.10 have irregular shape. The pieces can only be cut down into shape by CNC machines such as wired EDMs, which add our costs. Detailed CAD drawing of all pieces will be listed in appendix A.

4.1.5 Cost summary

The costs of everything required to make a mini CNC machine until now are listed in the table 4.2.

For now, the total cost is well below our budget. We have approximately 500 USD budget to purchase or build the “brain” of our mini CNC machine, which is the motion controller. The setup and design of motion controller will be discussed in detail in chapter 5.

4.2 Machine assembling

After gathering all metal parts and accessories required for assembling, the procedure of making the machine is listed below step by step. Each step has a corresponding figure listed in figure 4.11.

a) Start from the base
b) Install six rubber leg
c) Install four walls of Y axis
d) Install main support for Z axis
e) Install Z axis chamber
f) Assemble Z axis leadscrew
g) Assemble Z axis leadscrew and slides
h) Fix Z axis leadscrew and slides
i) Install Z axis motor
j) Build XY axis, start from table at the top
k) Install screw nut connector underneath the table
l) Install leadscrew

m) Fix leadscrew

n) Install cross roller guide of X axis

o) Complete X axis by add front and back cover

p) Install leadscrew beneath X axis

q) Fix X table on the base

r) Install cross roller guide

s) Install two motor and complete XY table

t) Complete machine with encoder and limit switch

After the machine is fabricated, alignment of X and Y axis, flatness of the working table surface, and verticalness of Z axis are all carefully inspected by eye and tools. Several issues occurred during the assembling procedure. First, the XY table is assembled top-down. This requires a lot of screw securing procedure to be done upside down. The alignment is another big issue. If the screw thread is slightly off its desired position, there is no way to adjust the alignment back to its proper position. These issues can be easily ignored during the design stage, so the next version of the machine will include various adjusting features to compensate various manufacturing defects.

4.3 Summary

This chapter gives a comprehensive view of how this prototype machine is fabricated. The process starts from selecting various key parts, followed by purchasing different accessories, raw materials, and machine raw metal plates, and ends with the step by step assembling procedure. The total cost of this prototype excluding the motion controller is 1449 USD. If this design eventually goes to mass production, volume discount can further reduce this capital cost to less than 500 USD per machine. The total time required to fabricate one machine is less than two hours.

4.4 Figures and Tables

Figure 4.1 Voice Coil motor

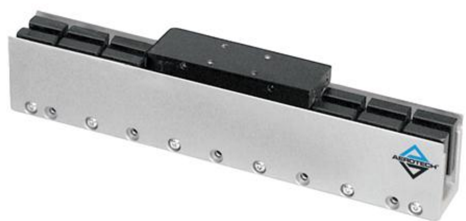


Figure 4.2 Linear motor

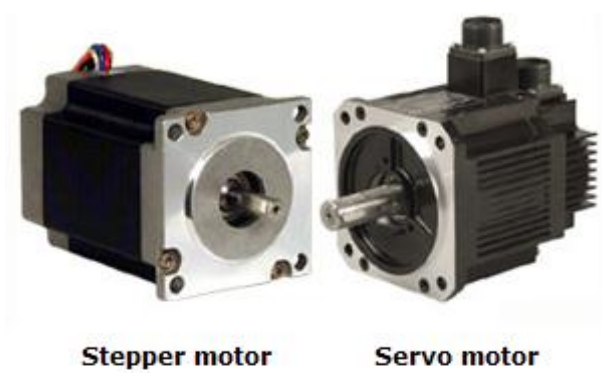


Figure 4.3 Stepper and Servo motor

DC36.10S1+BLM57180

Figure 4.4 24V DC Servo with its amplifier

Figure 4.5 1204 lead screw with circulating ball nut

(a) Cross-roller guide (b) Recirculating ball slide (c) rolling bearing slide

Figure 4.6 Linear guides

Figure 4.7 Rotary encoders and linear encoders

Figure 4.8 300W Spindle kit

Figure 4.9 Accessories required in mini CNC

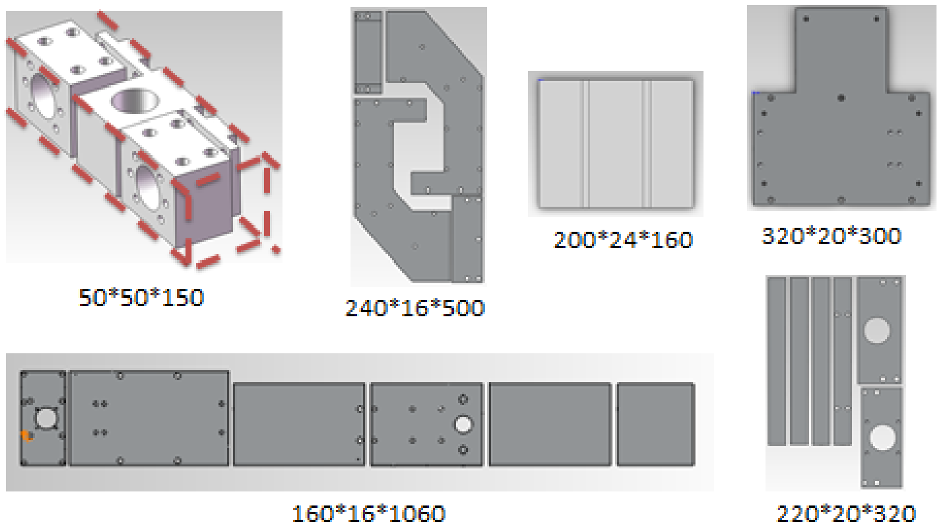


Figure 4.10 raw material layouts

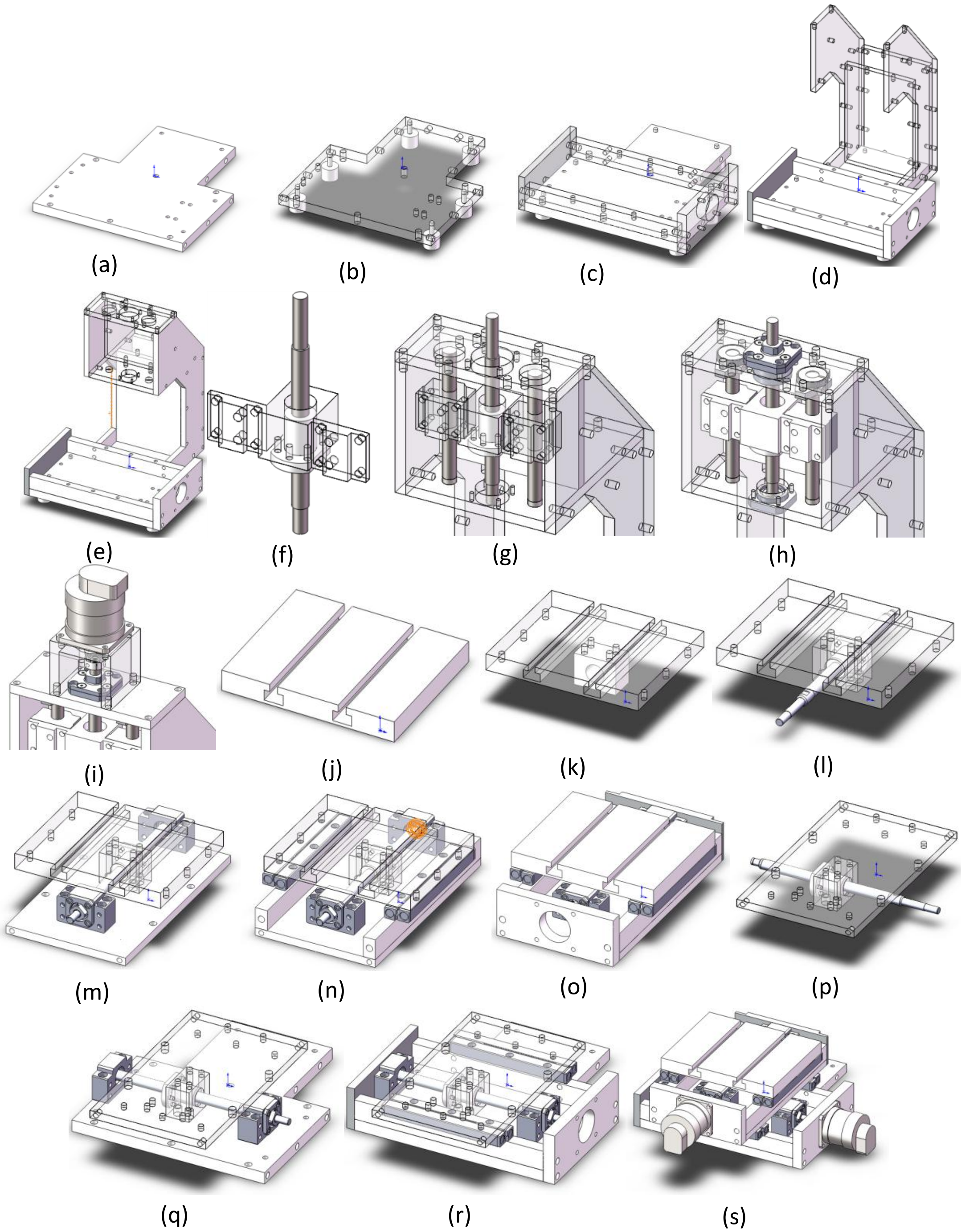
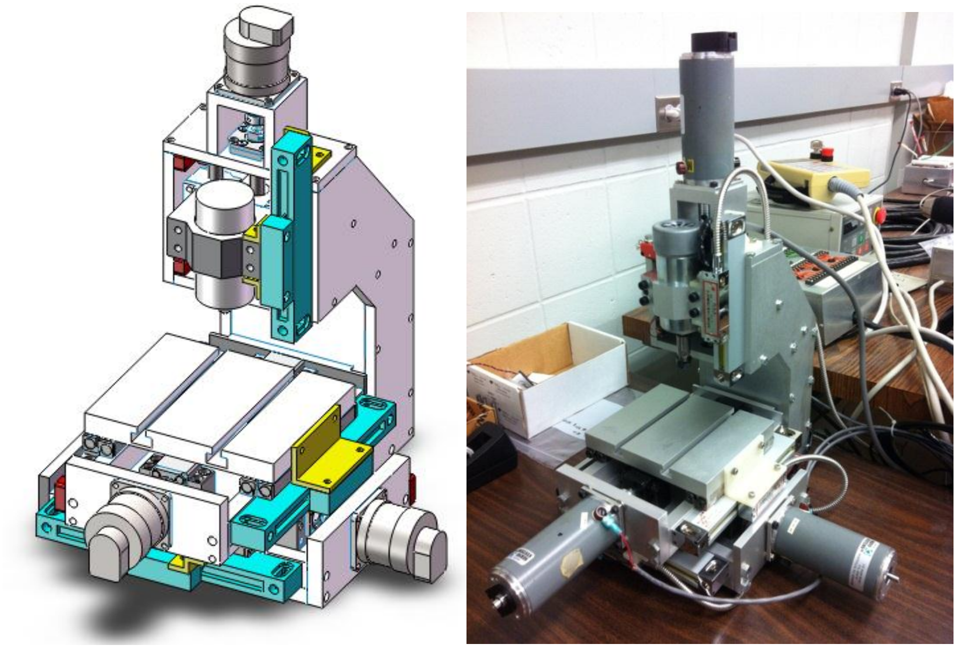


Figure 4.11 (cont.)



(t)

Figure 4.11 Step by step procedure of assembling mini CNC prototype

Table 4.1 Comparison between Steppers and servo

	Stepper	**Servo**
Price	Low	High
Control	Generally open loop	Close loop
Resolution	Determine by step/rev	Determine by encoder
Dynamic behavior	Low speed	High speed allowed
Accuracy	Low if using microstepping	High

Table 4.2 Cost summary for mini CNC prototype

Item	**Description**	**Price**
Material	LY12 Aluminum 22kg	$88
Mechanical accessories	Leadscrew *3, Leadscrew fix *3, shaft *2, slider *2, shaft fix *2, cross roller guide *4, rubber leg *6, shaft coupler *3	$231
Electrical accessories	Spindle kit, servo motor and amplifier *3, linear encoder *3, limit switch *6, motor power supply	$890
Labor cost	Roughly 50 hours of work	$240
	Total: Without motion controller	$1449

CHAPTER 5

Controller Design and Setup

The motion controller used for this mini CNC prototype machine is Delta Tau's UMAC Turbo system PLC, as shown in figure 5.1. The UMAC (Universal Motion and Automation Controller) is a motion controller system configurable to control virtually any kind of machine automation application. A single UMAC Turbo system can control up to 32 axes and thousands of digital I/O points with a great level of accuracy and simplicity of operation. The UMAC Turbo system can be configured to interface with virtually any kind of amplifier, motor and feedback device. In addition, the UMAC can use different kinds of communication methods with the host computer, including USB, Ethernet, RS-232 and PC/104 bus communications [5]. The UMAC used in our lab is a modular system built with one Turbo PMAC2 CPU board and two ACC-24E2A axes interfaces which is allowed to control up to 8 axes. The communication with PC is established through USB.

UMAC can be configured and controlled through many different Delta Tau's software interfaces. In this chapter, three software interfaces will be used to configure, tune, and control the CNC milling machine.

Pewin32 Pro2 is Delta Tau's PMAC Executive software for Microsoft 32-Bit Windows that enables the configuration, control and troubleshooting of a PMAC (Programmable Multi-Axis Controller). At its core, Pewin32 Pro2 provides a terminal, a text editor for editing Motion/PLC programs and a workspace environment. Additionally, there is a suite of tools used to configure and work with PMAC and its accessories. Pewin32 Pro2 is a development tool for creating and managing specific PMAC implementations. A screenshot of the workspace is shown in figure 5.2 [6].

PmacTuningPro is a configuration tool as well as a diagnostic tool to help create and manage the various aspects of tuning the motors. It provides basic tools for current loop tuning, PID tuning, extended servo algorithm tuning, trajectories, DAC calibration, open loop test, notch filter and low pass filter, and real-time motor status display. A screenshot of the workspace is shown in figure 5.3 [3].

The PMAC-NC Pro2 software is distributed as a CNC human machine interface (HMI) with built-in customizable standard features. The PMAC-NC Pro2 can be customized with respect to number of axes, type of machine, tool offset display, custom messaging, etc. A screenshot of the workspace is shown in figure 5.4 [8].

While a complete CNC solution has been provided by UMAC to control and operate our mini CNC machine, the cost of the UMAC motion controller alone is almost twice our total budget. UMAC provides a set of powerful software tools. We can use these tools to test our machine’s precision and ensure everything is running properly. However, this is not a long time CNC solution in terms of the cost. Therefore, a simple servo controller is designed and implemented to give a cheaper motion control solution.

5.1 Hardware connection and setup

The first step is to connect all physical devices to the UMAC system. The CNC prototype machine has three axes. Each axis is actuated by a servo motor and the position is read by a linear encoder. Two limit switches are mounted on each axis for safety. The spindle is controlled as the fourth axis but run in open-loop as there is no feedback related to spindle speed or position.

Limit switchs must always be connected and configured first in order to ensure safety operation. Figure 5.5 shows one approach to connect limit switches.

From figure 5.5, one terminal of all limit switches are all tied together and connected to the 24V power supply. The other end is connected to its corresponding LIM port on UMAC according to its position. The FL_RT port on UMAC is also required to be connected to the GND port of the same power supply.

Once the limit switches have been connected, a flag signal from limit switch can be checked using PEWIN32 software. We do this by defining a M-variables pointing to the address of these flag input. The M-variables definition are given in Table 5.1.

Using a Watch window and inserting the appropriated M-Variables according to the table 5.1. Manually togging the switch produces a change of value in the corresponding

M-variable to see if the physical wiring is done correctly. A value of zero indicates that the flag is closed or conducting current (limit switch off), allowing the motor to run in that direction. If the value is 1, the flag is open instead (limit switch on). This stops the rotation of servo motor in that direction immediately.

The next step is connecting encoders. The encoder connectors are located in the ACC-24E2A axes interface and accept all the signals for a TTL quadrature-type incremental encoder. Figure 5.6 provides an example of how to connect encoders to UMAC.

The encoders we use in our prototype are incremental type single phase TTL signal encoders. It is one of the most basic types of encoders with no index channel and no commutation. It only has four channels: A+, B+, +5V, and GND. Therefore, these terminals are connected to the corresponding sockets. The rest are left unconnected (floating).

Once the connection is established, PEWIN32 should display the current decode value in position window. The decode mode in UMAC is set using I7mn0 I variable. I7mn0 controls how the input signal for Encoder n on a PMAC2-style Servo IC m is decoded into counts. As such, this defines the sign and magnitude of a “count”. Table 5.2 lists some common settings used to decode an input signal.

In Table 5.2, P/D means Pulse and Direction mode. It is mainly used for open-loop stepper motor position observation. X1-X4 is quadrature decode mode. TTL signal is usually decoded in quadrature mode and X4 mode can give maximum resolution. CW or CCW is determined by how the encoders are installed. If moving stage in defined positive direction results in decrement in position count, I7mn0 should be switched from CW to CCW or vice versa. In our machine, all encoders are installed in its CW orientation in all axes. Therefore I7mn0 are set to be 3 for all three axes [2].

After correctly configuring the decode mode, we can roughly determine how many encoder counts corresponds to 1cm stage movement. We use a parallel caliper to measure an encoder header movement of 1cm. Observation from position window shows that the count number changes about 10000 counts, which means 1 count is corresponding to 1 μm. The resolution of our encoders is verified.

The final step in hardware setup is motor connection. Motors are not connected directly to UMAC. They are connected to motor amplifiers and then amplifiers are connected to UMAC. UMAC is only sending the control signal (±10V) to the amplifier and the amplifier sends the high voltage to drive the motor.

Our CNC machine uses three brush type servo motor to drive three axes and one PMDC motor as spindle. UMAC is not performing the commutation for the motor, so only one analog output is required to command the motor. Figure 5.7 provides an example of connecting amplifiers to UMAC.

The connection of motor is easy. We simply connect Ref+ port on amplifier to DACA+ (pin 1) and connect Ref- to GND (pin 12), leaving all the rest pins floating. The amplifier is pre-configured to receive ±5V command input. However, UMAC can generate ±10V command voltage. The output voltage from UMAC should be limited to prevent damage to the amplifier. This is done by configuring Ix69 variable.

Ix69 defines the magnitude of the largest output that can be sent from PMAC's PID position/velocity servo loop, where x represents axis number [7]. The range of Ix69 is between 0-32767, which is equivalent to 0-10V in voltage. If the maximum voltage is 5V, Ix69 should be set to 16384 accordingly.

By now all hardware wiring setups should be completed. Jog command can be used in PEWIN32 to test whether three motors are functioning. Spindle test is a little bit different from motor of axes. Since spindle doesn't have any feedback, all tests on spindle are open-loop. To run the spindle we should first set I400 = 0 to deactivate UMAC control on motor 4. Then create M-variable M402->Y:$7821A,8,16,S, this variable point to the address of DAC output port number 4. Finally set M402 to any value between -16383 and 16383 and see the spindle spinning accordingly. 16383 correspond to 5V output.

Now the hardware connection has been completely established. A complete conceptual wire diagram is shown in figure 5.8.

5.2 Software Configuration

5.2.1 Controller Setup

The controller implemented in this machine is a standard PID servo controller. The block diagram is shown in figure 5.9.

In our system, the encoder reads the current position of the stage as output and feeds this signal back into the controller. PC is used as interpolator and transfers a pulse train as reference input into the controller. The controller subtracted these two signals and sends the error signal into a PID algorithm which generates the control signal to be sent to our amplifier. We have already setup the sensors and actuators in this system. The next step is configuring this PID controller for precision movement.

PmacTuningPro is a powerful software that allows one to conveniently tune the PID gain in UMAC system. The whole procedure follows some standard steps.

The first step is called DAC calibration. The purpose of this step is to determine the DAC bias values as well as the friction deadband. When calibration begins, the DAC is incremented in small, positive steps until positive motion is detected. Then the DAC is decreased in small, negative steps until negative motion is detected. The calibration test will give two values, DAC offset and open-loop deadband. These effects can be compensated by set I-variable Ix29 and Ix68 accordingly. Figure 5.10 illustrates the concept of DAC offset and open-loop deadband.

Ix29 serves as the offset for the single command output value, usually a DAC command. Ix29 is added to the output command value before it is written to the command output register. After processing DAC calibration in PmacTunningPro, the software can set this I-variable automatically. Ix68 adds a bias term to the servo loop output of Motor x that is proportional to the sign of the commanded velocity. That is, if the commanded velocity is positive, Ix68 is added to the output. If the commanded velocity is negative, Ix68 is subtracted from the output. If the commanded velocity is zero, no value is added to or subtracted from the output. This parameter is intended primarily to help overcome errors due to mechanical friction. It can be thought of as a "friction feedforward" term. Because it is a feedforward term that does not utilize any feedback information, it has no direct effect on system stability. It can be used to correct the error resulting from friction, especially on turnaround, without the time constant and potential stability problems of integral gain. Ix68 should be manually set in PEWIN32 to equal half of the open-loop dead-band which is determined after performing DAC calibration. Table 5.3 shows the Ix29 and Ix68 value we set for this CNC prototype machine.

The next step is an open loop test. Open loop test is very useful to determine system characteristics, such as system gain and time constant in 1st order system. This information can be used for future close-loop calculation. In this test, system input is DAC voltage (bits), system output is motor velocity (cts/sec). Using these information you can calculate system gain and time constant and determine whether this system can be approximated as a linear system over certain range of inputs. Figure 5.11 shows the open loop response of three stages in our machine.

From figure 5.11, we can see the motor 1 signal contains some high frequency noise. This might be caused mainly by noisy encoder 1 signal and external noise. Motor 2 and motor 3 are less noisy. All three motors cannot achieve steady state when constant voltage is applied. This is due to mechanical friction in lead screw and linear guides as well as motor imperfection. From these responses, we can roughly determine the time constants and open loop gain of three axes, as shown in table 5.4

The next step is tuning the PID gains. PmacTunningPro2 provides an interactive way to tune these values. Basically we modify Kp, Ki, and Kd variables based on the motors step response.

The tuning procedure started with a small value of damping (i.e. Kd=500), with no Kp and Ki effect. Perform a step input and observe the response. If the overshoot is too large, increase Kd. If the rise time is too long, increase Kp. If there is constant steady state error, increase Ki. After several times of trial and run, the optimal value of Kp, Ki,Kd for three motors are listed in table 5.5 below.

The step responses of three motors after tuning is shown in figure 5.12

Figure 5.12 shows the step responses after PID tuning have less than 5% overshoot and fast response with no steady state error. The performances are acceptable. For this prototype machine, standard PID tuning is sufficient to achieve acceptable motion. However, there are other more advanced control techniques such as feed-forward control and notch Filter which can also be implemented in UMAC. Feed-forward can further reduce the response time and improves tracking. Notch Filter and low pass filter can attenuate high frequency noise and resonances. PmacTunningPro2 can also perform ramp response and sinusoidal response to determine the system tracking performance.

5.2.2 Coordinate system, home, HMI setup

The final step in software configuration is to setup the coordinate system, home position, and HMI interface for our prototype machine. This can be done all together in one software called NCSetup. The software will guild you through various steps of the CNC machine setup including machine coordinate system, unit, home position, feedrate and spindle speed override, etc.

The Axis-Motor tab in the software is used to configure coordinate system, units, and display format, as shown in figure 5.13. In this tab, since we define a simple Cartesian coordinate system for our machine, X axis corresponds to motor #1, Y axis corresponds to motor #2, and Z axis corresponds to motor #3. The Pulse Per Unit is set to be 1000 since we define our position units in metric (mm) and in section 5.1, we found 1000 encoder pulses correspond to 1 mm length.

In Std.PLC tab, we can setup the Machine Name, PLC path, control panel, override, home control, handle, and spindle for our machine, as shown in figure 5.14. The machine name is just for your reference. NCSetup will automatically generate all required PLC program and put the file in “PLC path” with the folder name “Machine name”. “Cntl Panel” should be enabled and the type should be set to “Software” since we don’t have an external hardware panel to control our machine. “Override” should be enabled. In this area, the spindle override and feedrate override range can be set. This allows us to override the feedrate and spindle speed in real time during operation. “Home” should also be enabled because we are using a PLC program to do home search movement. “Handle” is disabled because we don’t have this piece of hardware. “Spindle” is enabled and it is set to Open Loop type because we don’t have sensor feedback to tell the spindle speed. Max RPM is set to be 10000 as shown in spindle specification, but this won’t change any effect of actual spindle speed. It just assumes the max speed of spindle is 10000 RPM and set its current speed in 0-10000RPM scale linearly.

In Machine Setup tab, the jog speed (default G01/G02 speed), Rapid Speed (G00 speed), Soft Limit, Home Offset, Home Speed, and Home trigger type can be defined, as shown in figure 5.15. Usually we define the feedrate in G-code. In here, the jog speed and rapid speed set the default value when feedrate is not specified in G-code. We set the jog speed for three axis to be 120 mm/min and rapid speed to be 600 mm/min. Positive soft limit and negative soft limit are just safety insurance in case the hardware limit switch fails. We set these two values to be 5000 counts outside the boundary of hardware limit switch’s range. The Home Offset, Home Speed, and Home trigger type, should be correlated to each other. Since we don’t have home flag, we will use either positive limit switch or negative limit switch to trigger the home position. For example, If X-axis home search movement is moving in positive direction with a speed of 10mm/s, touch the positive end limit switch, then bounce back for 5cm, the home speed should be set to 10, Home Offset to -50, and select Home trigger to be Positive Limit Switch. All parameters should be correctly set otherwise the machine will be damaged. For this prototype, the home speed for X axis is set to 10, Y axis is set to -10, Z axis is set to 10. Home offsets are set to -50, 50, and -50 respectively. Trigger flags are set as positive limit switch, negative limit switch, and positive limit switch. The complete home search movement will set the origin of the coordinate system at the top right corner of the work piece and 40mm above the working table. In CS Setup section, Feed Rate defines the maximum feed rate the machine can operate. So this value should be greater or equal to Rapid Speed you set previously.

