Course Code	**MIE 243** **Mechanical Engineering Design**
Project	Printed Circuit Board Milling Machine
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1.Introduction :

1.1 Problem statement

Milling is a common machining process of removing various materials using rotary cutters. With the increasing popularity of computer numerical control (CNC) milling, both precise and macroscopic operations are evermore accomodable. Due to the enormous variability of this machinery, different sized organizations request in particular types of milling. One can imagine that the capabilities of an advanced milling machine is not mandatory for simple tasks such as cutting soft plastics or wood, and as a result, suggesting the best type of milling machinery will be more efficient for the design team and more cost efficient for potential clients.

As such, the design problem requires the team to construct a plan for an advanced conceptual design of an entry-level printed circuit board (PCB) milling machine. The term “entry-level” changes with varying projects, so many assumptions must be inferred. The problem requires the team to design the machine to adhere to “small to moderate sized businesses”, presumably with a budget less than $10000 USD, granted that most advertised machines are in the thousands range and that the largest milling machine as of 2009 costs $3.5 million. [1][2] The design must also fit in a “small to moderate” workshop, once again presumably within a (1-2)m^3 workspace, given that most machines with a smaller budget are around human size. [1] The design must also be able to remove copper from a sheet and then recreate patterns on the board, as that is the sheer purpose of a PCB milling machine [3]. In addition, accesibility to the components of the milling machine should be feasible. Lastly, the design must maximize safety of all operators, and pose minimal threat.

1.2 Stakeholders

This section will define the groups and individuals who will be interested or have a potential influence on our milling machine.

Stakeholder	Interest	Effects on FOCs
The machine shops in colleges and universities (The mechanical machine shop in University of Toronto)	A milling machine is a necessary tool in every machine shop and the entry-level machine can be further designed and revised base on the practical use in machine shop[1]	The design should be easy and safe for trainees to use. The cost should also be reasonable.
The PCB company(Advanced Circuits)	The entry-level PCB milling machine might be needed for them to manufacture the PCB[2]	The design should be able to work on standard and custom PCBs.
The PCB milling machine company(LPKF)	The new features on our design might have influence on their new model[3]	The design should have all the standard functions and features.

2.Engineering Specifications:

2.1 Functions

The following fuctions are targeted at designing a printed circuit-board milling machine which can make up a standard circuit board in an efficient, safe, and low-cost way.
The machine essentially has two kinds of funtional basis :

1. Transfer the electrical energy to kinetic energy
2. Remove mass

- **Primary Function (The design will -)**

(1) Remove areas of materials from a sheet to make circuit boards

- **Seconday Functions(The following impact or are a result of the primary function -)**

(1) Create the signal traces
(2) Carve the patterns
(3) Create the electrical isolation

- **Unintended Functions(The following functions are products of the solution that impact its surroundings -)**

(1) Alter the surface feature and structure of the circuit boards

2.2 Objectives

The list of the objective of the design problem are listed below .

RANK	OBJECTIVE	DESCRIPTION	GOAL
1	Efficient	Create circuit board in a short period	120 strokes/min(Drilling Speed) About 100 mm/s(Travel Speed) [1][2]
2	Accurate	Remove the required area	Have a precise front-to-back alignment[3] Adjust width automatically[4]
3	Inexpensive	Minimize expense	Small business; low budget [5]
4	Durable	Have a long functional lifespan	Stable base to support main body of machine[6] Strong inner structure[7]
5	Controllable	Be easy to control	Control machine by a low number of buttons through electricity
6	Sustainable	Require less energy	Lower power supply[8]
7	Portable	Adequate machine size and	Can be moved easily [9]

		weight	

2.3 Constraints

- The design shall obey the following safety standard.
    - ISO-8636[1]
    - ISO-3070[2]
- All parts of the design shall obey Machine Tools Performance Criteria for Safety
    - ANSI B11.19 - 2003[3]