In NCUI Registry tab, this tab manages all the files required to launch HMI interface. All settings can be left as default for now. Click Build & Download, software will automatically generate all the PLC programs, update corresponding I-variables, and download PLC programs into UMAC. If you check your PLC path directory, you will find a bunch of files contains everything required to run your CNC machine, as shown in Figure 5.16 below. These PLC files can be manually programmed to further customize the machine but is not required for this prototype machine.

After all PLC files have been downloaded into UMAC, the machine is ready to be controlled by HMI software called PMAC-NC. PMAC-NC provides a human machine interface which allows the user to graphically interact with the machine by just pressing buttons. The software also acts as interpreter and interpolator which read G-codes line by line and generate reference signals in certain frequencies to send to the servo loop.

5.3 Alternate servo controller design

The UMAC is an off-the-shelf motion controller solution for this CNC prototype machine. It provides all hardware and software interfaces to control a complete machine tool. However, due to our limited budget it is not feasible to equip one UMAC system on each machine. Therefore, we have to develop our own motion controller within the budget to meet at least some basic requirements.

The UMAC in fact is too powerful for this machine. It can simultaneously control eight axes while we only need four. Therefore, the new servo controller will only control three servo loops plus one open loop at the same time. The ideal architecture of this controller is shown in figure 5.17.

In this architecture, the Arduino UNO3 runs an open source motion controller program called Grbl. Grbl is a free, open source, high performance CNC milling controller written in optimized C that will run on a Arduino. It is written in optimized C utilizing all the clever features of the Arduino's Atmega328p chips to achieve precise timing and asynchronous operation. It is able to maintain more than 30kHz step rate and delivers a clean, jitter free stream of control pulses. A simple console script is used to stream the G-code through RS232 serial port. TI MSP430 is running in its own servo loop. It reads the encoder signal and the reference signal from Arduino, and generates controller signal using DAC which sends to the amplifier of the motor. Raspberry Pi and touch screen are additional solutions used as a replacement of PC. It can run in Linux OS which allows us to input the G-code file and develop a simple UI to operate the machine easily on touch screen.

Figure 5.18 shows the schematics of one servo controller for one axis using TI MSP430G2553. LS7366R encoder counter chip from LSI technologies is used to count TTL pulses from linear encoder and send the pulse number to MSP430 through SPI. DAC8581 chip from TI is used to generate analog voltage between plus 5 volts and minus 5 volts to be sent to the amplifier of the motor. The power on the board is supplied by two regulators, IA2405S-1W and LP295033V. IA2405S-1W DC to DC convertor took 24V as input voltage and generates ±5V as output. The linear encoder counter and encoder counter chip needs +5V to operate and the DAC8581 chip needs both +5V and -5V to operate. LP295033V power regulator took 24V as input and generates +3.3V as output. This +3.3V voltage source is mainly used for MSP430 microcontroller. Clearly various input and output pins are used on the same board. A 9 pin D-sub is used to connect to the linear encoder. Pinheads with different sizes are used for voltage input, voltage output, and debug purposes. One controller board is used to control one individual axis. Therefore it would be more flexible to increase the axis number in the future.

The internal servo loop in MSP430 is very similar to the servo loop used in UMAC except it reads pulse and direction information from Arduino as reference input. Every time it reads a pulse from Arduino, the reference position sent to servo loop is incremented or decremented by one BLU, depending on the direction information. The servo loop is running at much higher frequencies than input reference signals so it will always be able to catch up with the command speed.

The total cost for this alternative servo controller design would not exceed 300 USD. An Arduino UNO3 costs 30 USD and a raspberry PI board costs 35 USD. The cost for the PCB board running TI MSP430 would not exceed 40 USD each. The rest of the budget can be used to purchase a clean and delegate touch screen (approximately 120 USD). With the cost well controlled under 500 USD budget, the desired budget for the whole machine is achieved.

5.4 Summary

In this chapter the detailed procedures of setting up hardware and software are discussed. Delta Tau's UMAC PLC is used as the motion controller for this prototype. Detailed steps of hardware connection as well as software configuration are fully explored. The control algorithm we use in UMAC is a standard PID controller. We use trial and run method with the effects of different gain in mind to tune three axes until an acceptable movement is achieved. We've learned how to setup the HMI and how to use HMI to operate our machine. It gives us a lot of experiences and ideas about how real CNC machine is configured. In the final stage a servo controller using TI MSP430 and Arduino UNO3 microcontroller are explored and discussed to give a much cheaper motion control solution for our mini-CNC machine. The design idea proves to be feasible. The actual product fabrication has not completed yet. The controller will be fabricated and tested in the future.

5.5 Figures and Tables

FIGURE 5.1 Delta Tau's UMAC Modular Rack PLC

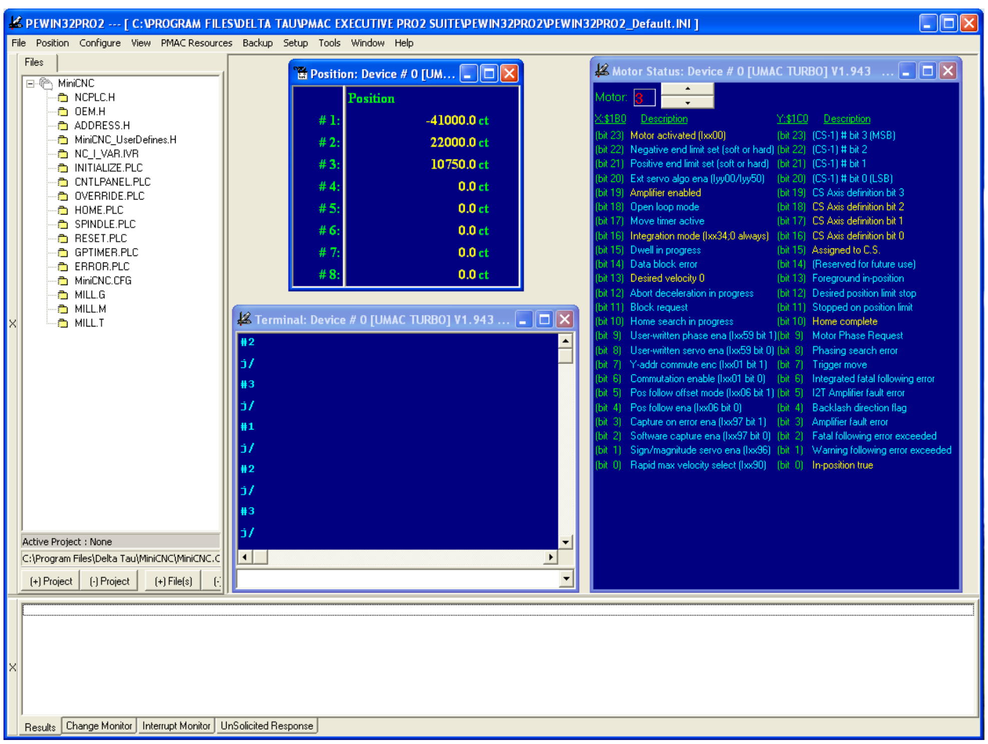


Figure 5.2 A standard interface of PeWin32

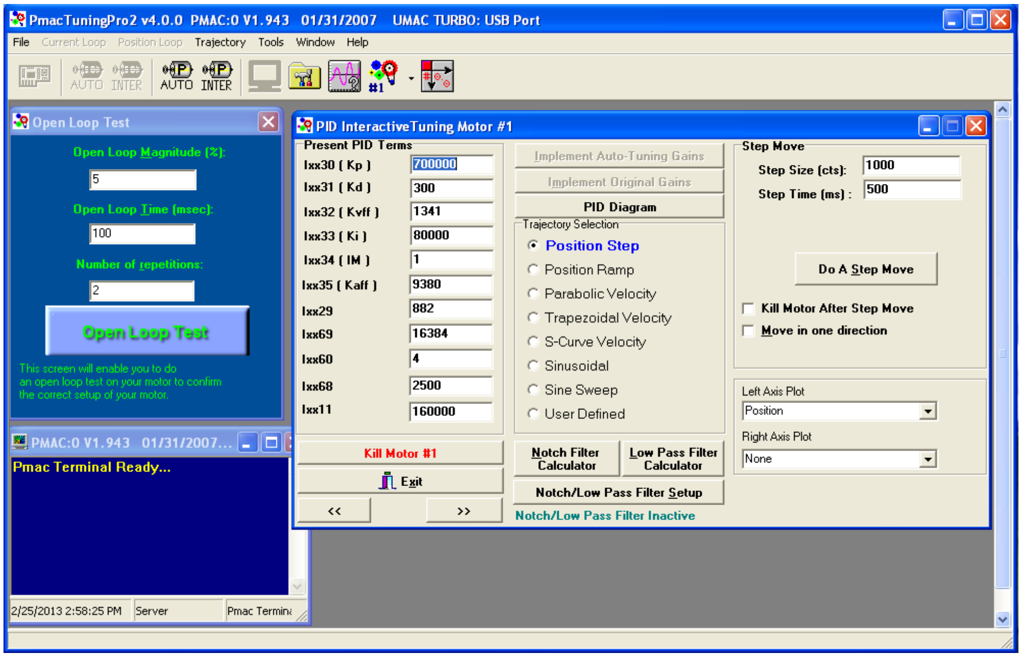


Figure 5.3 Interface of PMAC Tuning Pro

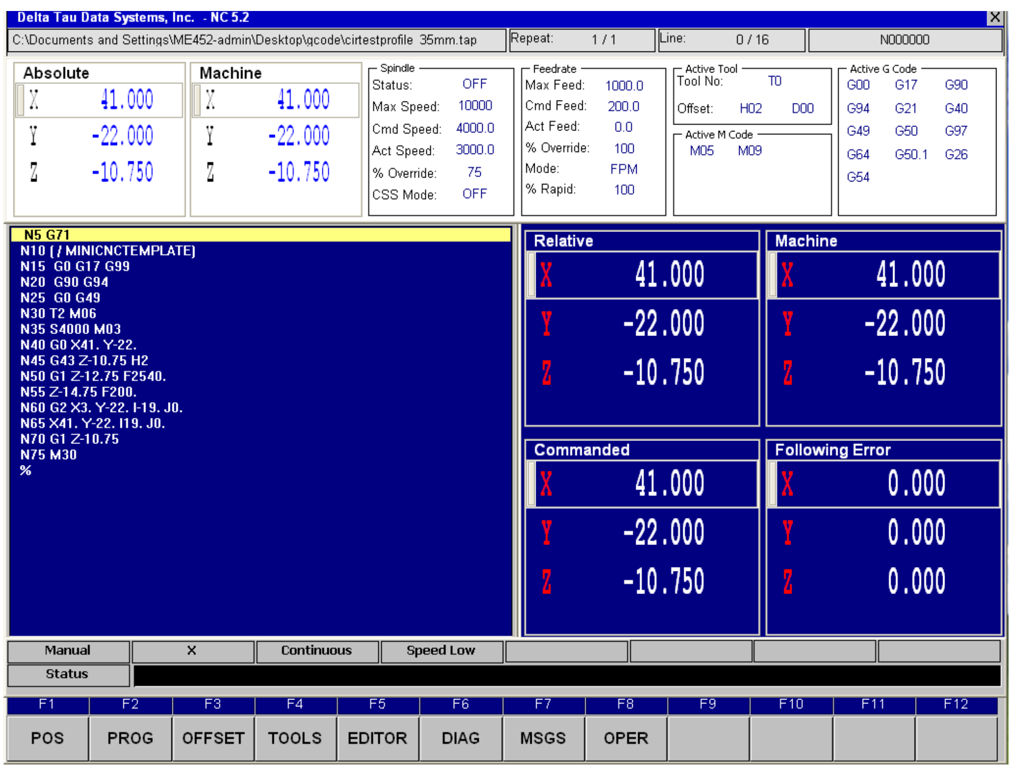


Figure 5.4 Interface of PMAC NC

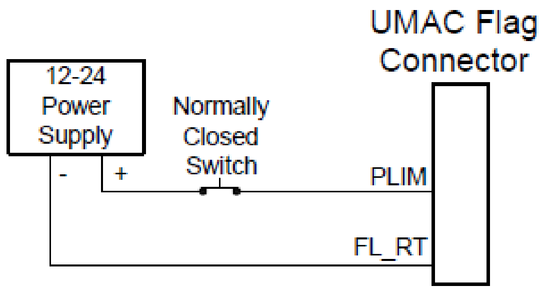


Figure 5.5 Limit switch connection example [5]

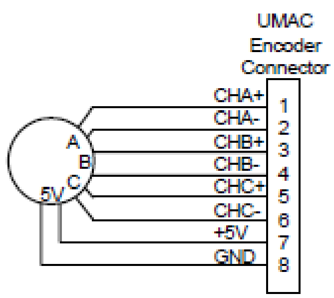


Figure 5.6 Encoder connection example [5]

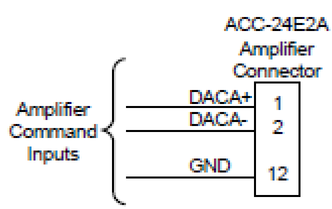


Figure 5.7 Amplifier connection example [5]

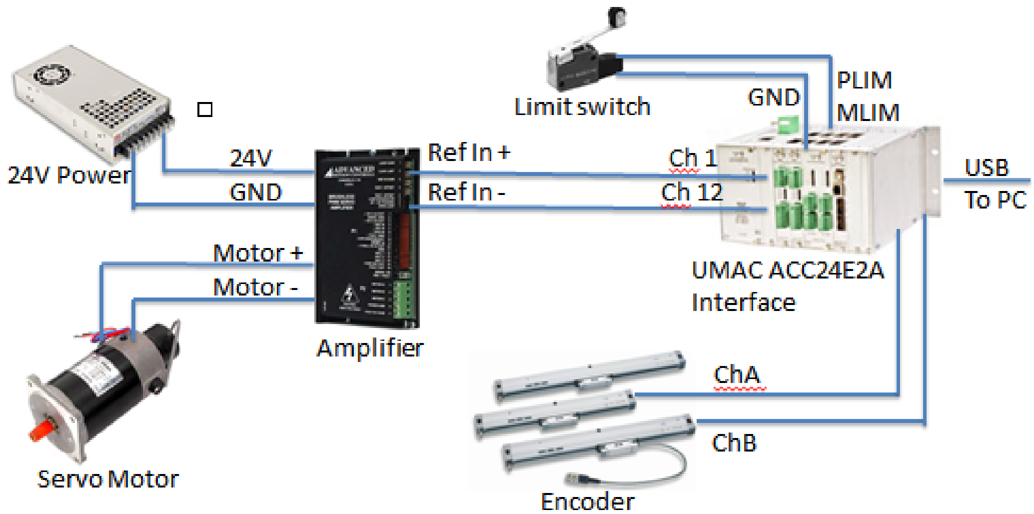


Figure 5.8 Hardware setup of CNC machine

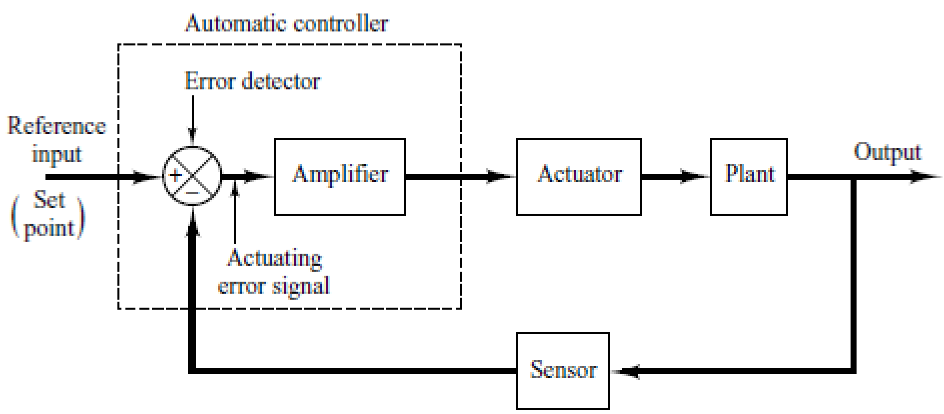


Figure 5.9 Block diagram of an industrial control system [16]

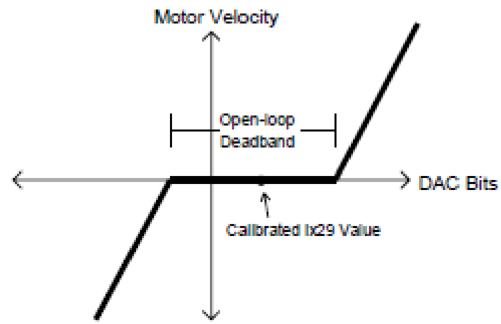


Figure 5.10 DAC Offset Illustration

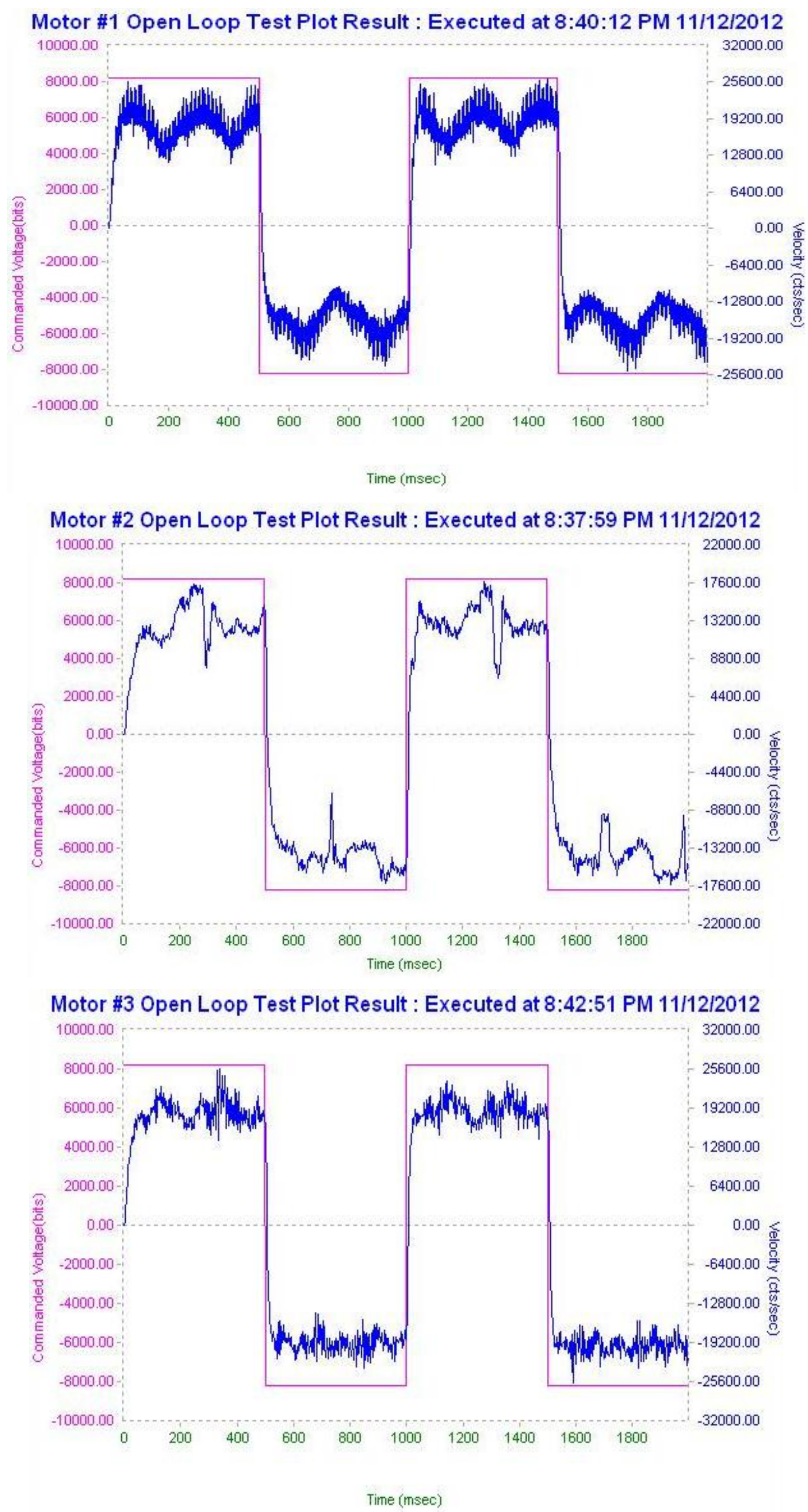
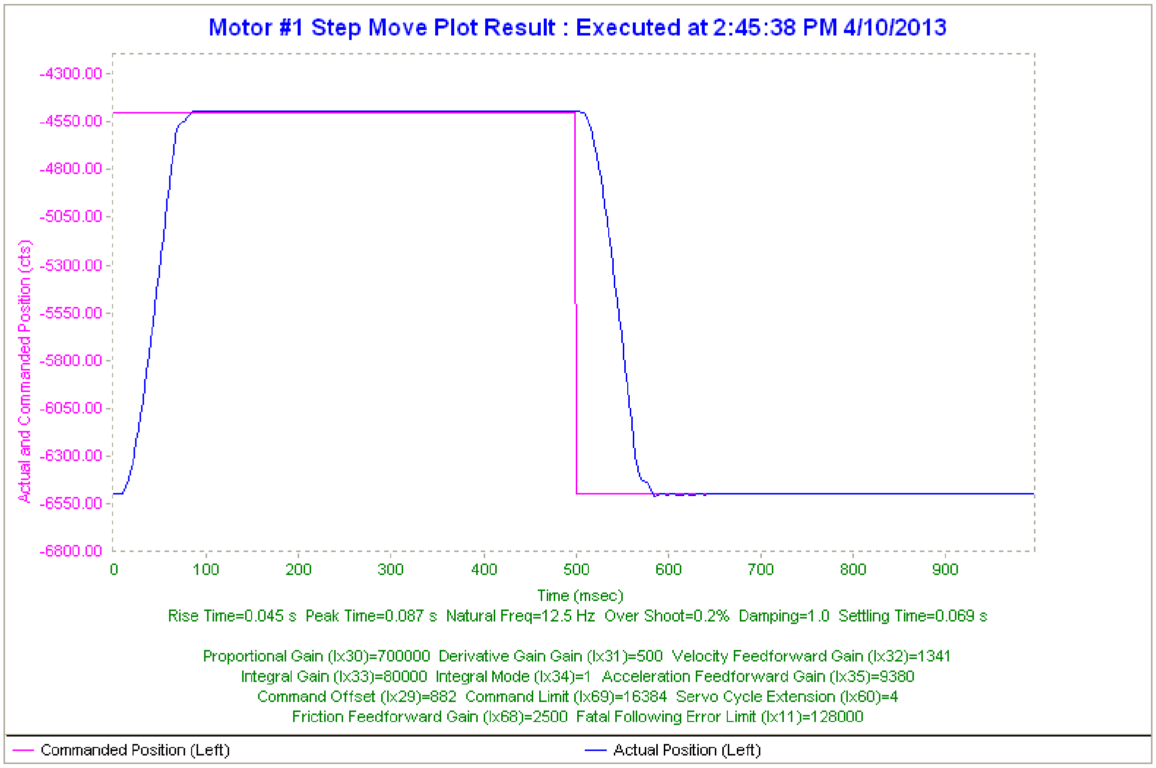


Figure 5.11 open loop responses of three motors in three axes



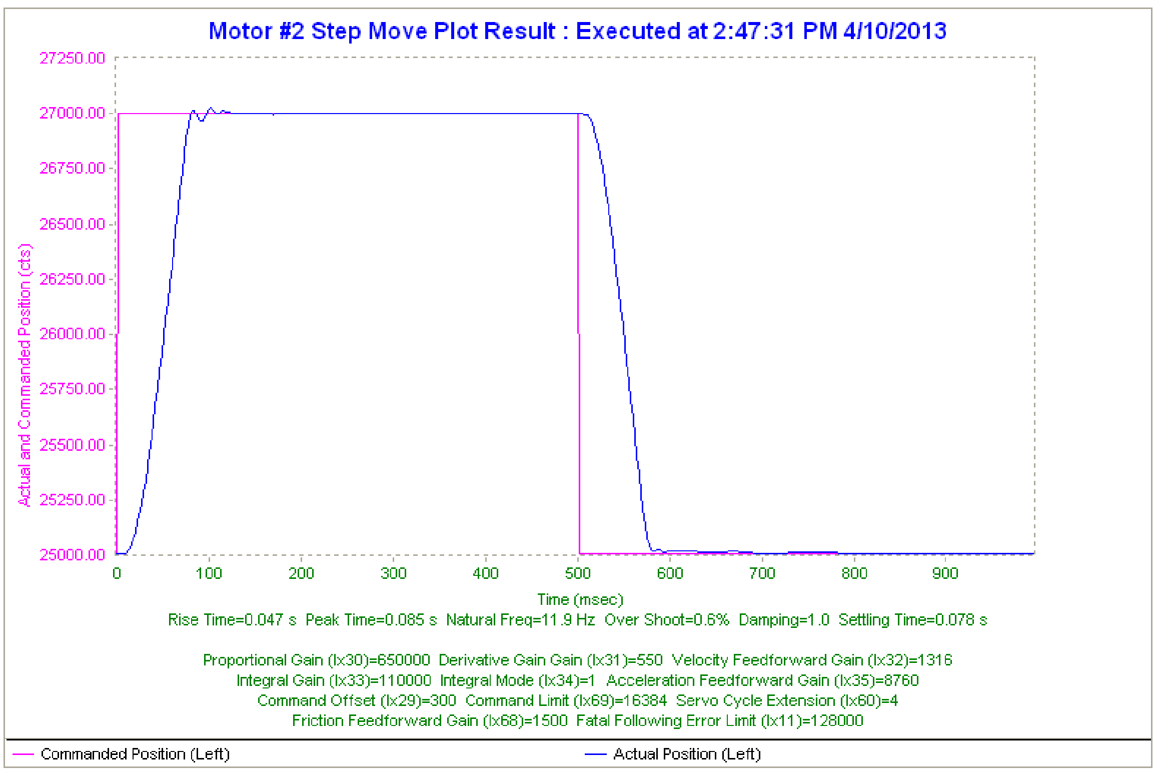


Figure 5.12 (Cont.)

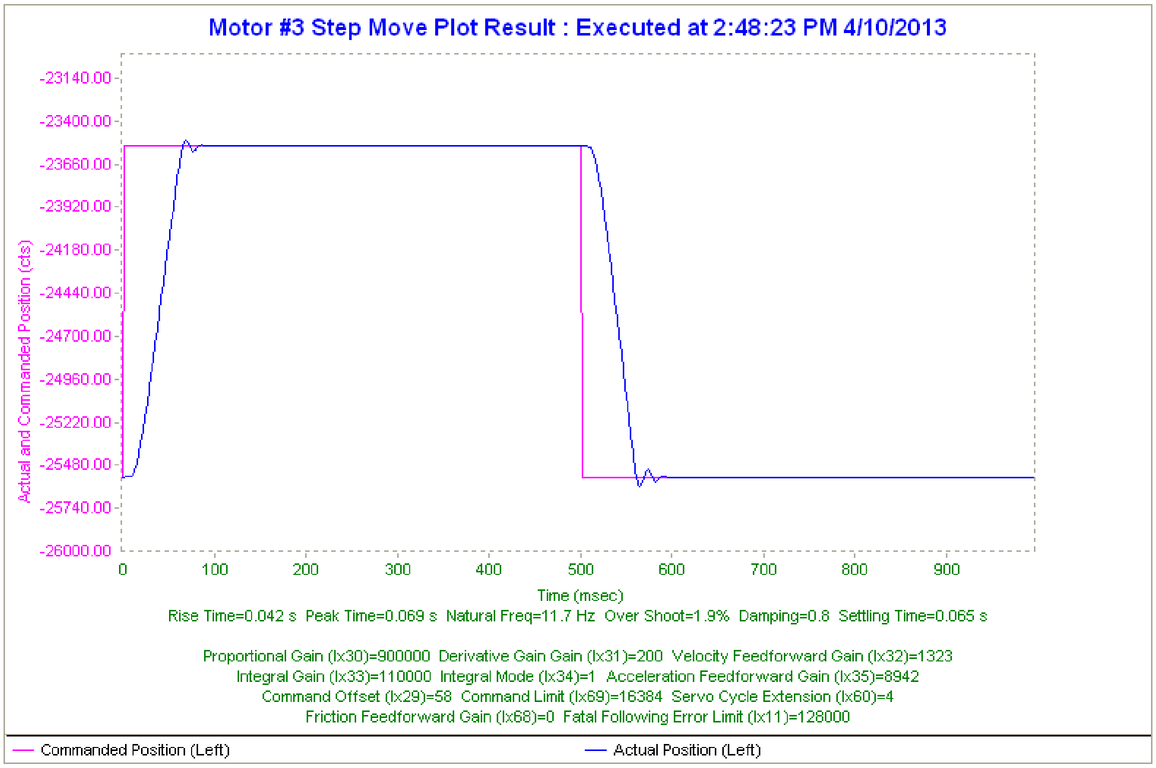


Figure 5.12 Step responses of three motors

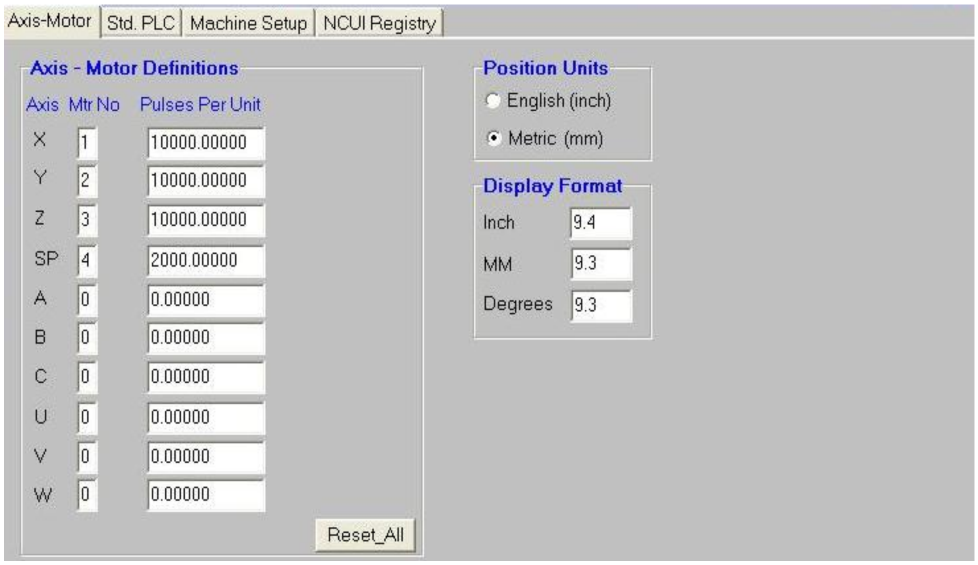


Figure 5.13 NCSetup Axis-Motor Tab

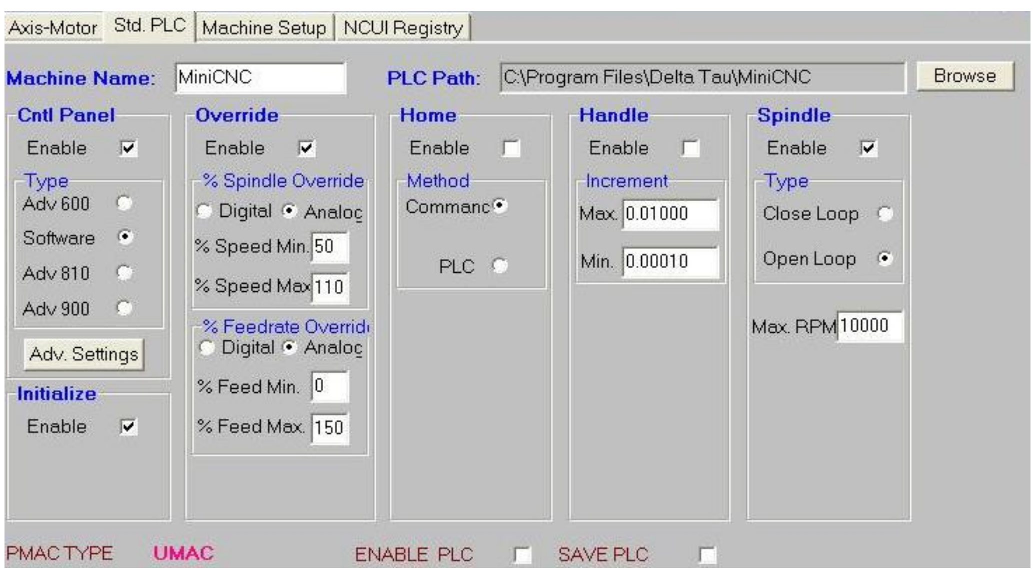


Figure 5.14 NCSetup Std. PLC Tab

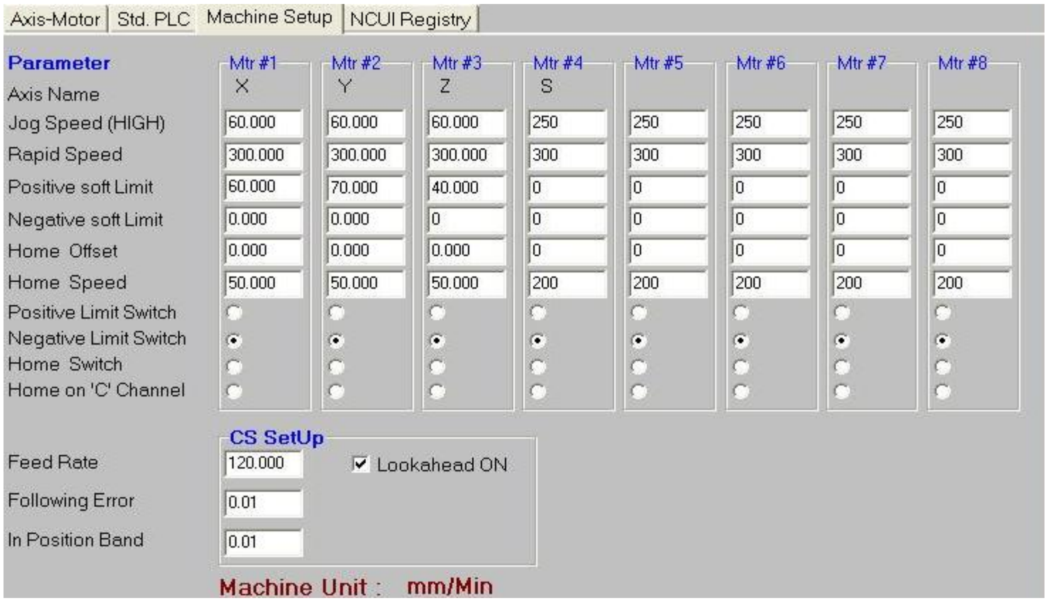


Figure 5.15 NCSetup Machine Setup Tab

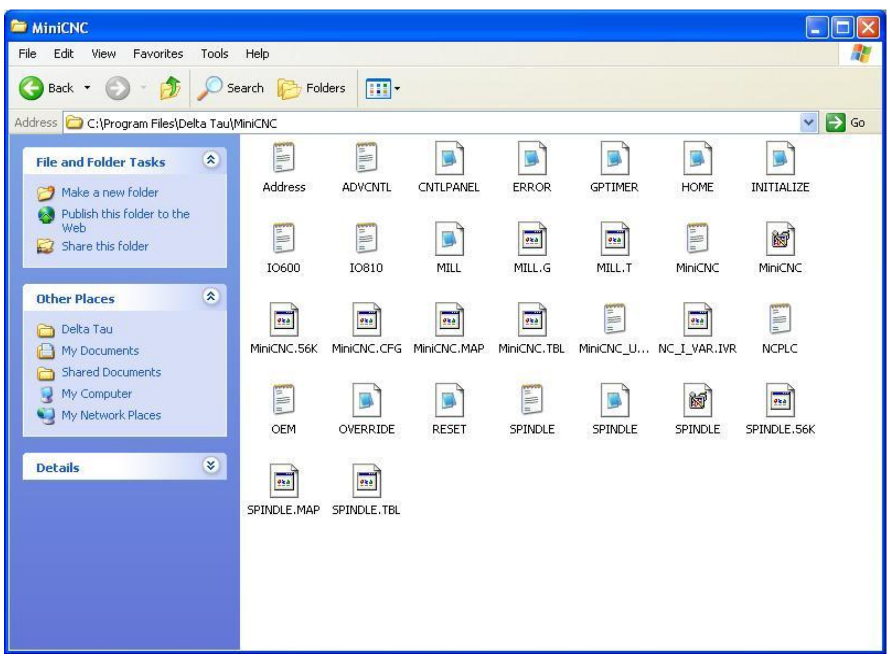


Figure 5.16 PLC programs generated by NC Setup

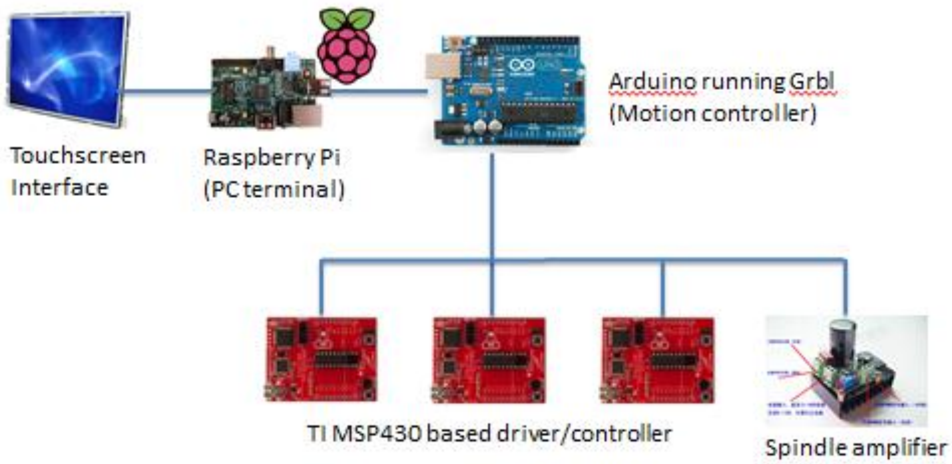


Figure 5.17 Servo Controller architecture

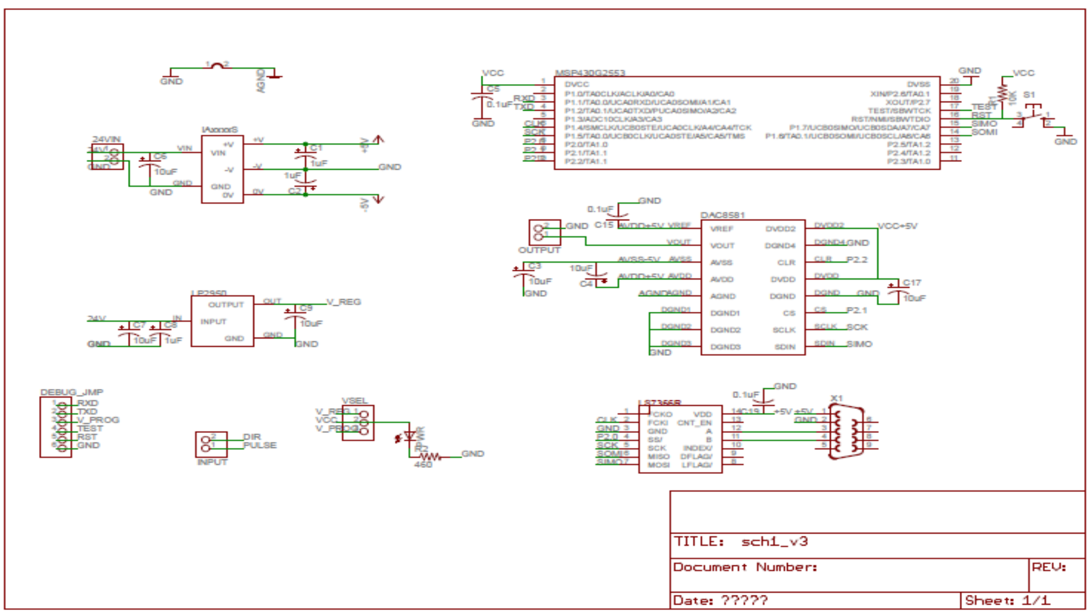


Figure 5.18 Schematics of MSP430 Servo Controller

Table 5.1 M-variable definition for limit switch setup [5]

Flag Type	Motor #1	Motor #2	Motor #3	Motor #4
HMFL input status	M120->X:$78200,16	M220->X:$078208,16	M320->X:$078210,16	M420->X:$078218,16
PLIM input status	M121->X:$78200,17	M221->X:$078208,17	M321->X:$078210,17	M421->X:$078218,17
MLIM input status	M122->X:$78200,18	M222->X:$078208,18	M322->X:$078210,18	M422->X:$078218,18
Flag Type	**Motor #5**	**Motor #6**	**Motor #7**	**Motor #8**
HMFL input status	M520->X:$78300,16	M620->X:$078308,16	M720->X:$078310,16	M820->X:$078318,16
PLIM input status	M521->X:$78300,17	M621->X:$078308,17	M721->X:$078310,17	M821->X:$078318,17
MLIM input status	M522->X:$78300,18	M622->X:$078308,18	M722->X:$078310,18	M822->X:$078318,18

Table 5.2 Common decode mode setting of I7mn0 [2]

I7mn0=	0	1	2	3	4	5	6	7
Function	P/D CW	X1 CW	X2 CW	X4 CW	P/D CCW	X1 CCW	X2 CCW	X4 CCW

Table 5.3 DAC offset and open loop dead-band value

	X=1	X=2	X=3
Ix29	899	300	58
Ix68	4240	7000	4600

Table 5.4 System characteristics of three linear stages

	Motor 1	Motor 2	Motor 3
K [cts/(s*bits)]	2.4	1.65	2.4
T [sec]	0.05	0.05	0.05

Table 5.5 PID parameters for three axes

	Kp	Ki	Kd	Kvff	Kaff
Motor 1	700000	80000	500	1341	9380
Motor 2	650000	110000	550	1316	8760
Motor3	900000	110000	200	1323	8942

CHAPTER 6

Machine Test and Calibration

In this chapter, the fabricated prototype mini CNC machine is subjected to several different tests to determine its accuracy and repeatability. Some common machine tool testing methods used in industry are ballbar analysis, laser alignment and lazer calibration. In these tests, ultra precision position sensing devices such as ballbars or lazer interferometers are used to tell the absolute position of the tool tip in the machine defined coordinate system. The error between desired position and actual position can be determined. However, these tests require expensive equipment and special training. Therefore, a much cheaper approach is used to at least obtain some basic information of this prototype machine's accuracy.

Three major tests are conducted in this research, i.e. surface flatness test, axes perpendicularity test and circular test. These tests can tell several geometric accuracies such as positioning, straightness, roll, pitch, yaw and perpendicularity by just machining a workpiece under certain tool path and feedrate. The dimension of created features on workpiece is then measured using CMM and the data are analyzed in MATLAB.

6.1 Flatness and perpendicularity test

Flatness test is done by machining a flat surface on a workpiece and then measuring the flatness of the created surface. The flatness test can tell whether our XY axes are horizontal and moving in a plane as well as whether our working table is tilting or not.

Two different surfaces are created in two tool paths, one along X-axis and one along Y-axis, as shown in figure 6.1, 6.2. Theoretically machining a surface in two directions won't affect the surface feature. Therefore, any differences among two surfaces can tell the existence of error in Z-axis.

For each surface created, six data paths are measured on the surface, three along X axis and three along Y axis, as shown in figure 6.3 and 6.4.

Ideally, measurement paths in all directions should all have constant height in Z direction. However, due to errors in XY axes, the surface is slightly tilted. Figure 6.5 shows the profiles of three paths in X direction measured on surface created by X direction tool path. Figure 6.6 shows the same three paths in X direction but measured on surface created by Y direction tool path. 6.7 shows the profiles of three paths in Y direction measured on surface created by X direction tool path. Figure 6.8 shows the same three paths in Y direction but measured on surface created by Y direction tool path.

From figure 6.5 – 6.8 of profile measurement, we can clearly see both our X axis and Y axis stage is tilting. Three sets of data measured in the same direction on the same surface are generally consistent to each other. The profile in x direction on both surface have a slope value of approximately 0.005. This is approximately 0.28 degree tilting on X axis. The profile in y direction on both surface have a slope value of -0.013. This represents -0.74 degree of difference between Y axis direction and horizon level. We can also observe that the surface profiles in Y direction are much more consistent than profiles in X direction. Table 6.1 shows the Norm of residuals of a linear fit model on both X direction profile and Y direction profile on two surfaces.

From table 6.1, we can see the Y direction profile on Y tool path surface gives the best linear and smooth profile. X direction profile on Y tool path surface gives the roughest profiles. For X tool path surface, the direction of cutting has less effects, but both profiles are still rougher than Y direction profile on Y tool path surface. The reason behind this cutting direction effect is actually due to the material fiber alignment of the workpiece itself. The material of the workpiece used to conduct this test is wax. The formation of this type of wax material is actually aligned in certain direction. If the cutting is performed in the same direction as the material's fiber alignment direction, the result should be uniform and smooth. If the cutting is performed in the direction perpendicular to the fiber alignment direction, due to inconsistent material structure and density, the chip formation would be varying along the cutting path, which results in non-uniform and uneven surface. As shown in figure 6.9 and figure 6.10. We can clear see the cutting along Y axis generates much smoother and more uniform path than cutting in X axis direction.

The next test is perpendicularity test of X Y axes. A tool path is created to cut the edge of a workpiece purely in two directions: X and Y, as shown in figure 6.11.

After two flat vertical surfaces is created, the straightness of two surfaces can be measured using CMM. The slope of two lines in XY plane can be measured. The angle between these two lines can be calculated using these two slope values. Figure 6.12 shows the data points collected on the two machined surface.

Then, a linear fit was applied to these two sets of data individually. The slope of two straight lines can be measured. The norm of residuals of this linear fit also indicates the straightness of these two surfaces, which equivalently determines the straightness of XY axes movement. Figure 6.13 and 6.14 shows the linear fit of two measurements taken from two surfaces.

The path in X direction has a slope value of -0.0126. The path Y direction has a slope value of 83.199. The angle between these two lines can be calculated using:

$$\begin{aligned} \text{angle} &= \tan^{-1}(p11)-\tan^{-1}(p12) \\ &= \tan^{-1}(-0.012632)-\tan^{-1}(83.199) \\ &= 90.0351° \end{aligned} \tag{6.1}$$

Therefore, there are 0.0351° differences between the X axis alignments and Y axis alignments. This is a relatively small value. The perpendicularity of XY axes is within the acceptable tolerance.

One more result to be drawn from figure 6.13 and figure 6.14 is that the straightness in Y direction is better than that in X direction. The linear fit in figure 6.13 gives a R^2 value of 0.9657 and the linear fit in figure 6.14 gives a R^2 value of 0.9981. Both still move pretty straight, and no obvious curvature is observed.

6.2 Circular test

The circular test is a fast method of testing the geometrical accuracies of three-axis machines. To perform the circular test the machine is programmed to move on a circle and the deviations from an ideal circle are measured. The magnified deviations can be plotted. The calculated mean square fit diameters, standard deviations and Fourier analysis can be used for analysis of the error sources and of the geometric error components. Circular tests can also provide information on the machine control including the influences of speed and interpolation if various feedrate are applied during the test [10].

The circular test is influenced by three basic geometric errors, i.e. linear movement of an axis, a non-perpendicularity between two axes, and the straightness of the movement. These three basic geometric errors are a combination influence from 21 error components of a three axis machine, which consists of six error components per axis (positioning, straightness, roll, pitch, and yaw) plus three angles of non-perpendicularity between the axes. Research from Knapp [10] shows that the circular test is sensitive to all the 21 error components of a three-axis machine even if the size of these errors is below 5 µm or below 2 arc-sec.

To perform circular test, machine is told to create a circular workpiece using circular interpolation in different feedrates. This is called an indirect circular test because we don't have the equipment to perform an on-line testing. The surface contouring profile of the created circular feature can be measured using a CMM. In this research, six test trials are performed. The test parameters are listed in table 6.2. For all tests, the spindle speed is set to be 4000RPM.

The test results are shown in figure 6.15-6.20 below respectively. Several interesting features can be observed from the results.

The first thing can be noticed from the results is the surface along X axis is much rougher than the surface along Y axis. This error can be coming from two major sources, the workpiece or the machine. To test the influences of workpiece itself, an additional circular test is done using the same feedrate tool path but with the workpiece orientation changed by 90°. The test result is shown in figure 6.21. It can be noticed that the waving behavior still occurs along the X axis no matter what orientation the workpiece is at. Therefore, workpiece is not an effect to cause this error. After several more tests, it is determined that the major source of error is coming from the bending of the leadscrew in X axis, as illustrated in figure 6.22. The rotation of this curving leadscrew caused the shaking of the working table in both Y direction and Z direction. Therefore, waves can be observed in both circular test and in previous surface profiles along x direction. This assumption can be further proved by observing the relationship between circular diameter and the number of waves occurred. When the diameter of circle is reduced by 4mm, the number of waves occurred is reduced by 1, which is consistent with the leadscrew pitch number 4mm/rev. The peak deviation and valley deviation mostly occur along the X axis surface and in low feedrate cases. They almost occurred at the same spot, which can tell that this process is highly repeatable. In low feedrate cases, the circular test still shows a relatively round shape, which means the error in X positioning, Y positioning, X straightness, and Y straightness are all relatively small. However, in the case 6 with high feedrate, we can clearly see the path becomes noisier. This is because faster material removal rate results in big chip formation which leads to a rougher surface.

6.3 Summary

In conclusion, this chapter has discussed three different methods used to test the performance and accuracy of this prototype machine. Due to the machine component inaccuracy and alignment issue during assembling, this prototype contains 0.0351° non-perpendicularity in XY axis, 0.28° tilting on X axis and -0.74° tilting on Y axis. Circular test shows that increasing feedrate will decrease machine accuracy and surface flatness. Due to lack of adjusting features in our original design, it is very hard to calibrate the machine even if the error source is determined. The workpiece used is not suitable for this high precision testing process. Aluminum would be a better choice in the future.