2.4 Service Environment

Generally , entry-level PCB milling machines are used in schools for trainees . However , It does not mean that professional workers do not use it in industry. Therefore, we set two types of basic service environments that will probably be used with the entry-level PCB milling machine.(**As for physical environment , we would only consider the environmental factors which can influence the function of the PCB milling machine**)

School:

PHYSICAL ENVIRONMENT	
Average Room Temperature(°C)	20 - 29[1]
Average Room Humidity Level(%)	30 - 50[2]
General Power Supply(V)	110 - 120[3]

Industry:

PHYSICAL ENVIRONMENT	
Average Room Temperature(°C	20 - 24[4]
Average Room Humidity Level(%)	20 - 25[5]
General Power Supply(V)	120 - 600[6]

(As for living things , we only take people and tiny organisms into account)

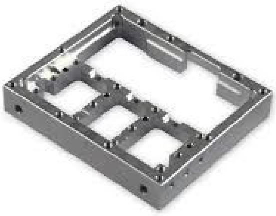
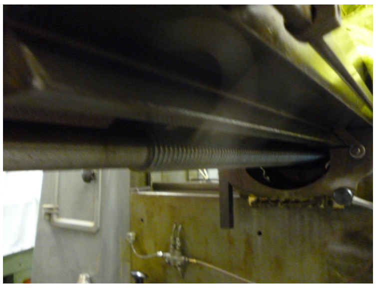
LIVING THINGS	
People	Workers and trainees
Germs	Air, Plants, Humans Pollution[7]

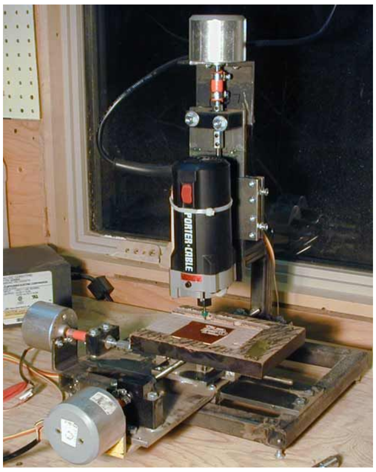
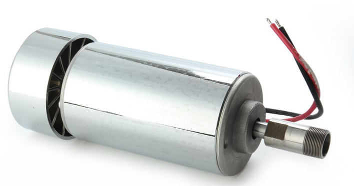
3.Conceptual Candidate Design:

3.1 Moving platform(x-y) with moving milling cutter(x-y-z)

Introduction: The goal of this design is to improve the portability while retaining the accuracy of milling. So, the milling cutter and platform can both be moved and adjusted in x-y-z and x-y direction separately. To be more specific, most of the current PCB milling machines have the milling cutter move along the x axis while the supporter of the cutter moves along the y axis with two slideways on each side of the machine.In this design, the supporter will move along the x- axis while the slideway on the back of the machine and the milling cutter will be able to move along the y axis through an extention and shortening device between the cutter and supporter. This reduces the number of materials and overall cost. This idea will make it possible for the supporter and milling cutter to be disassembled from the platform to make the whole machine easy to clean and move. Besides the platform and milling cutter, two computer devices will be added to this design, one with a screen to show the coordinates of the PCB on the platform to improve the accuracy and the other one to transfer the design of the PCB from a computer software to the machine. Additionally, a motor and power supply device will be needed in this design. For the power supply, a rechargeable battery will be added in this design to improve the portability, and the motor will be designed mainly to save energy while producing sufficient power.