6.4 Figures and Tables

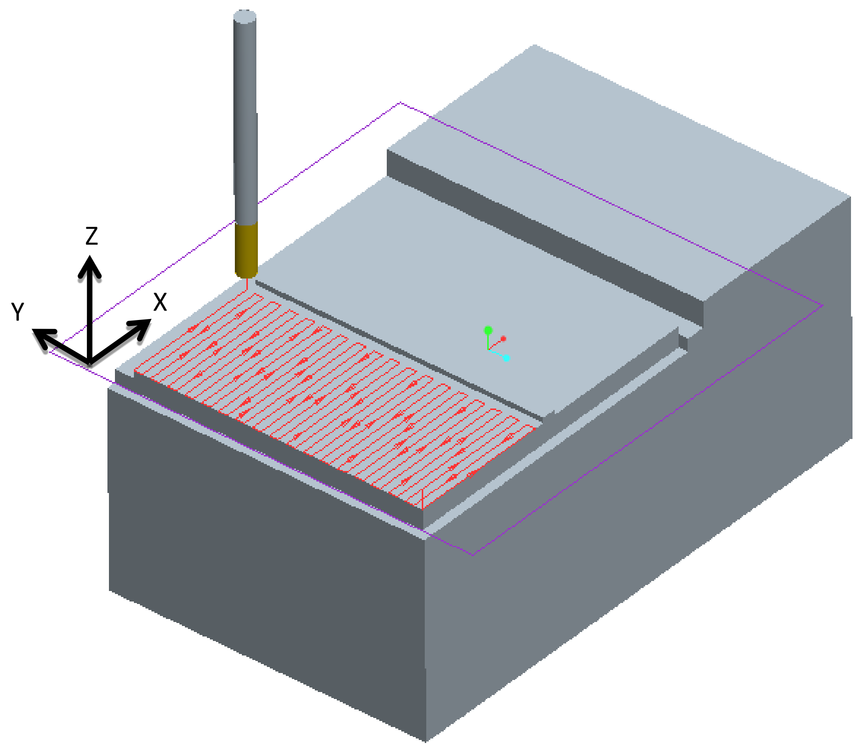


Figure 6.1 Flatness test X direction tool path

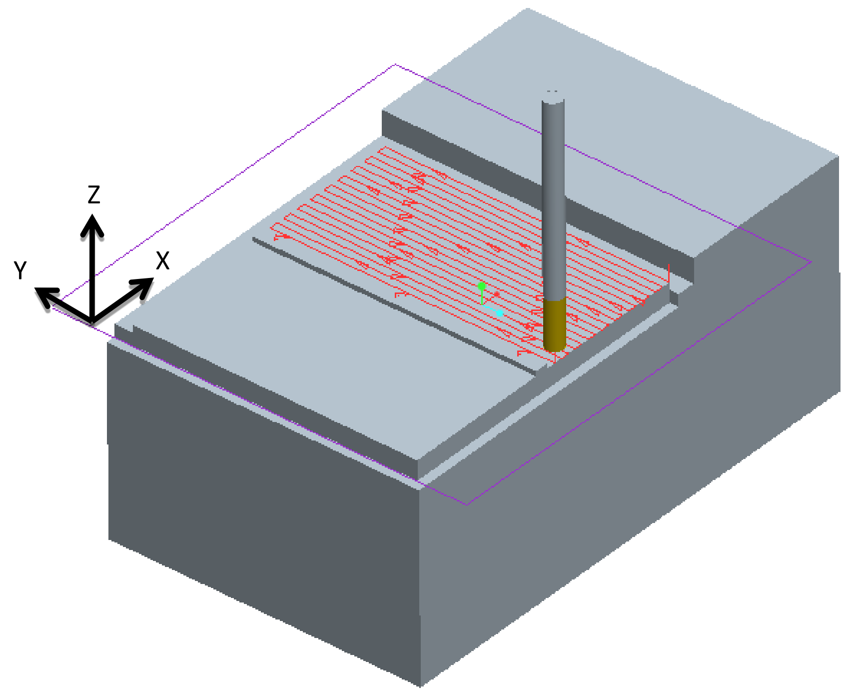


Figure 6.2 Flatness test Y direction tool path

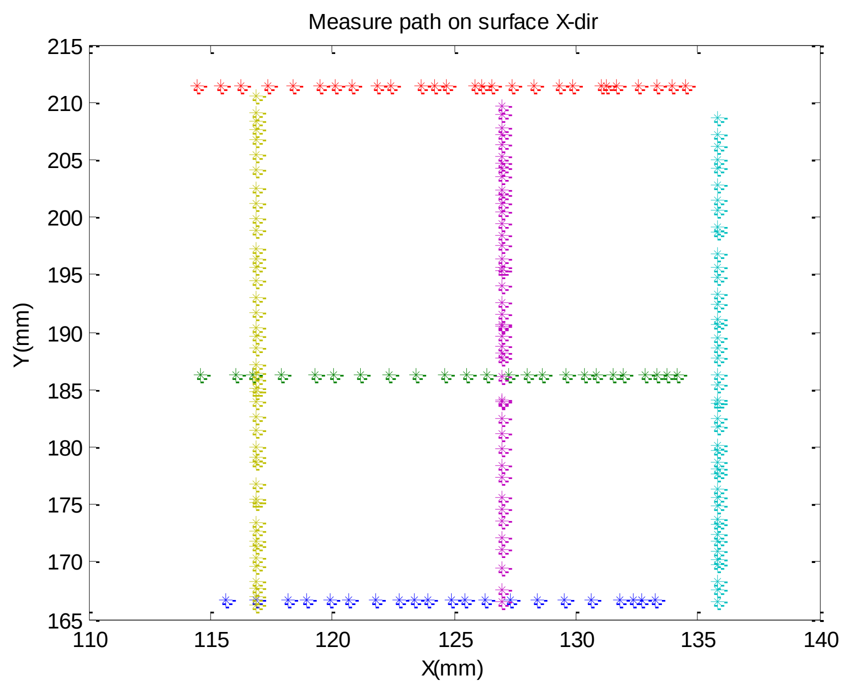


Figure 6.3 Measure path on surface of X-direction tool path

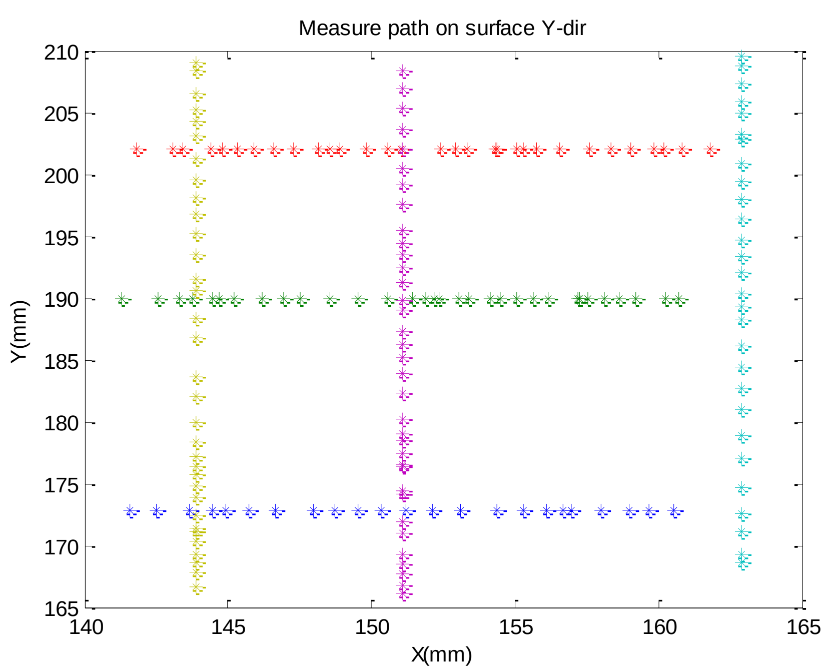
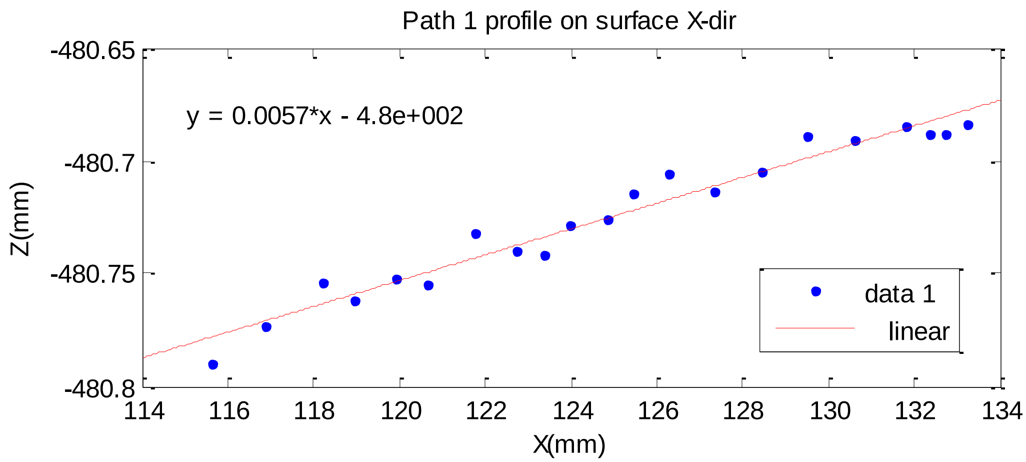
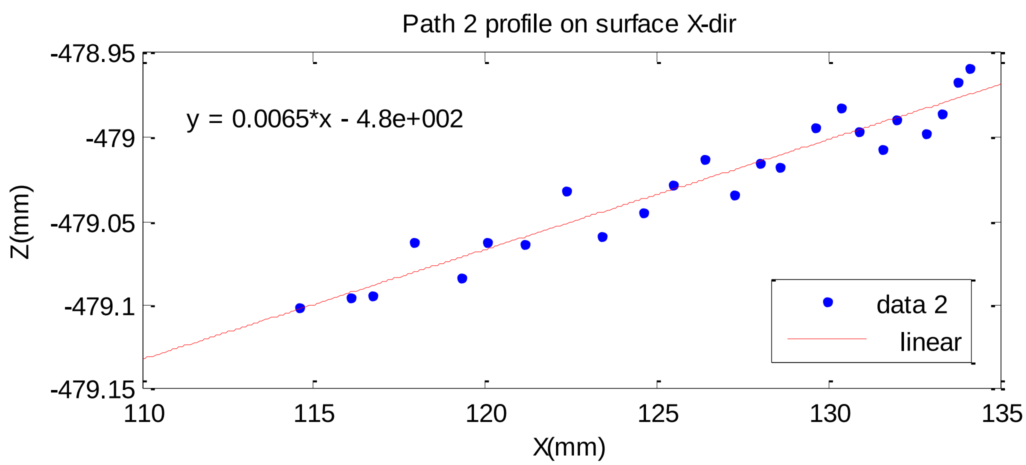


Figure 6.4 Measure path on surface of Y-direction tool path





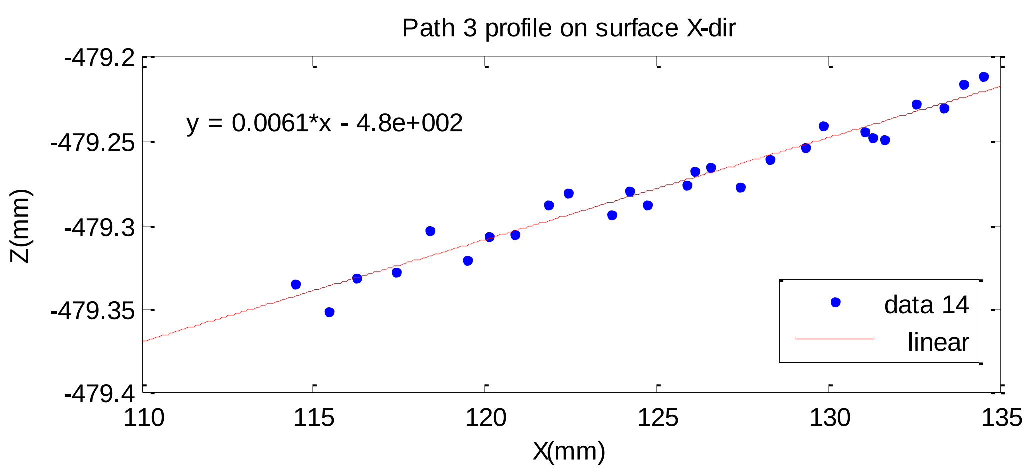


Figure 6.5 Profiles of three paths in X direction on X surface

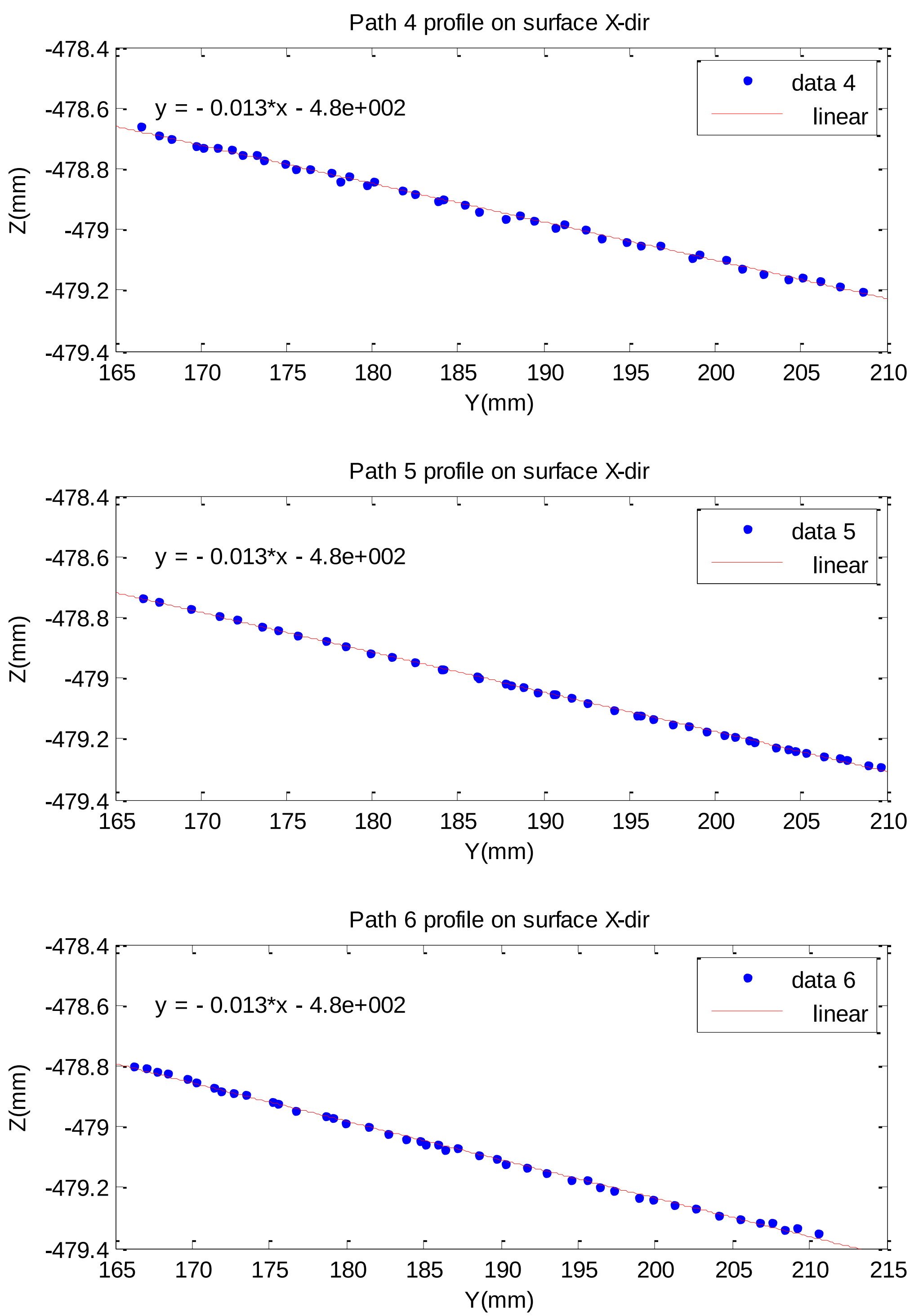


Figure 6.6 Profiles of three paths in Y direction on X surface

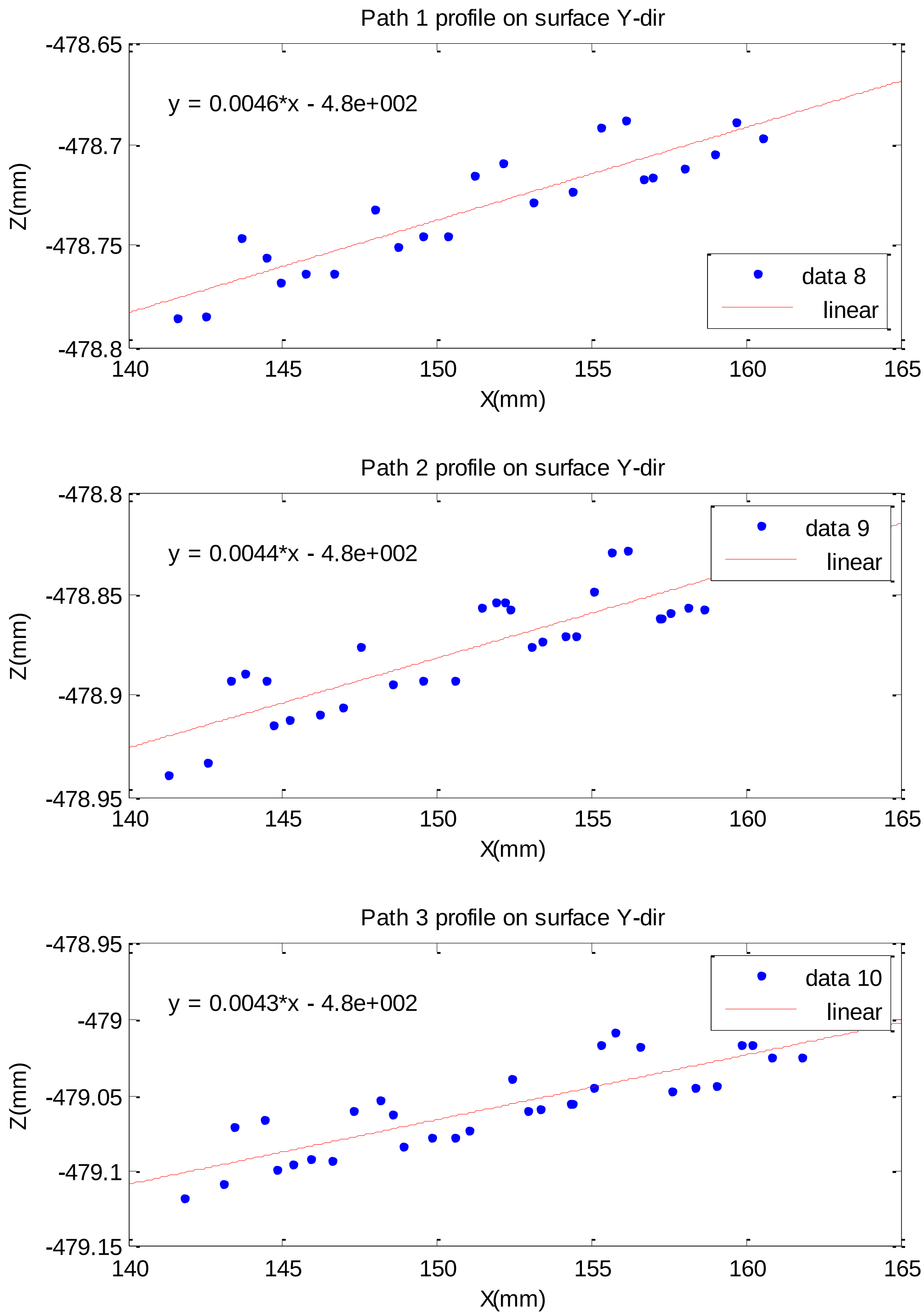


Figure 6.7 Profiles of three paths in X direction on Y surface

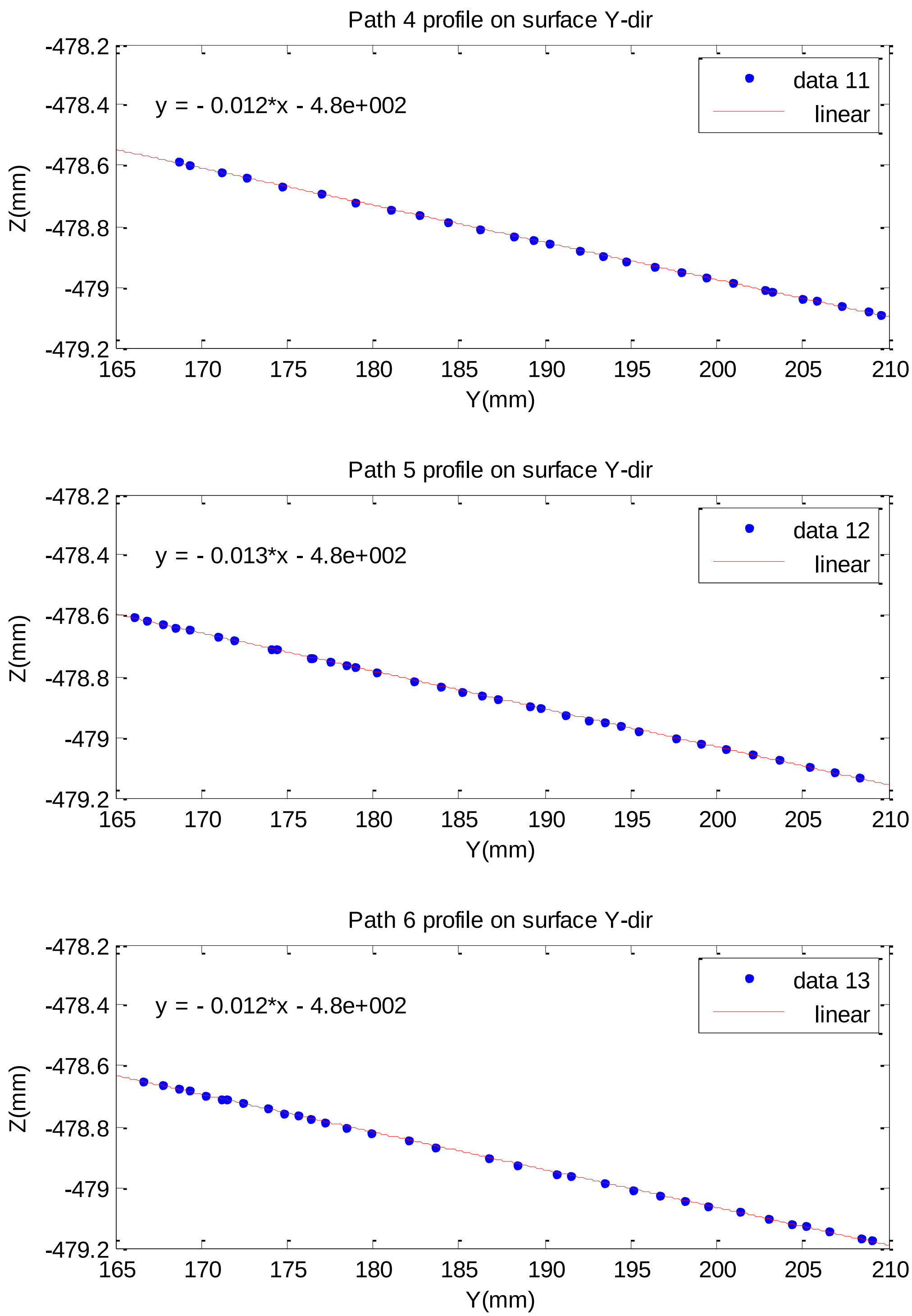


Figure 6.8 Profiles of three paths in Y direction on Y surface

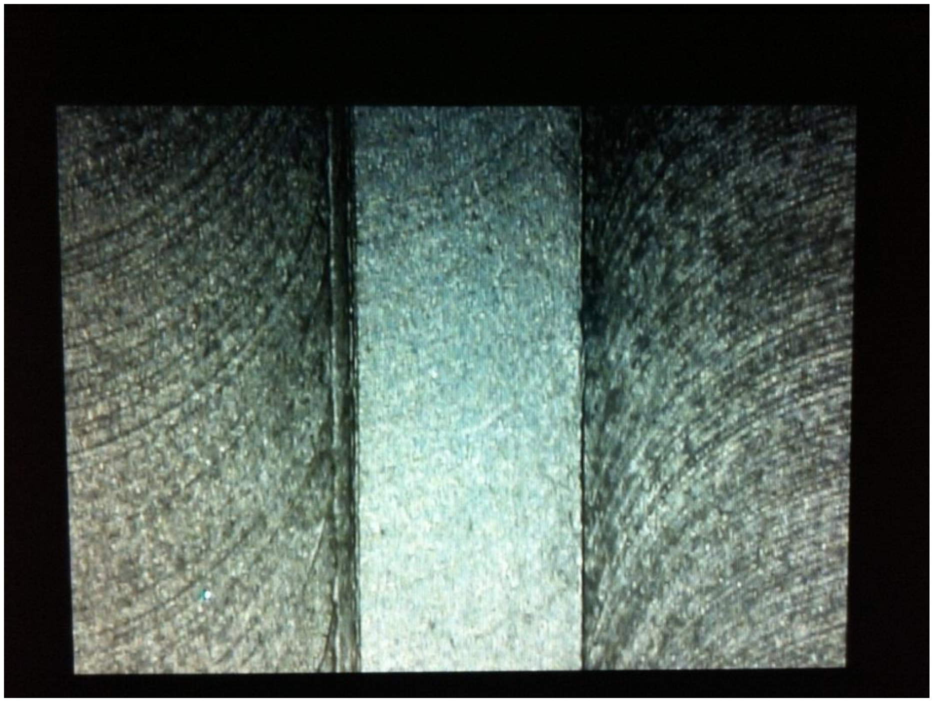


Figure 6.9 Surface of cutting path in Y direction

Figure 6.10 Surface of cutting path in X direction

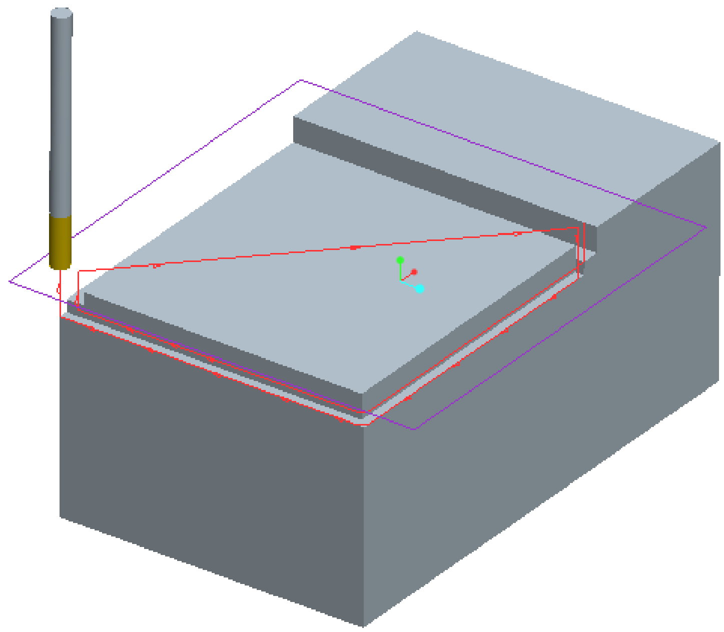


Figure 6.11 Tool path of perpendicularity test

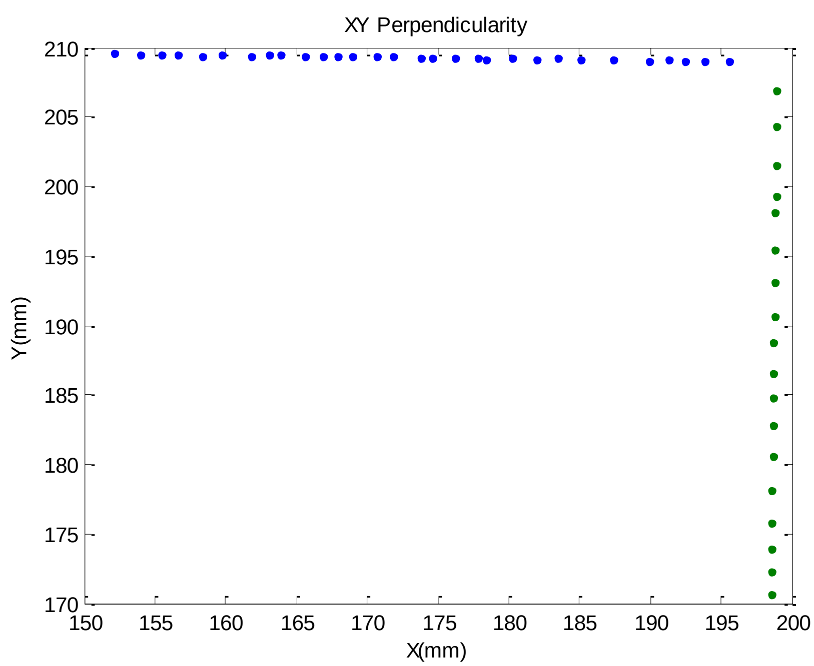


Figure 6.12 Data collected for perpendicularity test

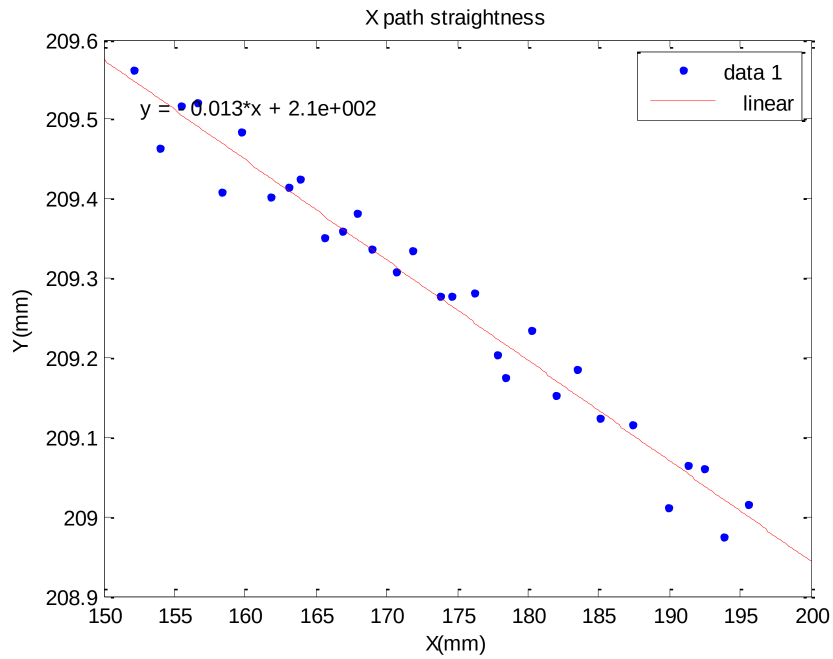


Figure 6.13 X path straightness

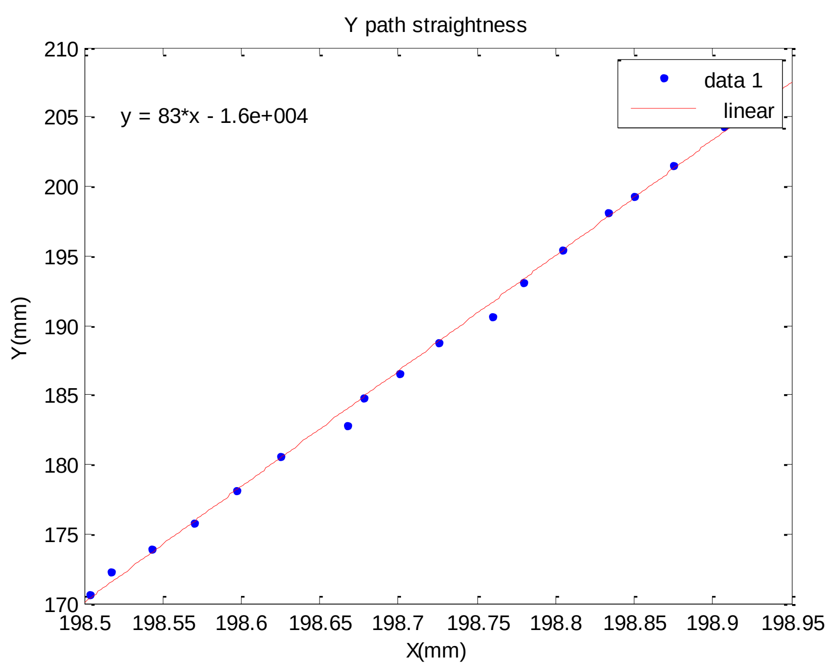


Figure 6.14 Y path straightness

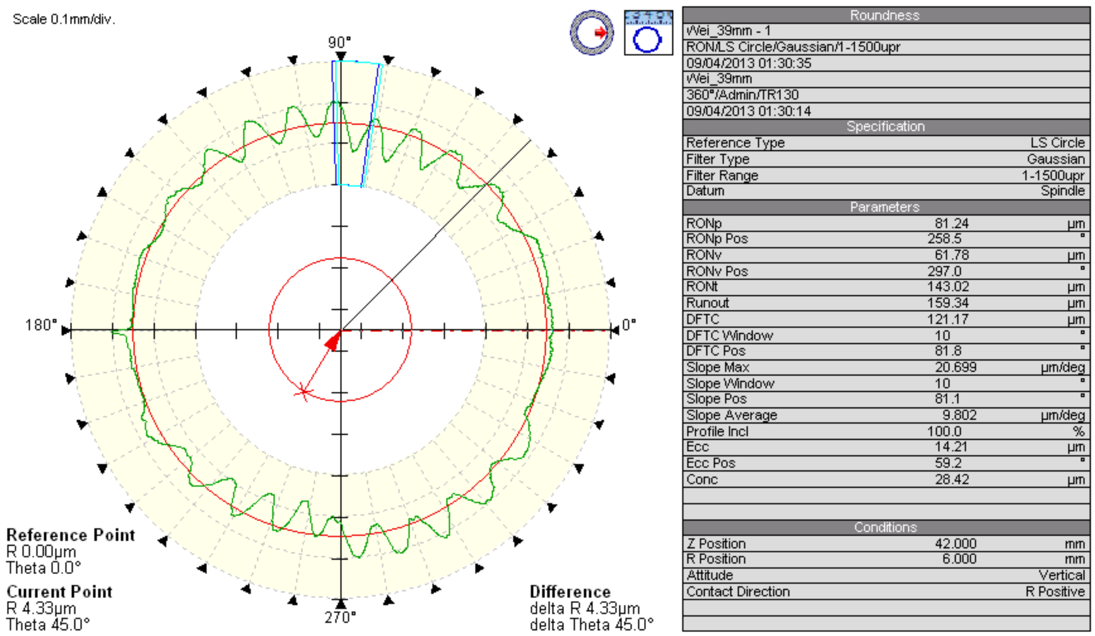


Figure 6.15 Circular test #1 result

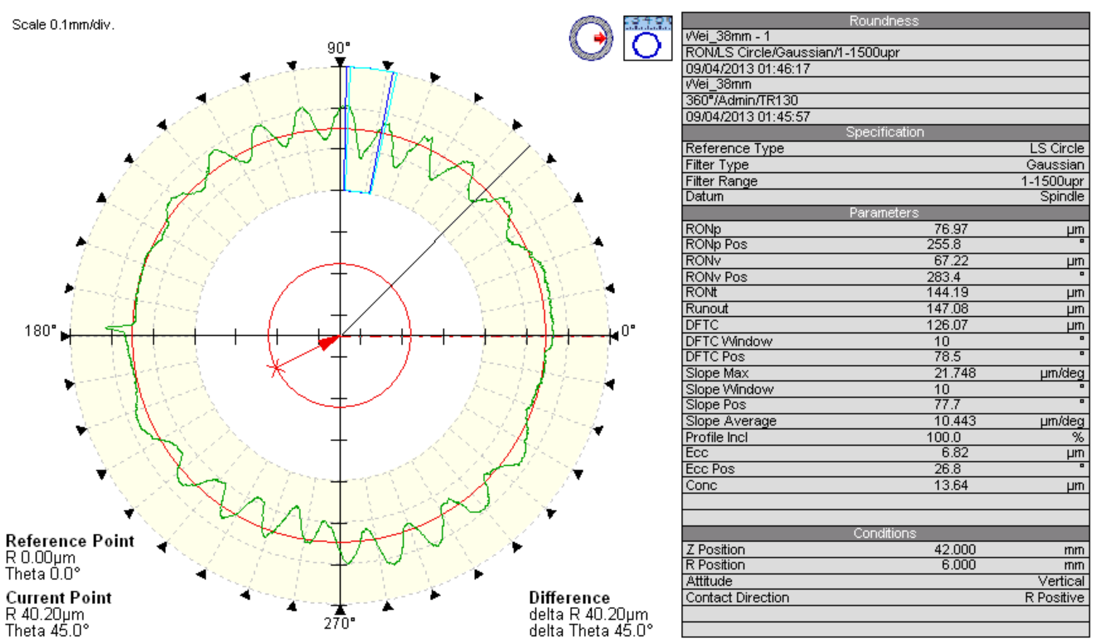


Figure 6.16 Circular test #2 result

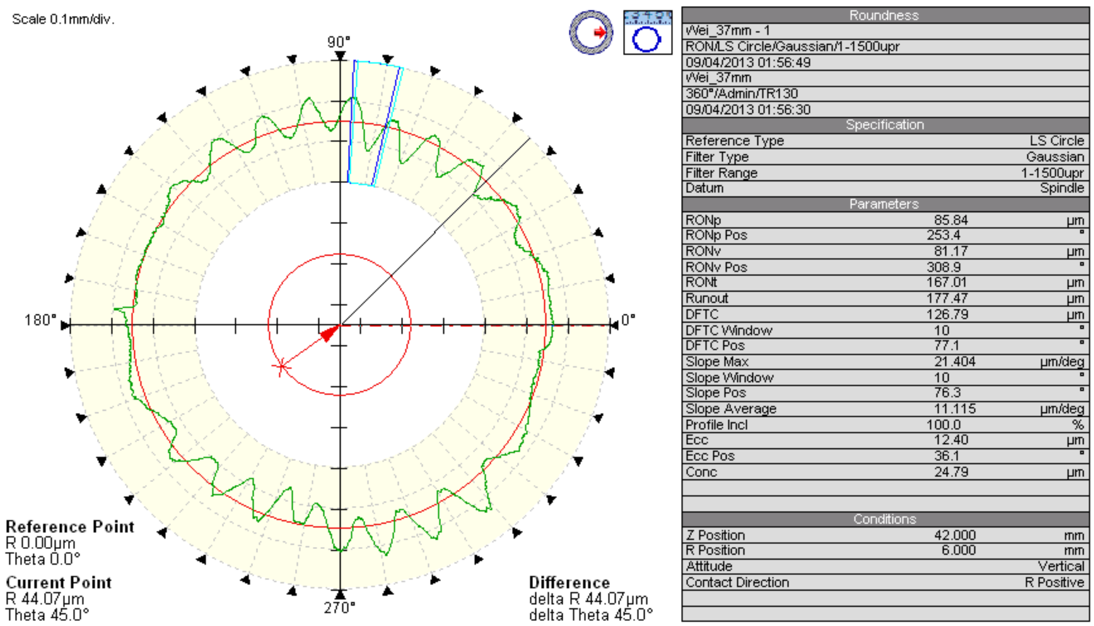


Figure 6.17 Circular test #3 result

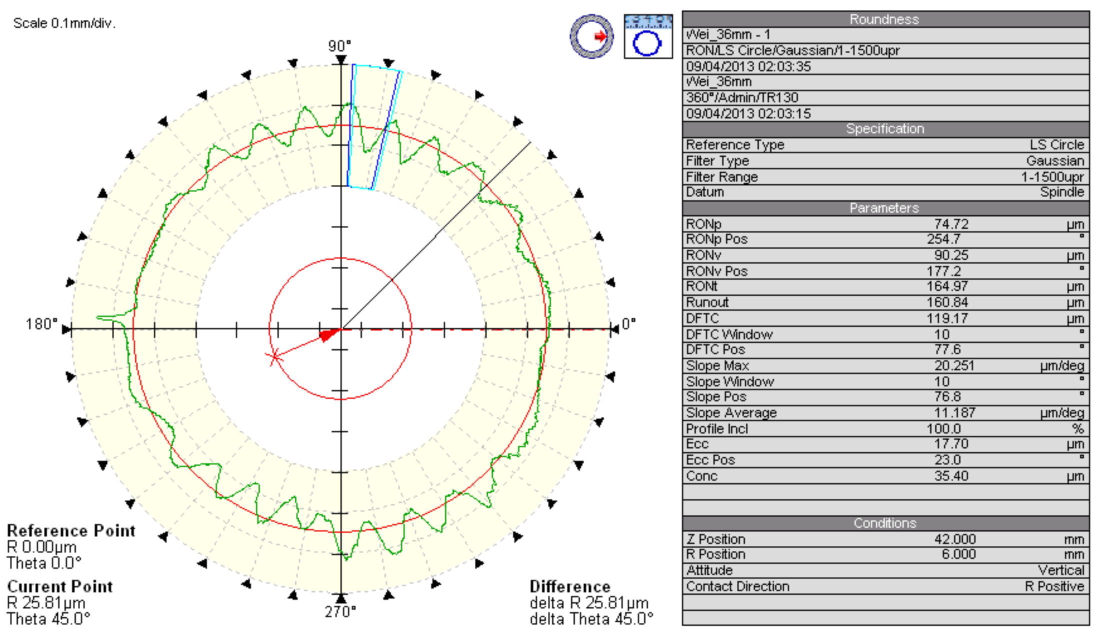


Figure 6.18 Circular test #4 result

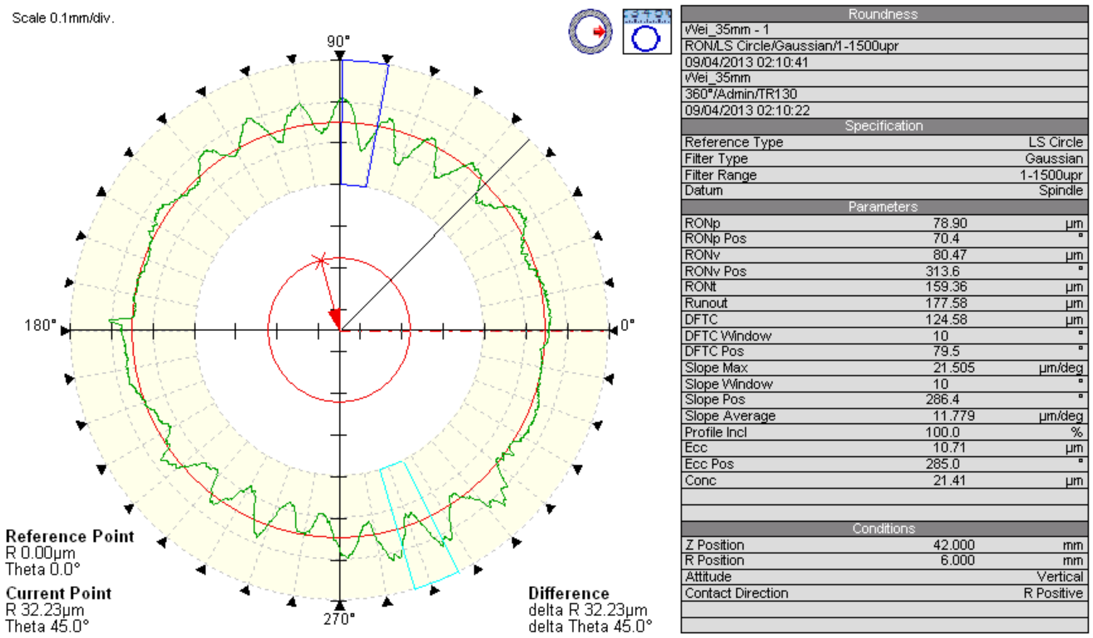


Figure 6.19 Circular test #5 result

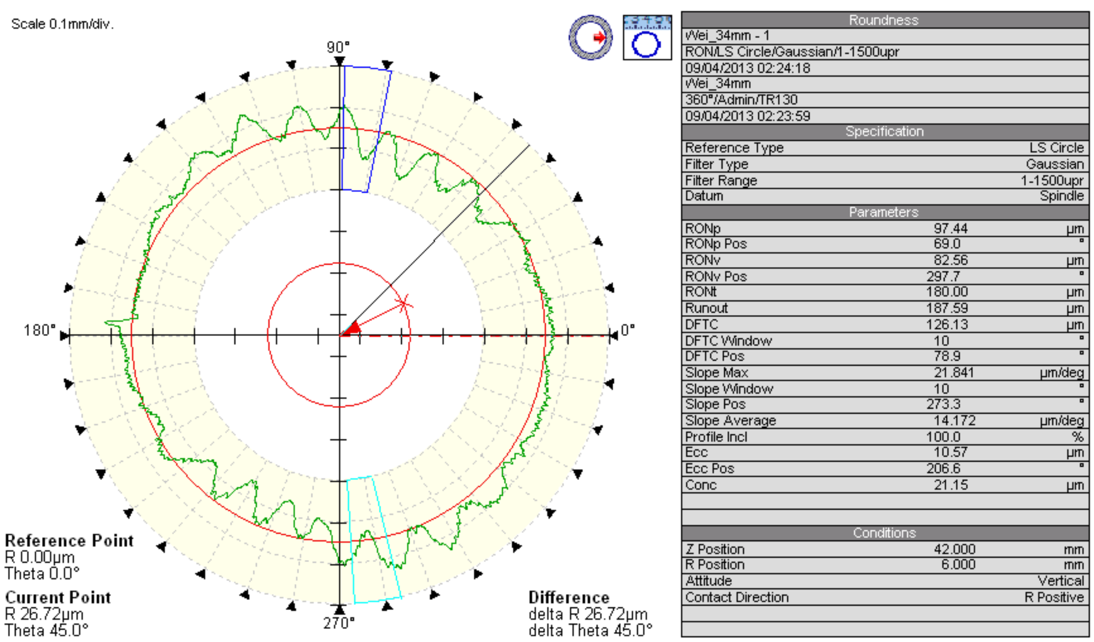


Figure 6.20 Circular test #6 result

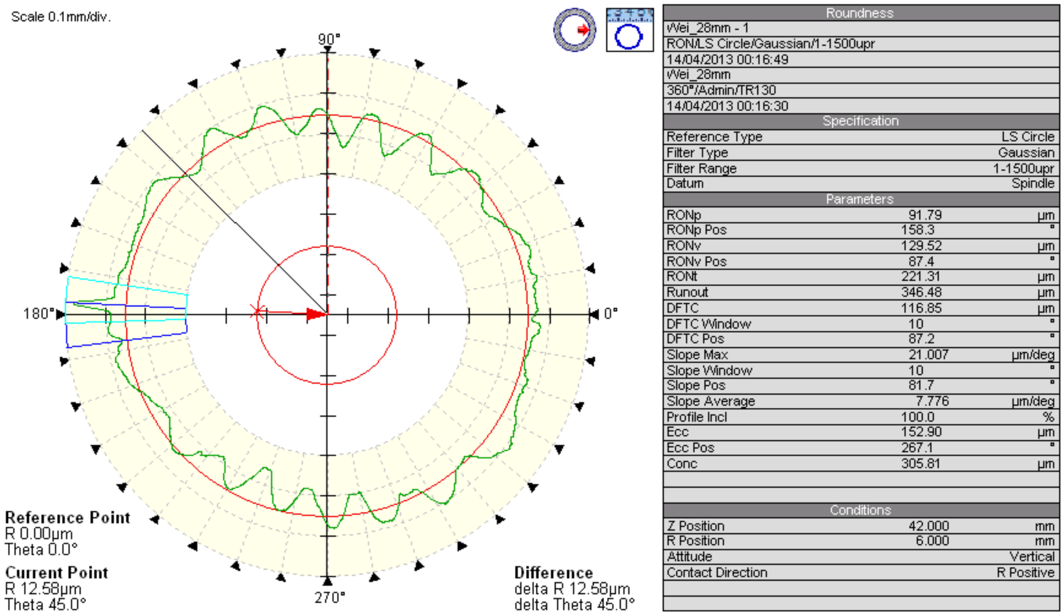


Figure 6.21 Circular test result with 90 degree workpiece orientation shift

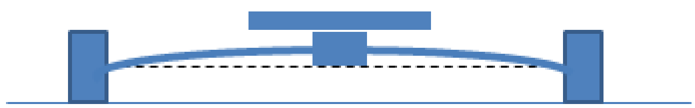


Figure 6.22 Illustrated major error source of waving in x direction

Table 6.1 Norm of residuals of linear fit

	X direction	Y direction
X tool path	0.030,0.054,0.041	0.05,0.026,0.051
Y tool path	0.033,0.080,0.084	0.0084,0.012,0.013

Table 6.2 Circular test conditions

Test #	Diameter [mm]	Feedrate [mm/min]
1	39	120
2	38	240
3	37	360
4	36	480
5	35	600
6	34	1200

CHAPTER 7

Conclusion

With the increasing demand for small scale high precision parts in various industries, the market for small scale machine tools has grown susbtantially. Using small machine tools to fabricate small scale parts can provide both flexibility and efficiency in manufacturing approaches and reduce capital cost, which is beneficial for small business owners and hobbyists. In this thesis, a small scale three axis CNC milling machine is designed and analyzed under very limited budget of 2,000 USD. During the structure design stage, various common structure frames are explored and analyzed. The most suitable structure frame, the open frame vertical type structure, is chosen. Critical components such as linear guides, motors, and enocders are selected among few different options. The best value components are selected to accommodate stiffness requirements and budget constraints. The issues of assembling mechanical components and emerging electrical parts into mechanical structure are all well considered. A prototype machine is assembled in the lab and Delta Tau's UMAC PLC is used as motion controller of the machine. The detailed steps of how to setup and configuring the PLC is described in chapter 5. An attempt to make a servo controller particularly for this machine is also conducted. The completed machine is tested using three different techniques, i.e. surface testing, perpendicularity testing and circular testing. The possible error sources are determined. The prototype machine has been used to create several parts already. Due to inaccuracy of the machine body parts and rough assembling, the machine fails to achieve the desired precision and repeatability level. However, it is still sufficient to create small features such as letters and graphs with sizes less than 1cm. A new design is created after evaluating this prototype with features of calibration and ease of assembling. This will certainly help to achieve the desired characteristics with the same amount of budget.

7.1 Future studies

The future studies heavily rely on the design of motion controller. In order to cut cost, a motion controller must be designed and fabricated by ourselves. This requires creating the hardware, making the connection, writing the servo loop program, writing the interpolation program, and creating the HMI. In chapter 5, a schematic for hardware board has already been created. The servo loop program has also been done and tested successfully. The TI MSP430 microcontroller can now read pulses and accumulate pulses as reference input. It can read the encoder signal and generate control signal using a simple PI controller. However, the function to tune PI gain in real time is yet to be created. Arduino UNO3 board has been used to run the Grbl motion control firmware. However, there is still lack of a HMI for this firmware to allow more user friendly operation. The HMI still needs to be created. The best possible solution is using Raspberry Pi as the “PC” terminal of the controller and using a touchscreen as the interface. This allows the whole controller to be made within a few square-inches box. Since Raspberry Pi has its own embedded Linux OS, the user can easily transfer machine code file into the system using a USB drive. Raspberry Pi can then stream the machine code into Arduino through another USB port easily.

Another thing that can be done in the future is optimization of the fabrication process for mass production. The components of the machine should be machined using the cheapest manufacturing process possible. The main frame should be better optimized for casting. Machine testing should be conducted in a more accurate manner with better equipment and better methodology. Then the actual number of precision and repeatability can be determined.