Components

Name	Pictures	Description
Platform		The platform can be moved along the x direction by hand with a slideway under it and the material of it will be hard with low density.
The base		The base will be able to support the whole machine and be stable while working, and will be designed to be light
Slideways		The slide will be designed to be durable and light[1]

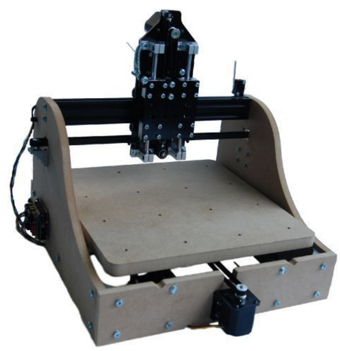
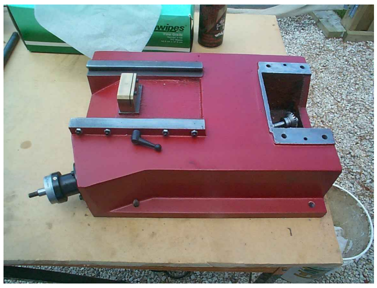
The supporter of the milling cutter		The supporter will be designed to be moved along the x axis and y axis. It will be designed to be able to bear force along z direction.
Milling cutters		Different types of milling cutters will be used for different tasks
Motor		The AC motor will be chosen to be the power input[2]
Power supply		The power supply will be designed to be a rechargeable battery

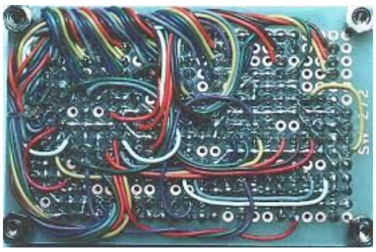
3.2 Stationary platform with moving milling cutter(x-y-z)

Introduction:

The cutter in this design moves in all 3 directions(x-y-z) while the platform is stationary. Left-right direction is defined as x-axis; forward-back direction is defined as y-axis and up-down direction is defined as z-axis. This combination of platform and milling cutter is stable and accurate. It also satisfies movements in all directions. The rotation of the cutter is generated by a motor, while the linear movements of the platform and millng cutter is generated by electricity and programming.

Components:

Name	Picture	Description
The Platform		The design should have a platform that is stationary[1]
The Base		The base should be able to support the whole machine and have a high durability[2]
Motor		Choose a high precision motor to ensure the accuracy of the cutters. Converts electrical energy to kinetic energy[3]

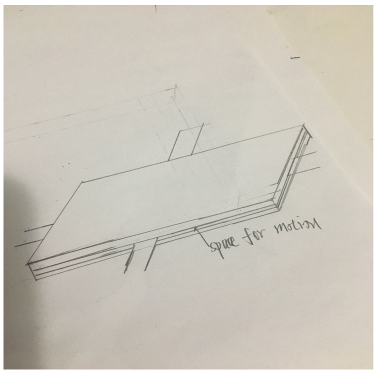
Power Supply		The power supply should provide enough electricity when the PCB Milling Machine achieves maximum energy consumption rate[4]
Milling Cutters		The design should include a series of milling cutters with different dimensions. The cutter should be able to move freely along x,y,z axis[5]
CNC Controller		A CNC Controller is required in the design so that users can command the machine to operate[6]
Wiring		The design should include wirings to connect the PCB to other components[7]

3.3 Moving platform(x-y) with lifting milling cutter(z)

Introduction:

Compared with design 3.1 and 3.2 , this design is mainly focused on the platform. Basically , the platform can move in right-and-left direction and forward-and-backward direction which are defined as “X” direction and “Y” direction respectively . As for the milling cutter, the rotational milling cutter is highly preferred and is moving in upward-and-downward way which is defined as “Z” direction . In this design , users still need to pay attention to both the platform and milling knife because of odd combination of motions in platform and miling cutter which occasionally produces some inconvenience. As for an entry-level PCBmilling machine , the inner electric structure is not as complicated and the high-powered motor is unnecessarily needed .