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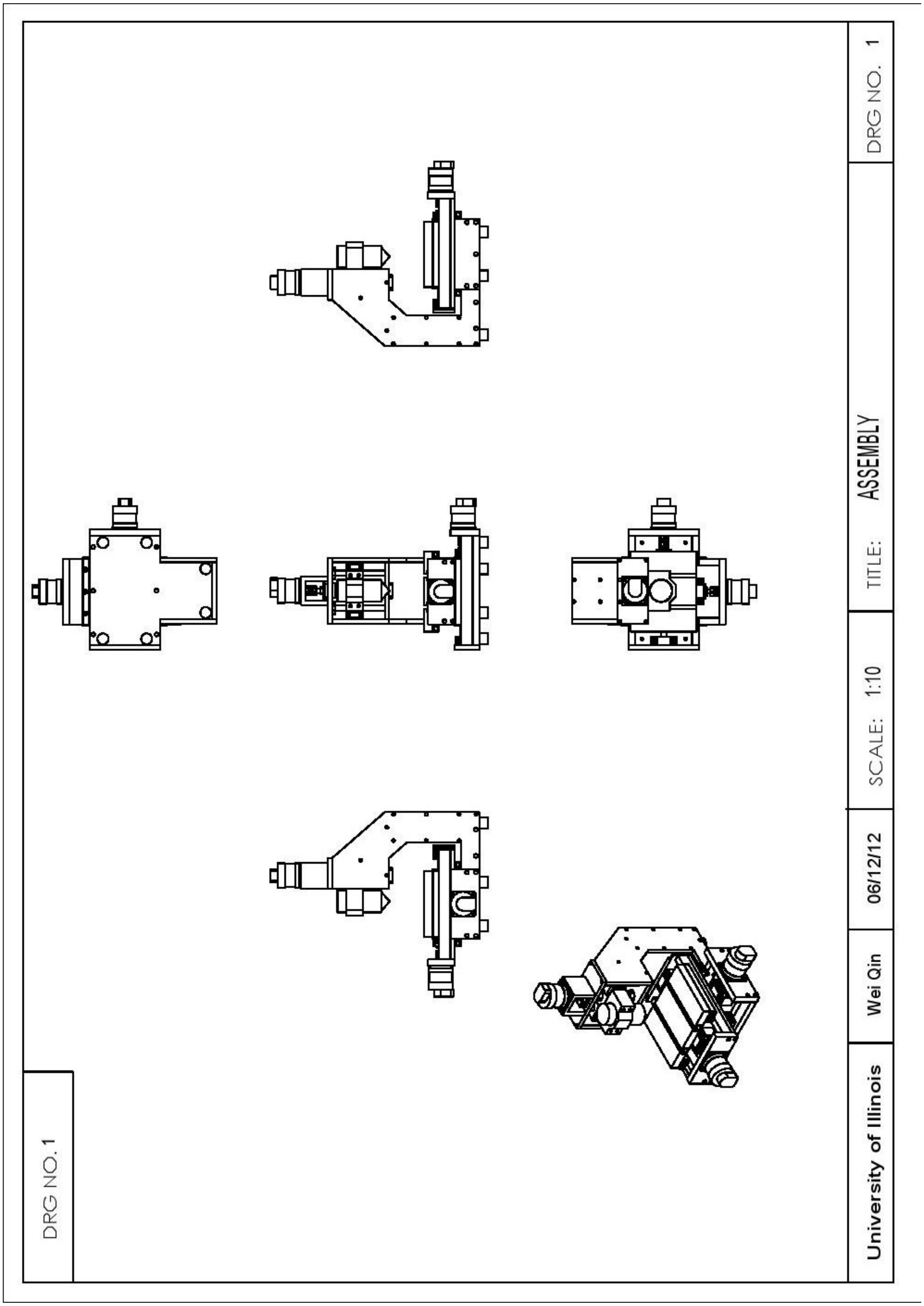
APPENDIX

CAD Drawing of all machine parts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Wei Qin
University of Illinois
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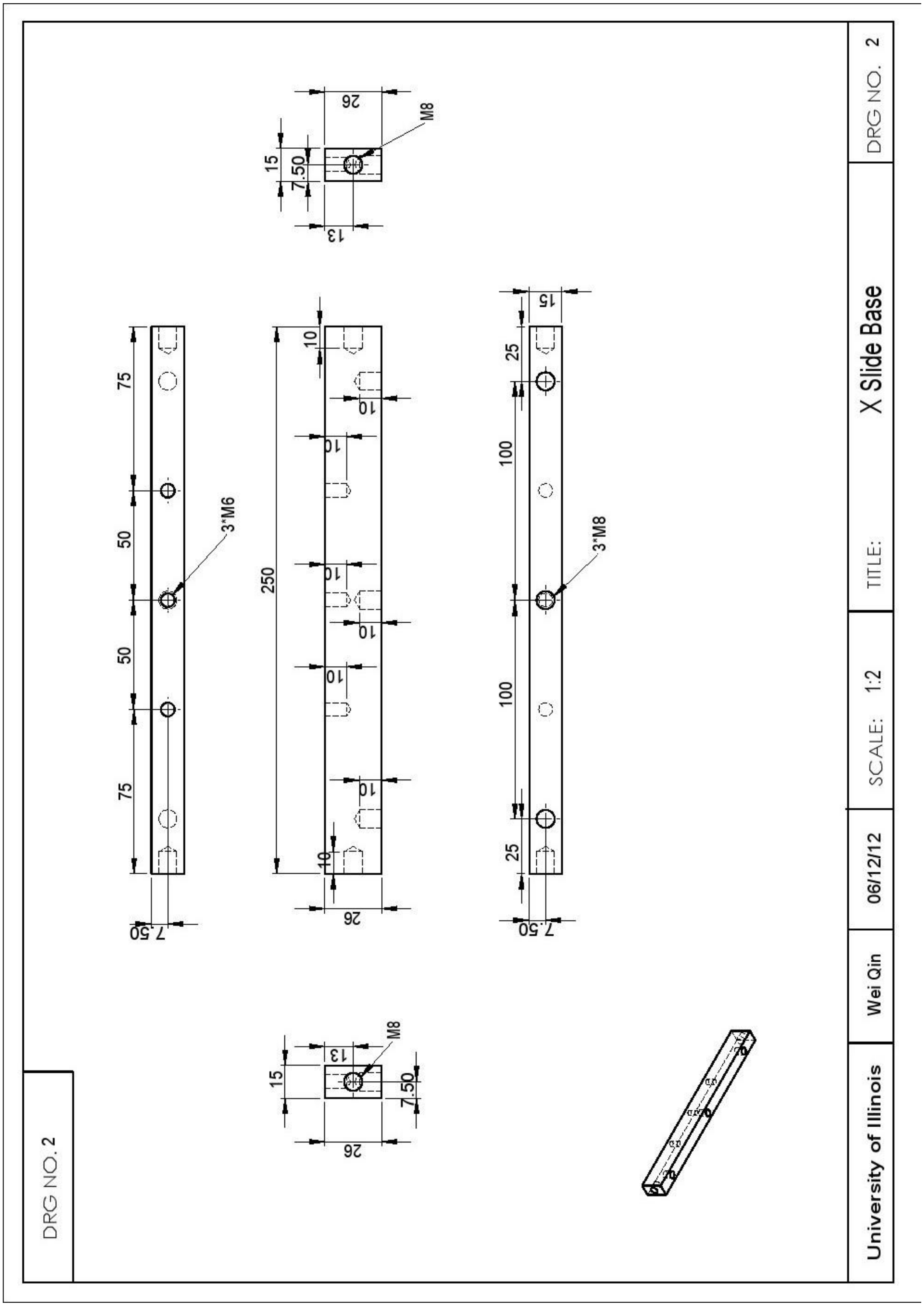
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Wei Qin
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DRG NO. 2
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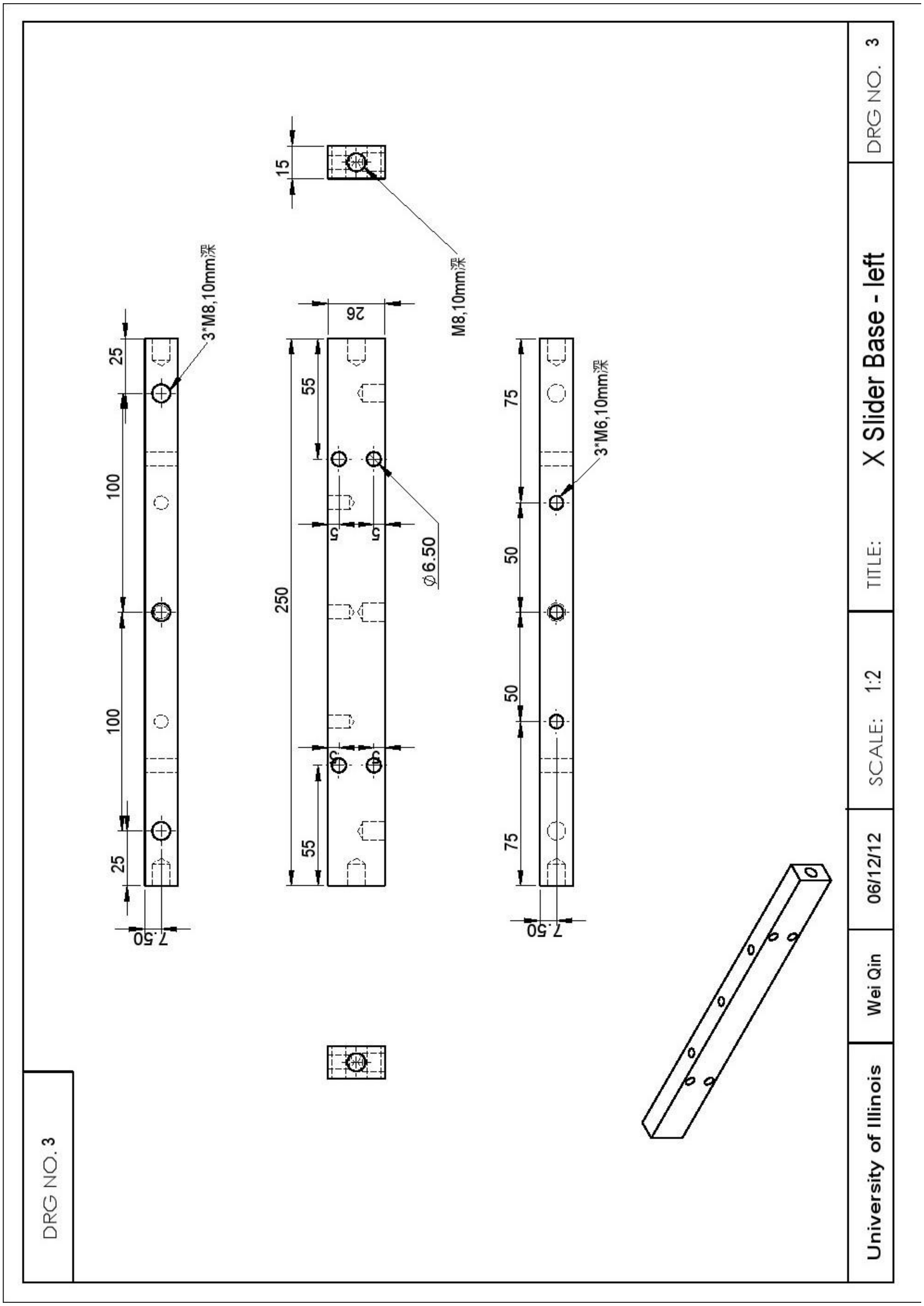
3*M8
M8
M8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25
100
100
25
7.50
15
M8,10mm深
26
55
250
55
5
5
ϕ6.50
3*M6,10mm深
75
50
50
75
7.50
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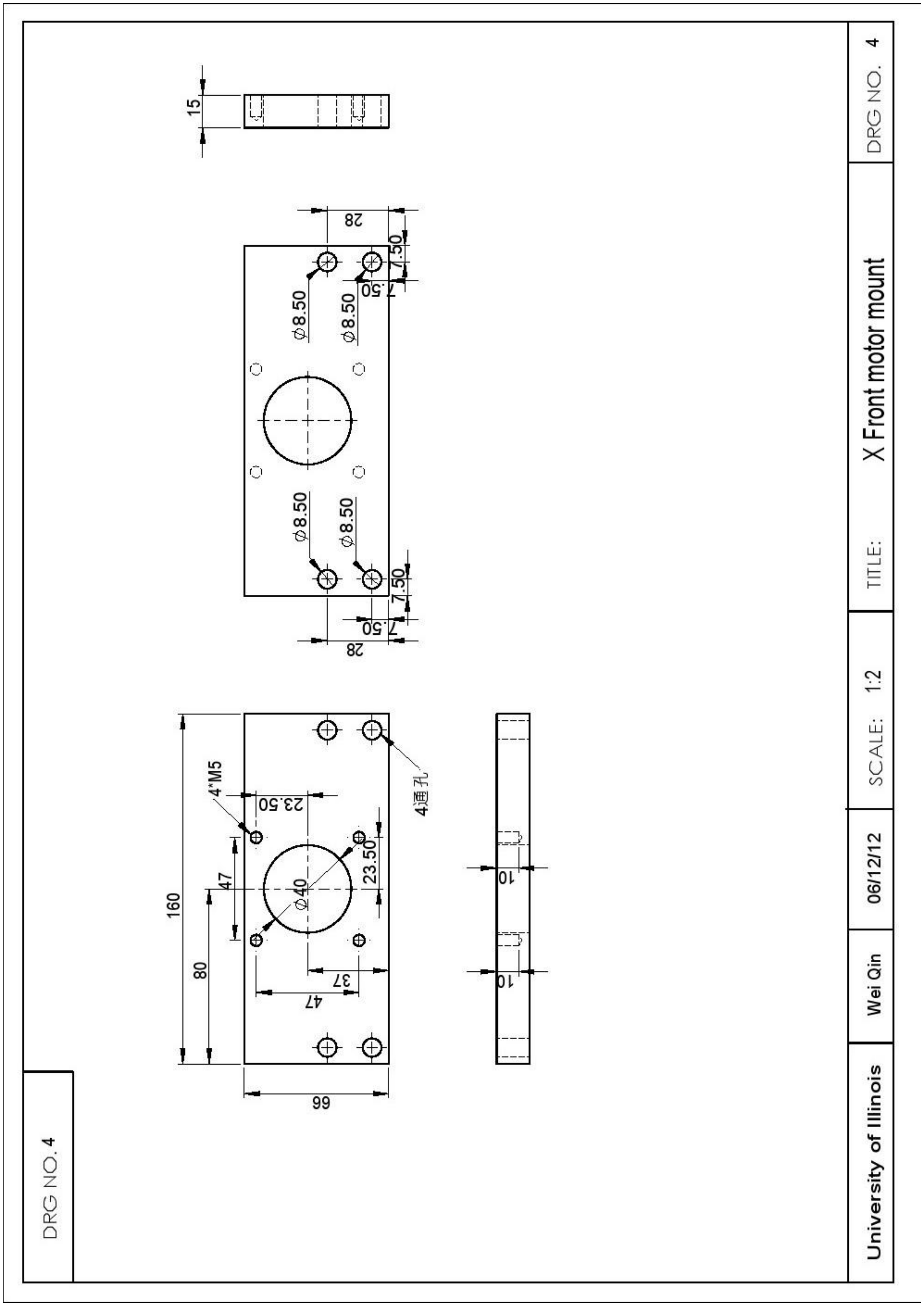
06/12/12
Wei Qin
University of Illinois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Wei Qin
University of Illinois
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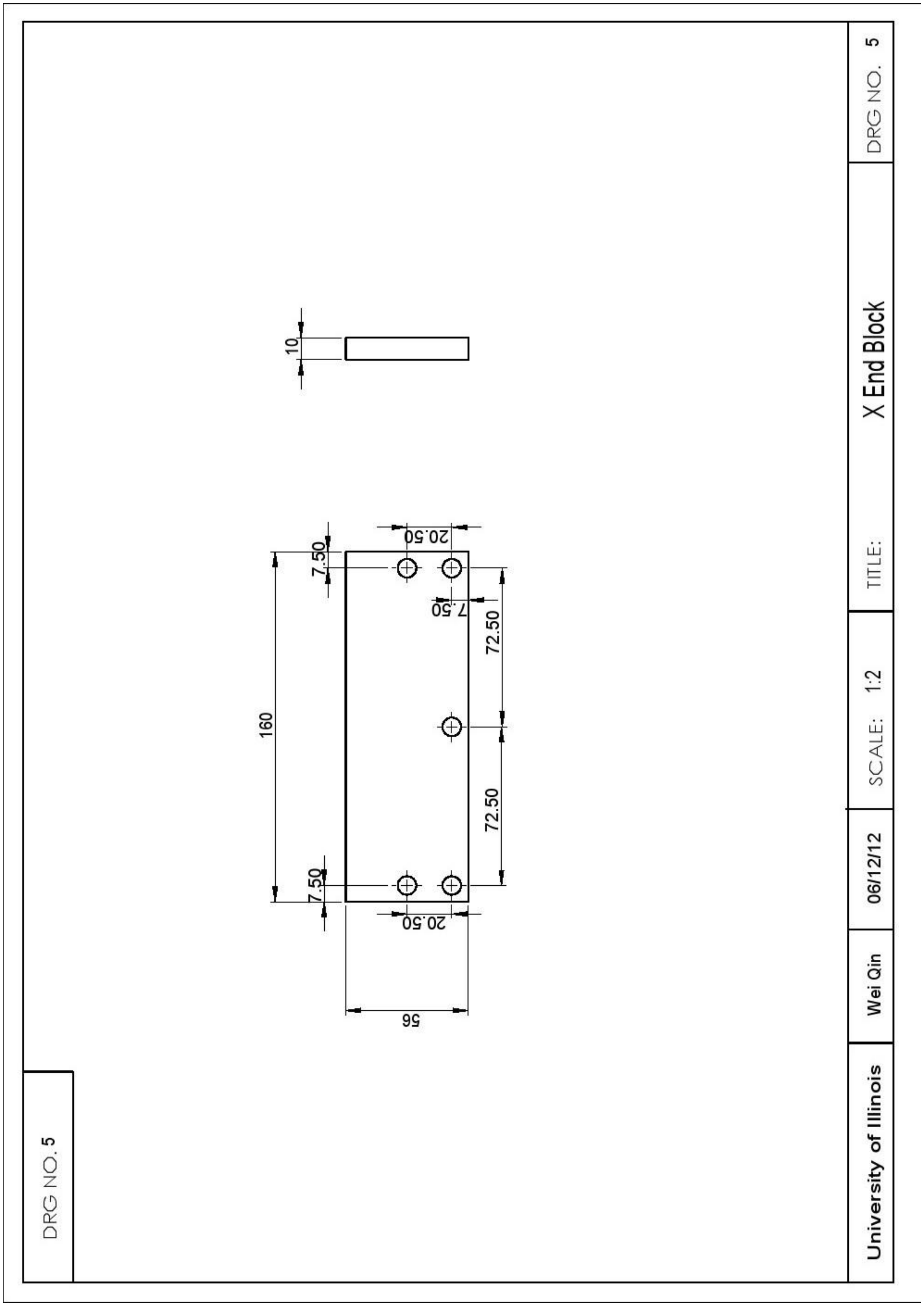
47
47
37
23.50
23.50
⌀40
4*M5
4通孔
⌀8.50
28
7.50
15
10



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University of Illinois
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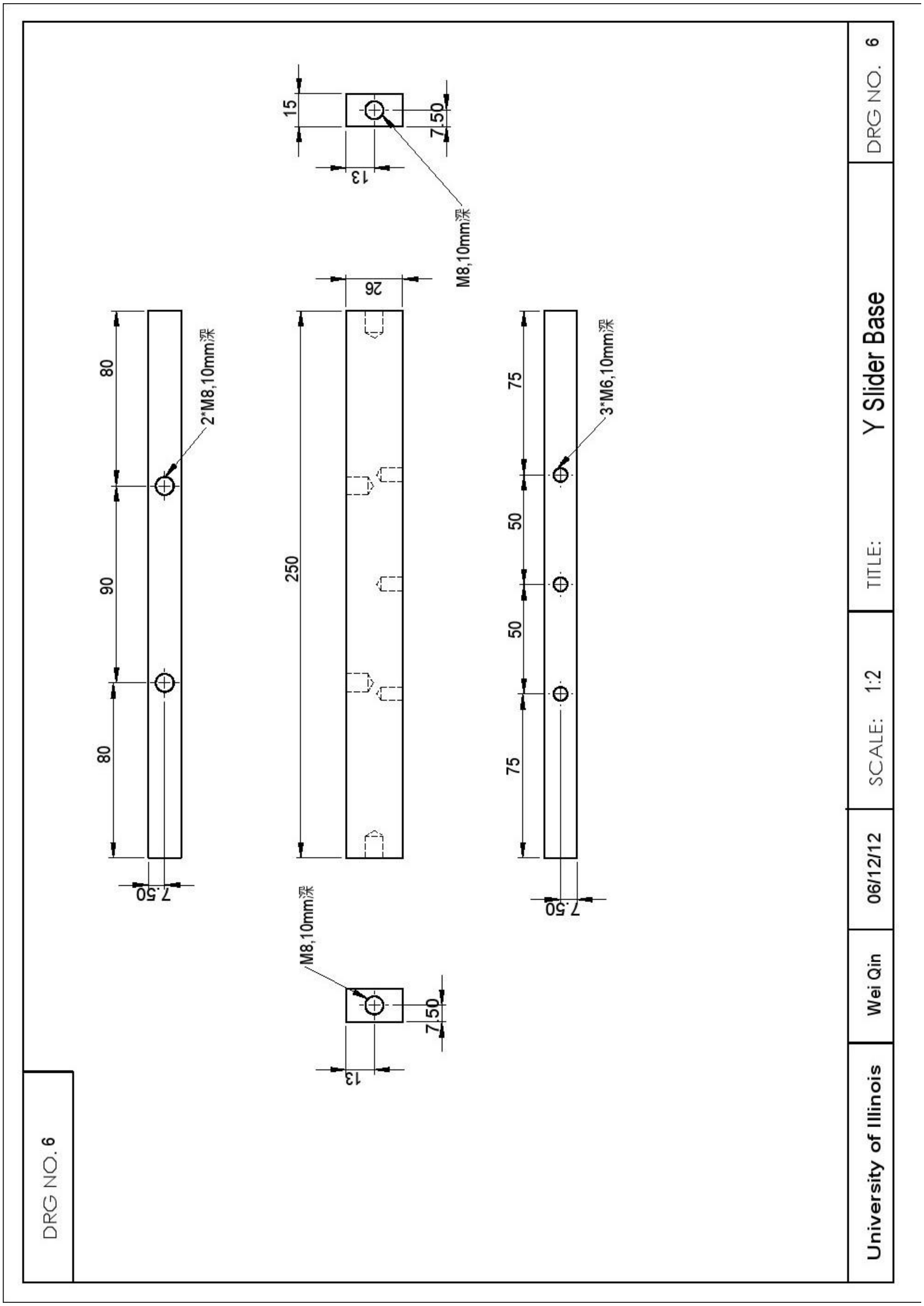
72.50
7.50
7.50
7.50
20.50
20.50
56
10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Wei Qin
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M8,10mm深
M8,10mm深
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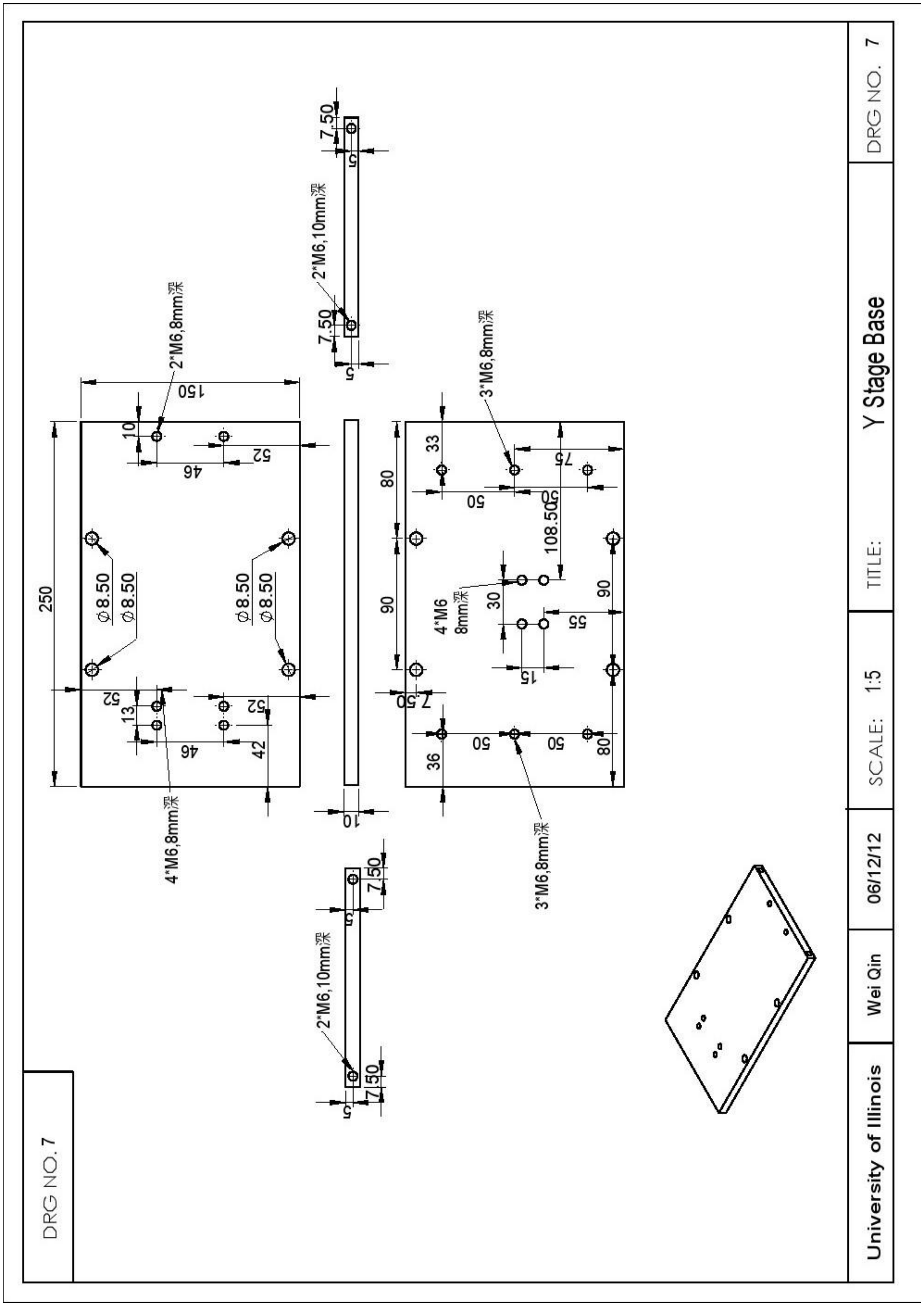
90
80
250
26
75
50
50
75
15
7.50
13
7.50
13
7.50
7.50
DRG NO. 6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Wei Qin
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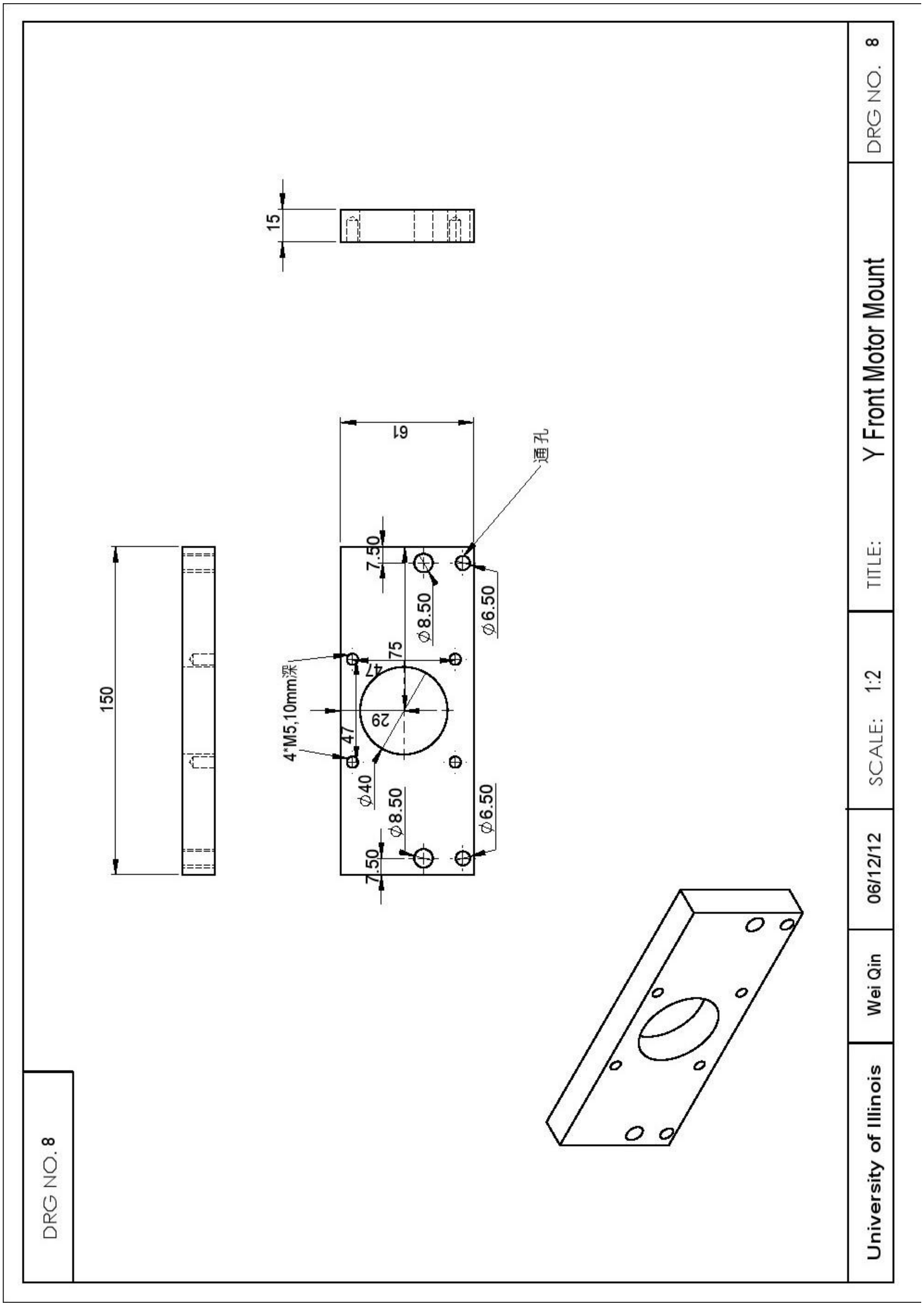
DRG NO. 7



150
15
61
7.50
7.50
75
47
47
29
ϕ8.50
ϕ8.50
ϕ6.50
ϕ6.50
ϕ40
4*M5,10mm深
通孔
DRG NO. 8
University of Illinois
Wei Qin
06/12/12
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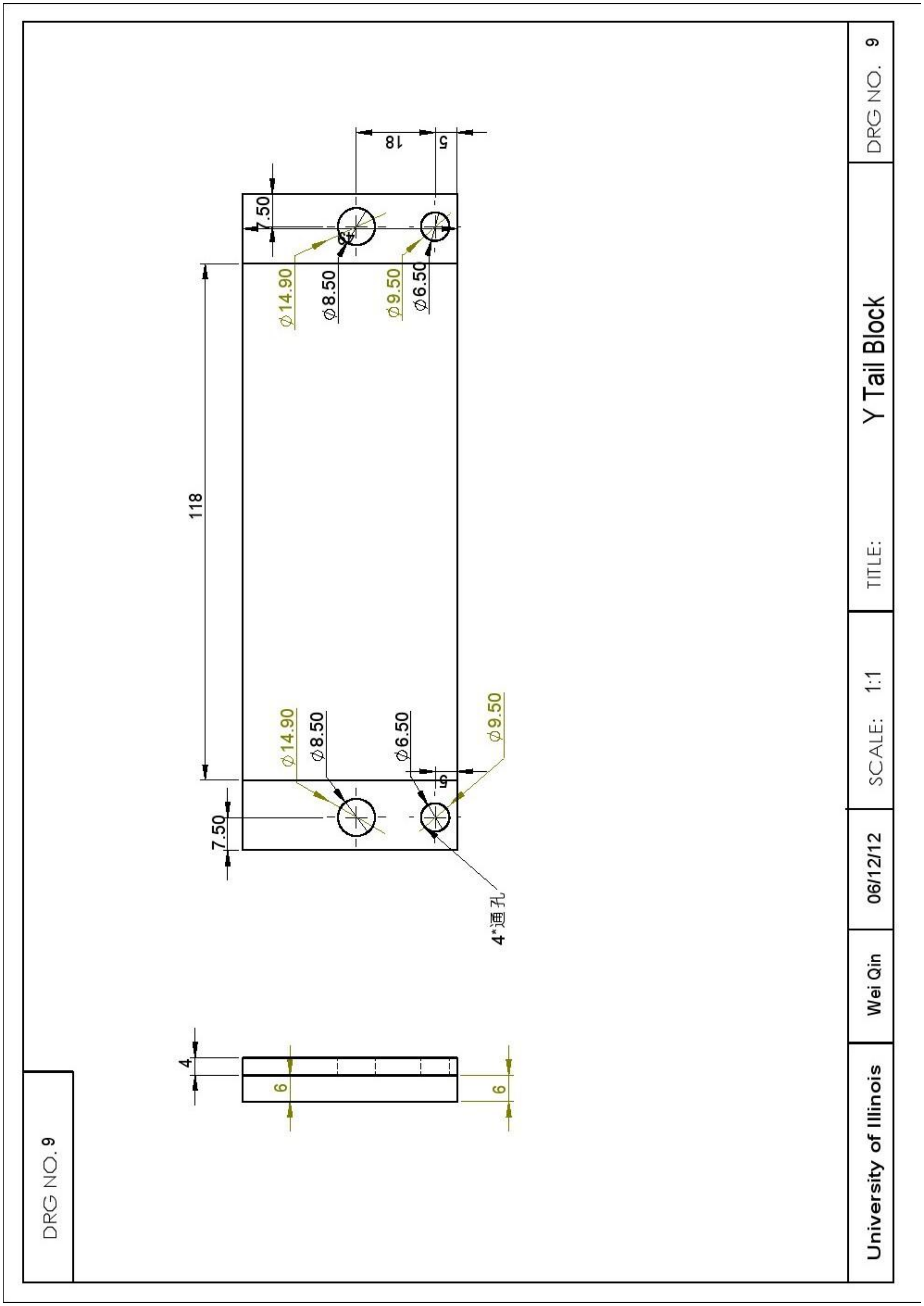
Y Front Motor Mount
DRG NO. 8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Wei Qin
University of Illinois
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DRG NO. 9
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7.50
7.50
18
5
5
⌀14.90
⌀8.50
⌀9.50
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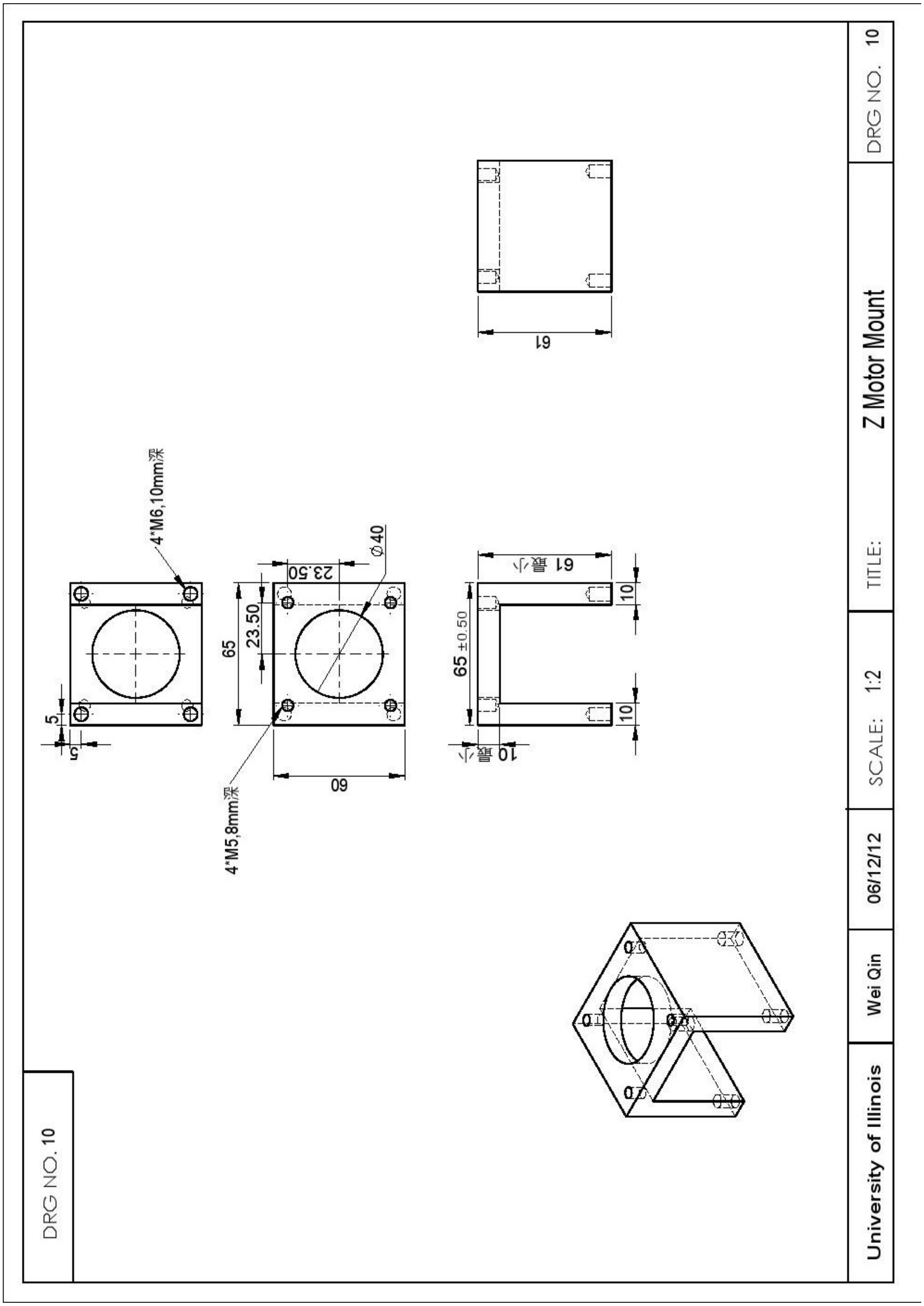
⌀6.50
⌀9.50
4*通孔
4
6
6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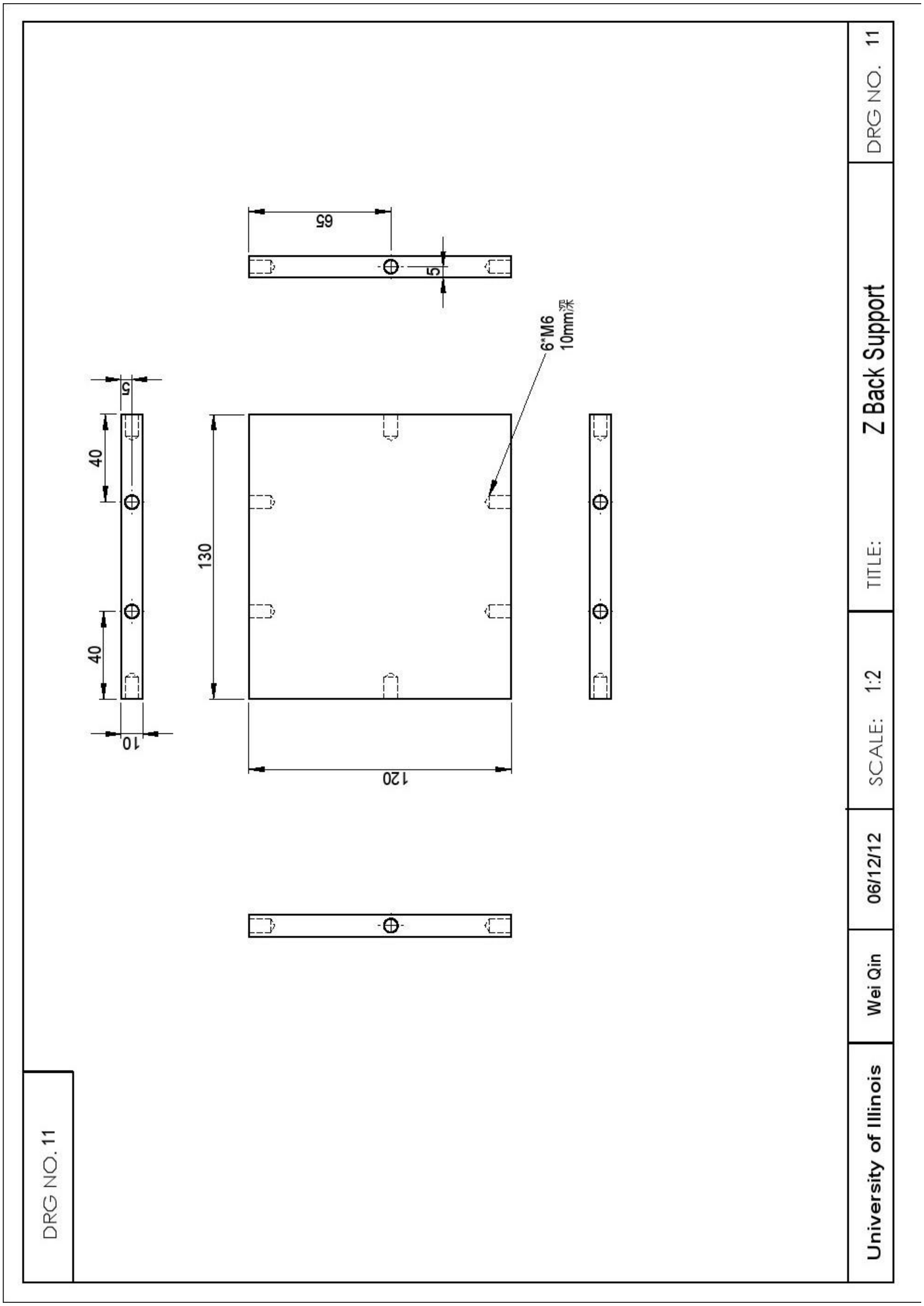
4*M5,8mm深
Φ40
23.50
65
60
5
5
61
65 ±0.50
10
10
61 最小
10 最小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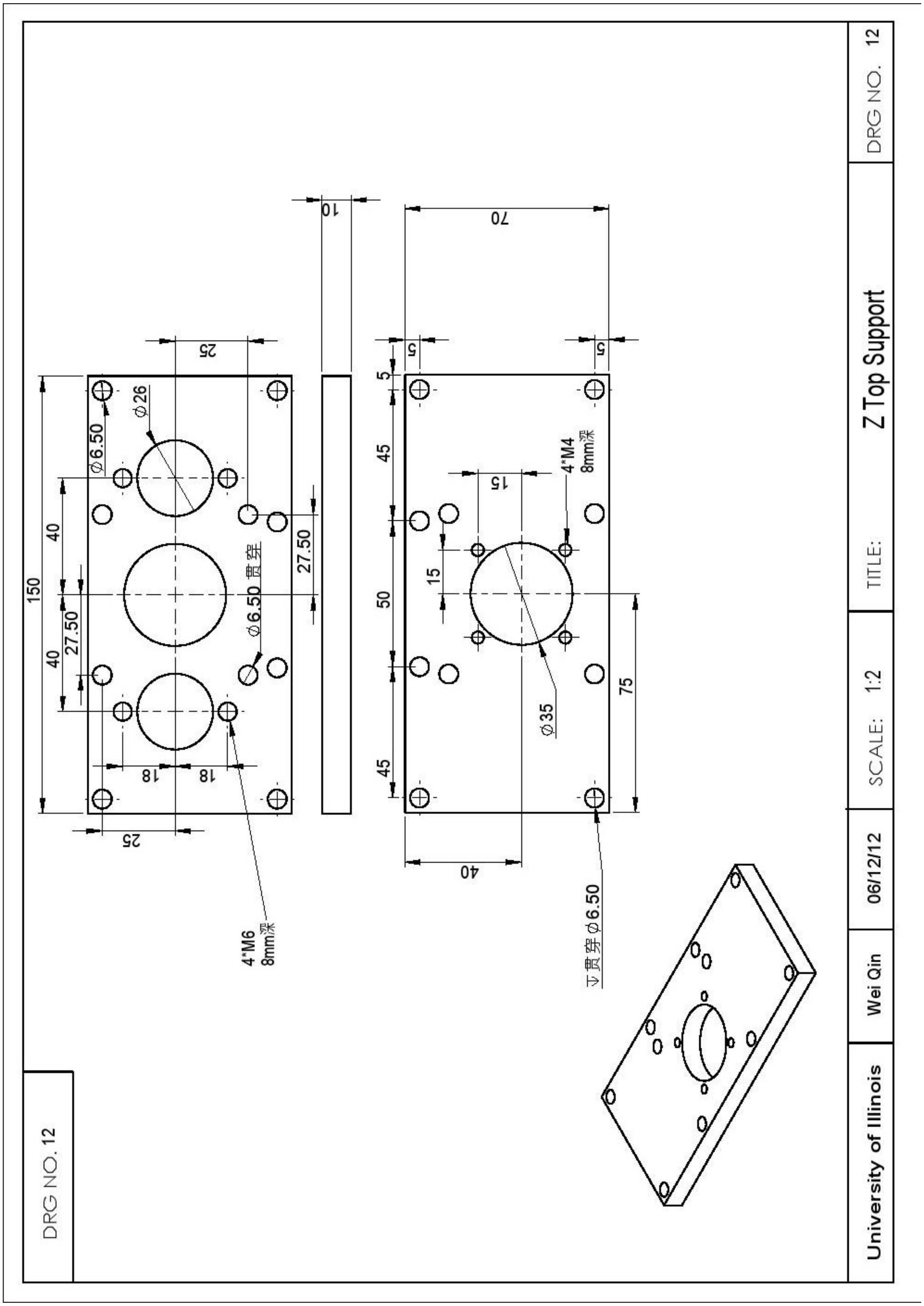
120
40
40
10
5
65
5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4*M4 8mm深
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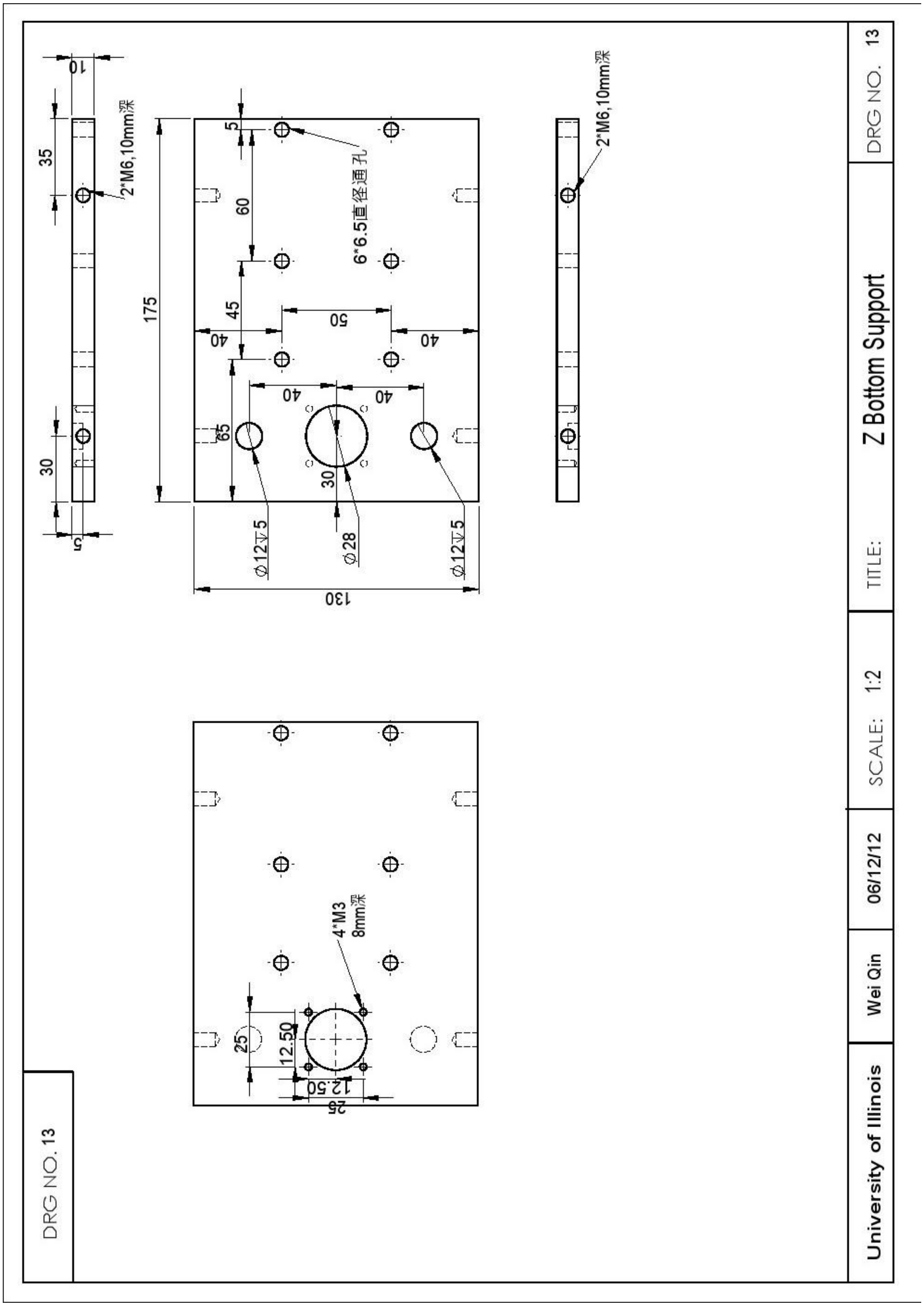
⌀26
⌀35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University of Illinois
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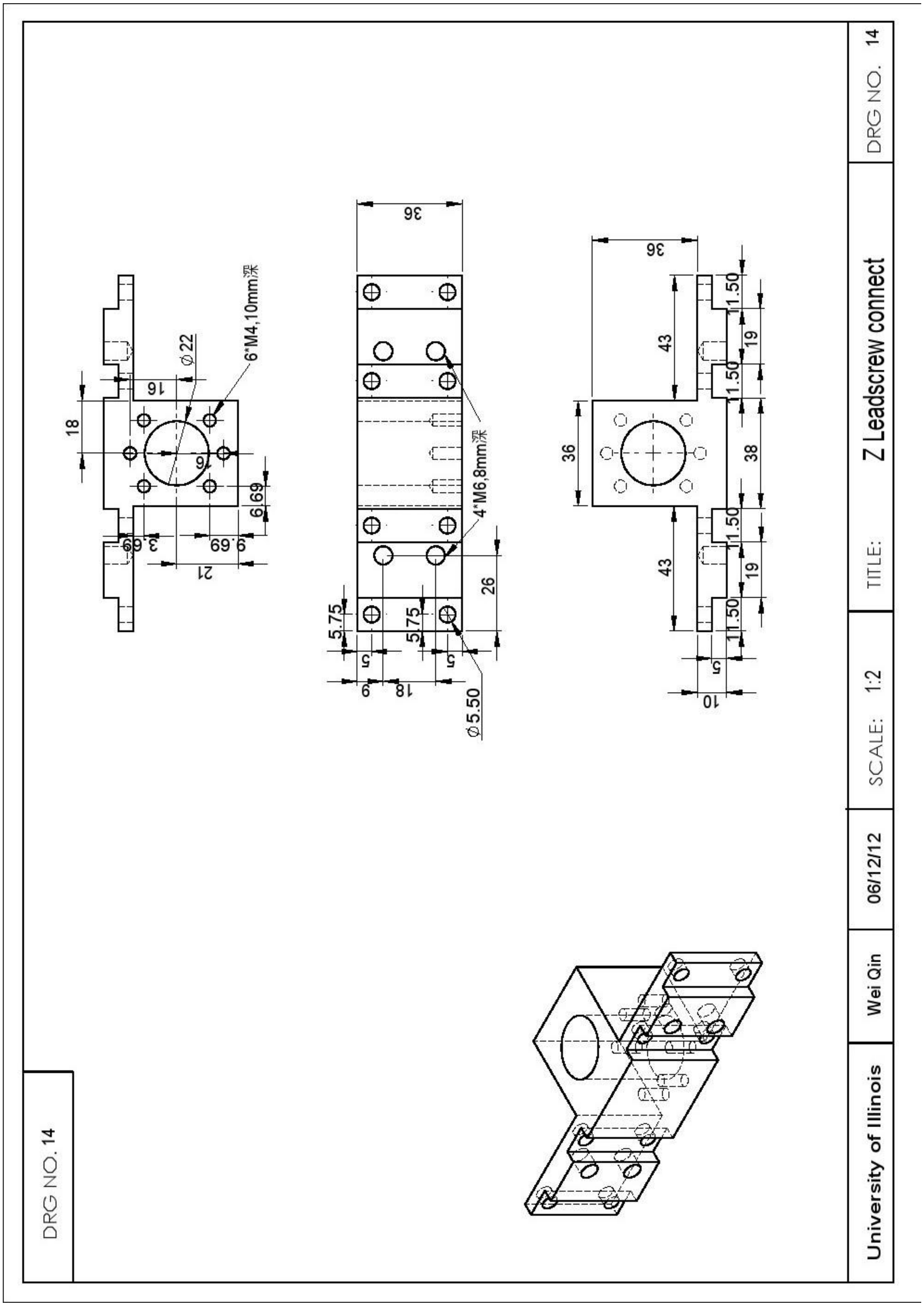
6*6.5直径通孔
4*M3
8mm深
Ø12⊽5
Ø28
175
130
DRG NO. 13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Wei Qin
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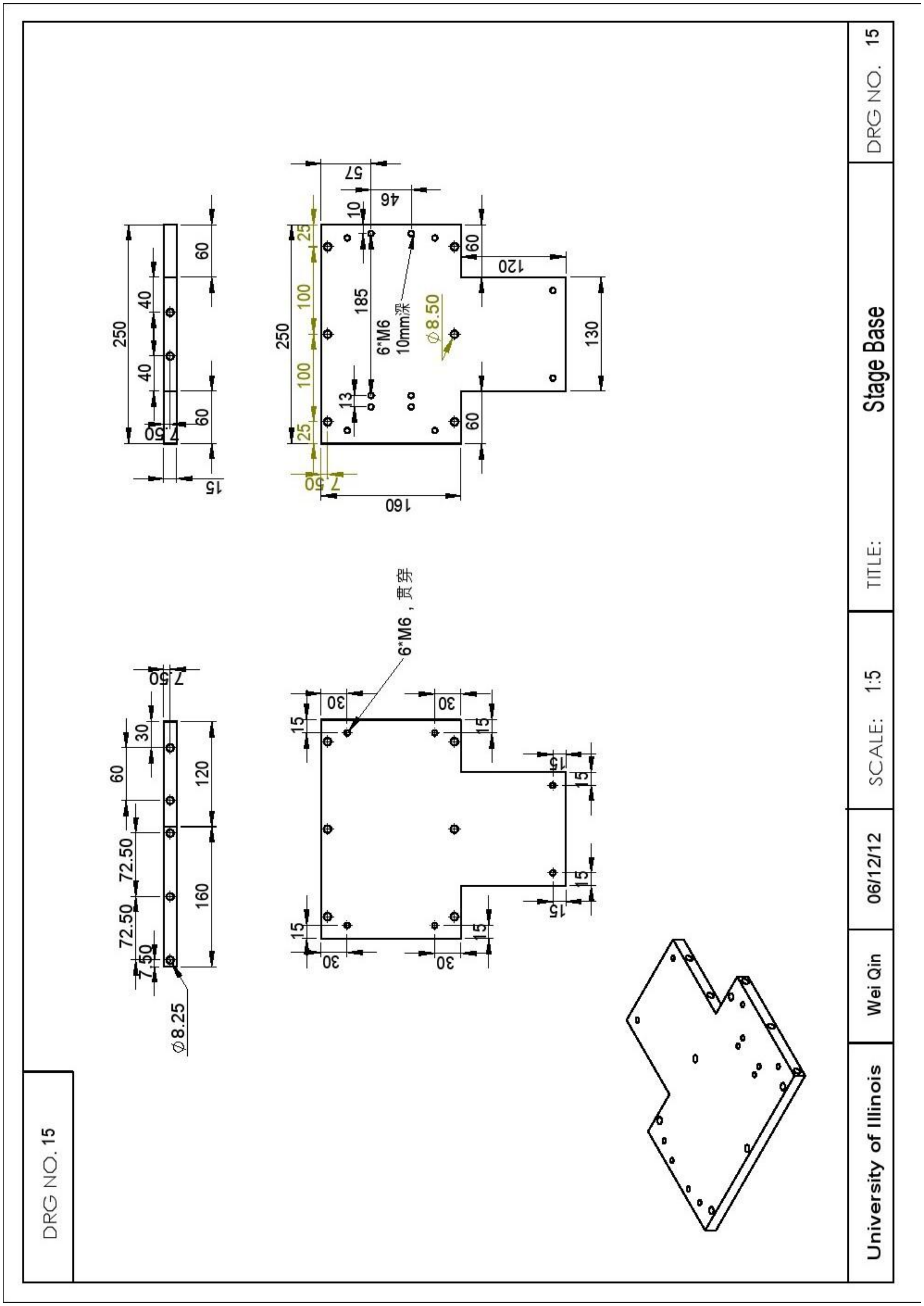
DRG NO. 14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6*M6
10mm深
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⌀8.25
University of Illinois
Wei Qin
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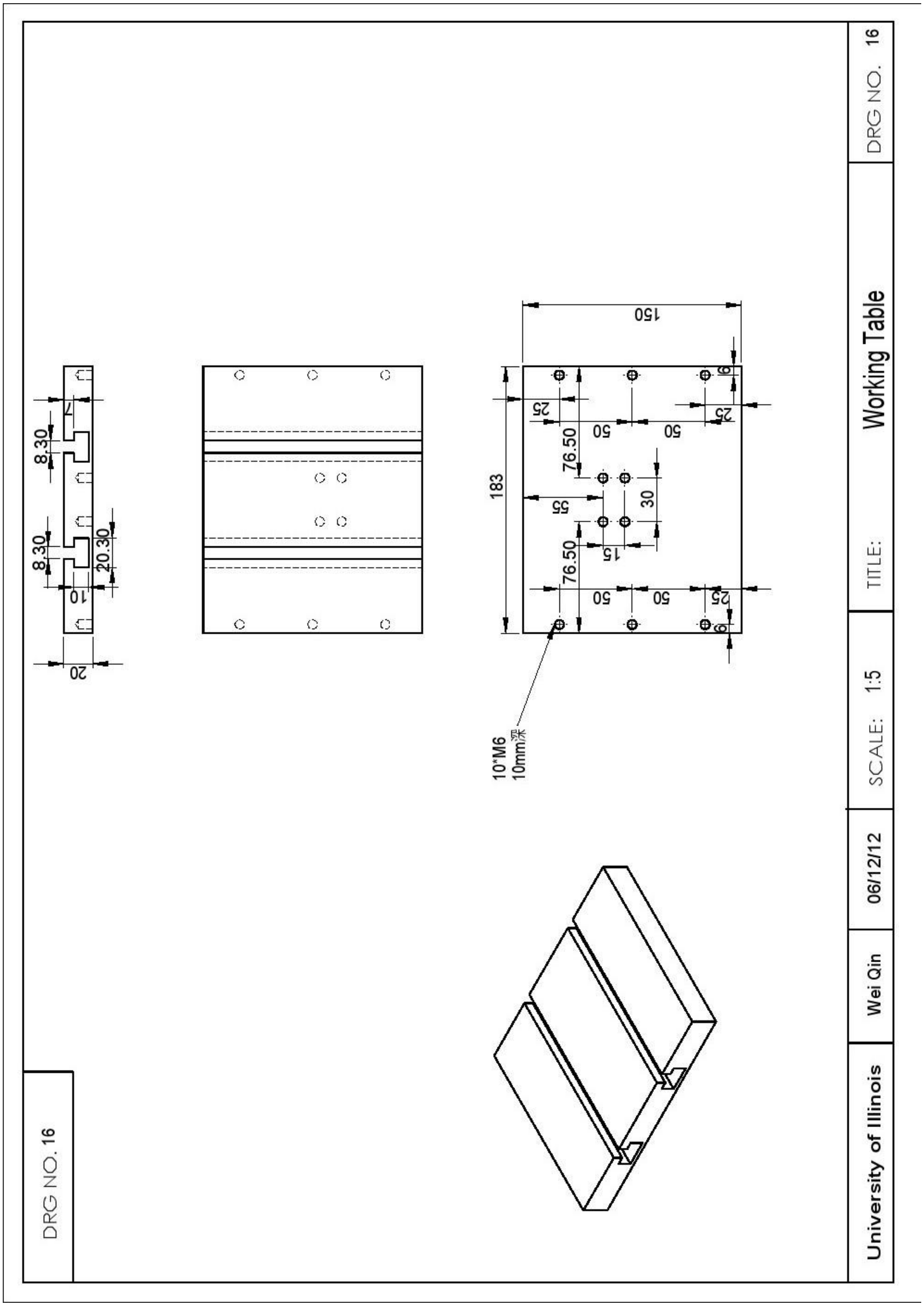
DRG NO. 15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Wei Qin
06/12/12
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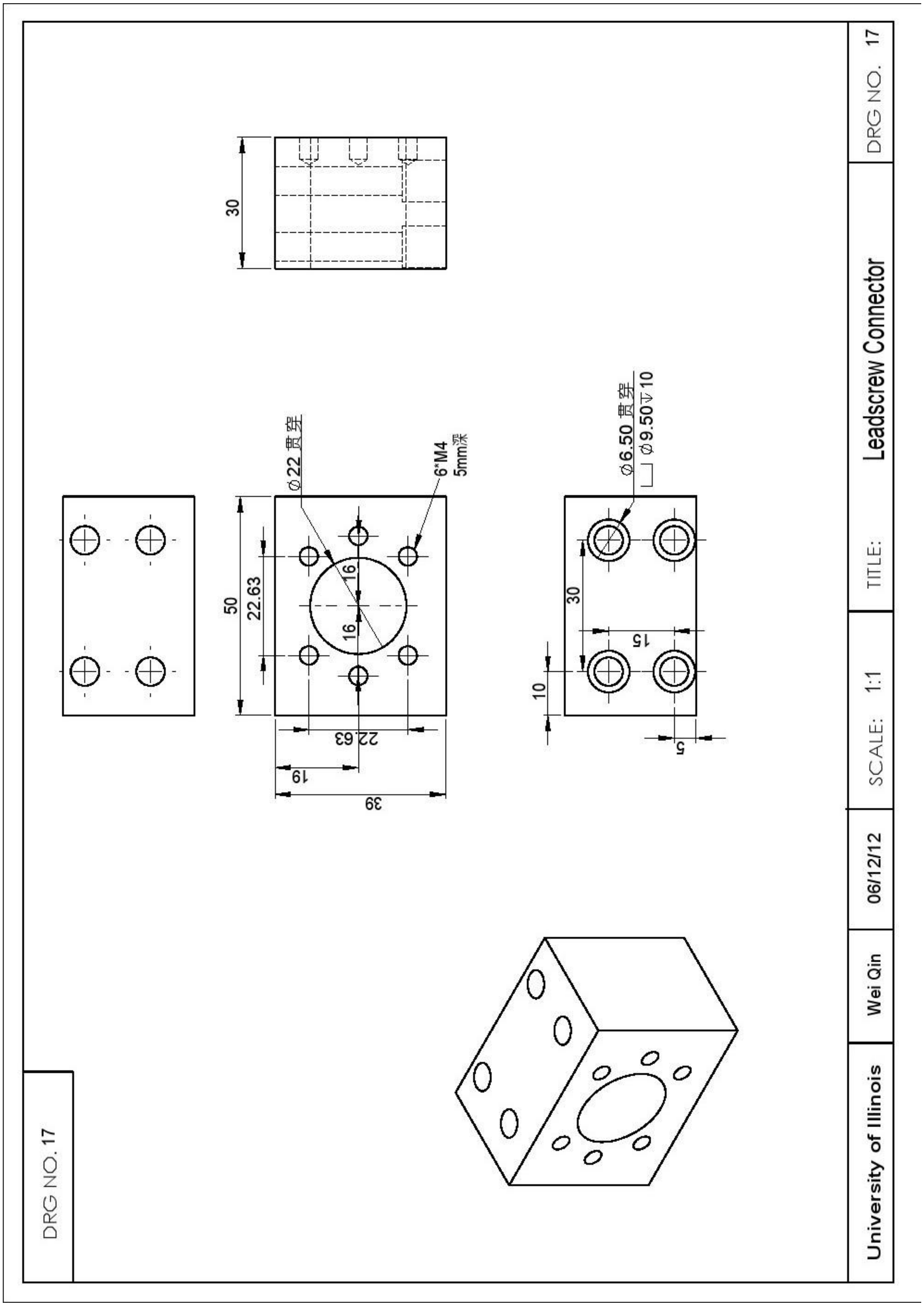
10mm深


University of Illinois
Wei Qin
06/12/12
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Leadscrew Connector
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DRG NO. 17
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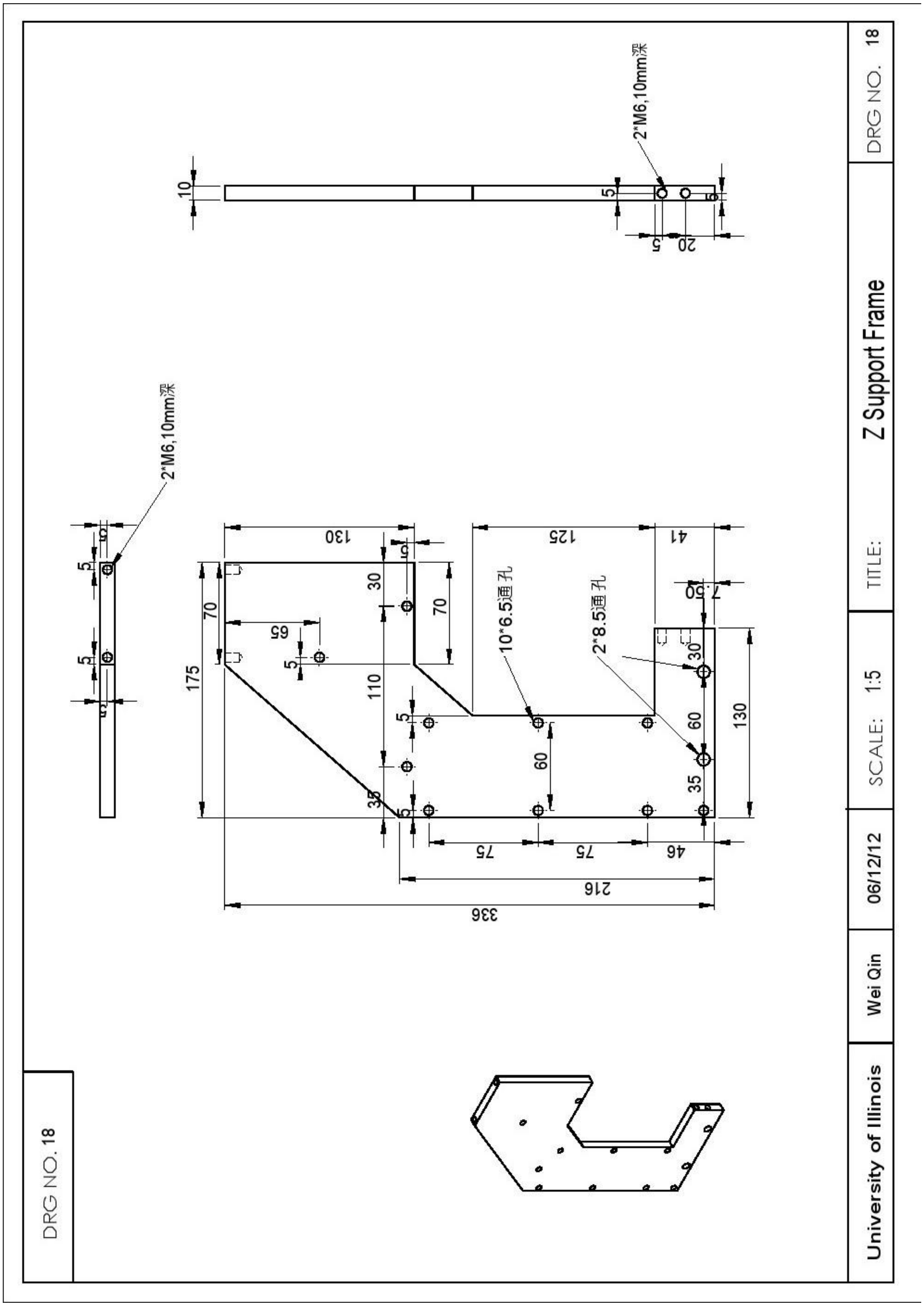
50
22.63
16
16
ϕ22 贯穿
6*M4
5mm深
22.63
19
39
ϕ6.50 贯穿
ϕ9.50 ⌴ 10
30
15
10
5



University of Illinois
Wei Qin
06/12/12
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DRG NO. 18
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10*6.5通孔
2*8.5通孔
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175
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125
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70
65
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35
30
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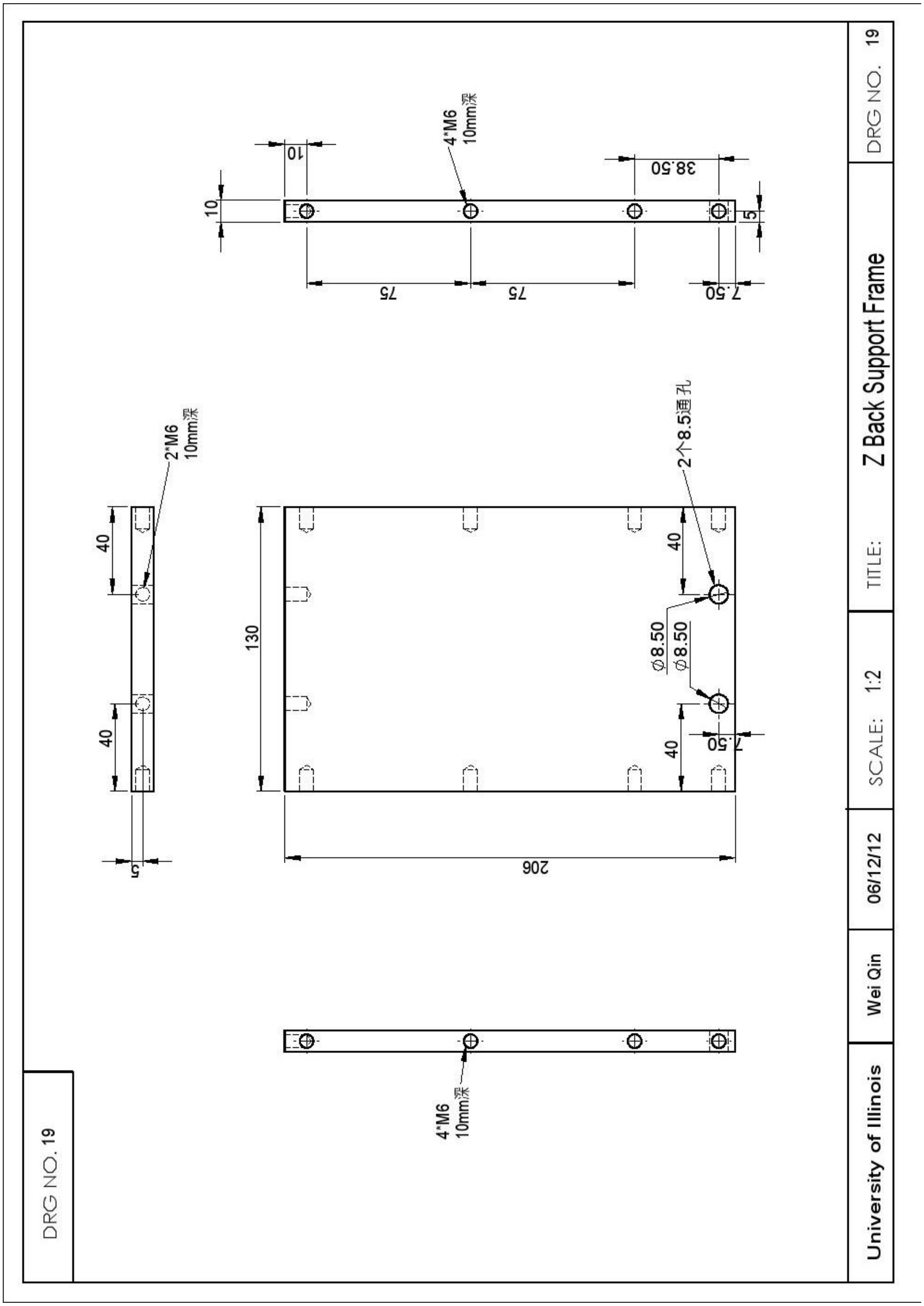
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06/12/12
Wei Qin
University of Illinois
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4*M6 10mm深
2*M6 10mm深
2个8.5通孔
Ø8.50
Ø8.50
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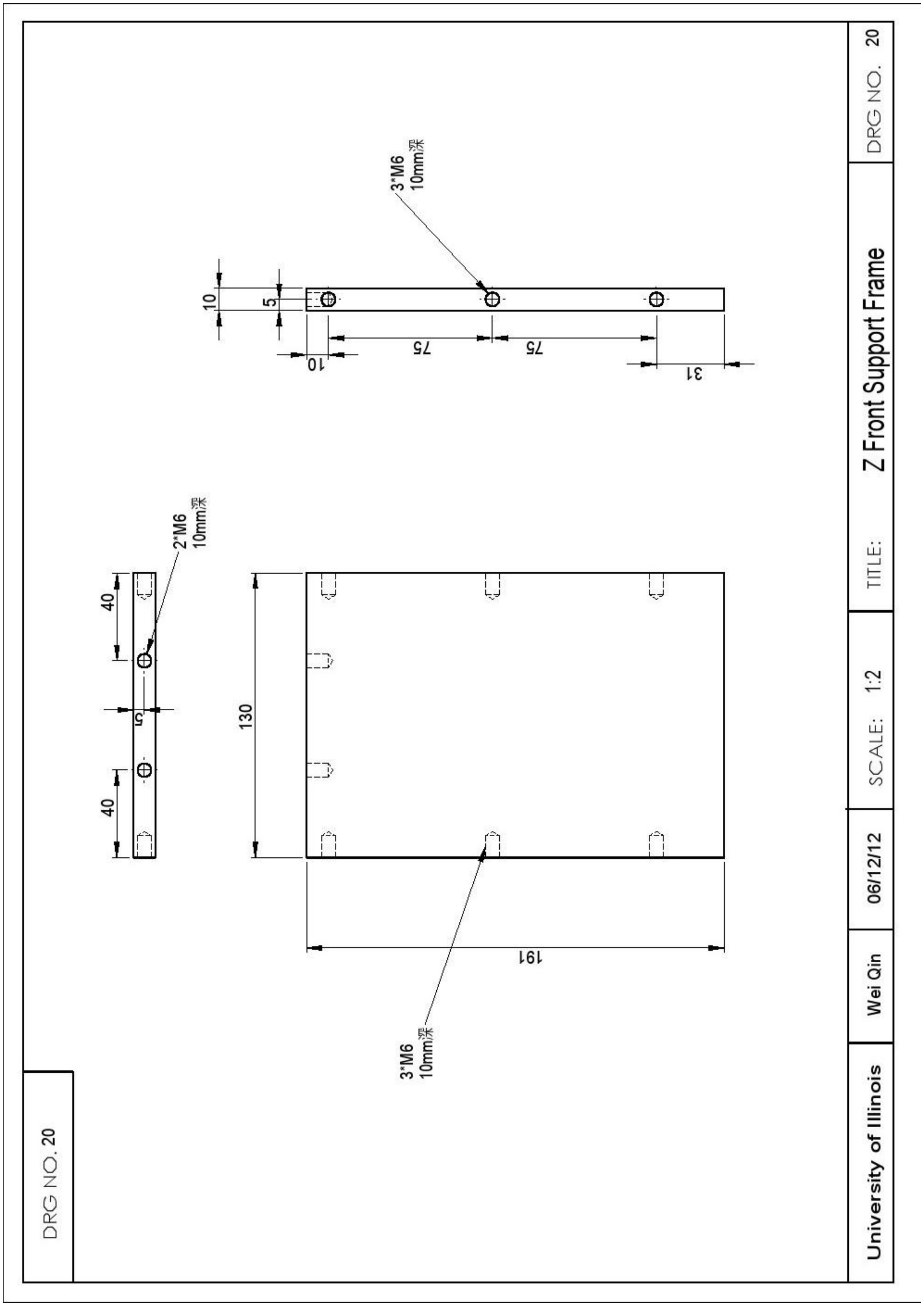
40
40
40
75
75
38.50
7.50
7.50
10
10
5
5



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10mm深
2*M6
10mm深
40
40
5
130
191
10
5
10
75
75
31
University of Illinois
Wei Qin
06/12/12
SCALE: 1:2
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DRG NO. 20