Components:

Name	Picture	Description
Small Electric Motor		Transfer electrical energy to Mechanical energy , then mechanical energy is converted to kinetic energy to milling cutter[1]
A Series Of Milling Cutter		Different size of milling cutter can carve different kinds of circuit board.[2]
The Base		The base can support the main body of the milling machine.[3]
The platform		The platform should have a high mobility in right-and-left direction and forward-and-backward direction.
Wire		This is the connection between main body of machine and the power supply[4]

Power Supply		This simple power supply is only ready for condition of blackout.[5]
Small Transformer		Adapt the power supply to make it suitable for milling machine[6]
Basic Electric System	 	It mainly consists of controlling button , outputing screen and switch button .

3.4 Summary:

In short, the group was able to accomplish the following:

- Set out a design scope
- Identify major functions, objectives, and constraints of what an entry level PCB milling machine must meet
- List potential candidate designs (i.e preliminary ideas)
- Lots of research on existing products, and what can be termed "entry-level"

In the next parts of the project, the team will:

- Narrow down candidates
- Determine which candidate can be further expanded on
- More drawings and diagrams

4.Final Design

4.1 Decision Making:

For our final design, we will consider all factors in our objectives.We decided to create a new kind of design based primarily on the Candidate design 2(3.2). At the current stage, we will describe all mechanisms of Candidate Design 2 due to similar mechanisms for this design and our final new design.

4.2 Final Design Analysis and Description

This part describes the detailed design of the final design. it includes the input and output form of the motion, the mechiansm that transit the motion and the motor as well as the battery that we choose. Then, each component and mechanism will be clearly listed with detailed explanation.

Basic Design Information(Dimension):

Details Design	**Dimensions**
Max. material size and layout area(platform) ($L \times W \times H$)	$180 \times 160 \times 2.5$ mm[1]
Travel speed diagonal ($X \times Y$)	100 mm/s[2].
Milling spindle	Max. 30000 rpm[3]
Drilling speed	100 holes/min[4]
Tool hoder(Slide Ways)($X \times Y \times Z$)	$150 \times 75 \times 75$ mm [5]
lead screws(Length,Radius)	400 mm,10 mm 450 mm, 10mm
motor($H \times W \times L$)	$60 \times 60 \times 60$ mm
Spindle(Milling Cutter Holder) ($H \times W \times L$)	$85 \times 75 \times 75$ mm
Repeatability	± 5 μm [6]
Mechanical resolution(X/Y)	± 0.8 μm [7]
Accuracy in the fitting hold system	± 20 μm [8]

Overall Dimensions($H \times L \times W$)	$458 \times 450 \times 450$ mm[9]
Weight	15 kg[10]
Ambient temperature	15 degree - 25 degree[11]
Power supply	100 - 240 V, 50 - 60 Hz, 120W[12]
Required accessories	PC, Exhaust unit[13]

4.3 Engineering Specification Justification:

When we design the final project, all the dimensions which we provide should be well-suited to our primary function and objective.

Mandatory specification:

4.3.1 Primary Function:

1. We regard the platform as one of the most important functional parts to the design. In our engineering specification, the primary function of our design is to remove the area on the circuit board to produce the signal traces on it.

4.3.2 Objective:

Effiecient:

1. Travel Speed Diagonal($X \times Y$): 100 mm/s
2. Milling Spindle: Max 3000 rpm
3. Drilling Speed: 100 holes/min
4. Milling cutter can move in X,Y and Z directions.

Accurate:

1. Repeatability: $\pm 5\ \mu m$
2. Mechanical Resolution: $\pm 0.8\ \mu m$
3. Accuracy in the fitting hold system: $\pm 20\ \mu m$

Inexpensive:

1. Total cost is around 2000 dollars.[1][2]

Durable:

1. Depend on materials(we will talk it later)

Controllable:

1. Controlling by computer programming
2. Working under the ambient temperature

Sustainable:

1. Depend on materials of interior and exterior structure(we will talk it later)
2. Working by electric power : 100 - 240 V, 50 - 60 Hz, 120W

Portable:

1. Dimensions($X \times Y \times Z$): $370 \times 400 \times 450$ mm
2. Weight: 18 kg (lower than similar-sized machines) [5]

Add-in specification:

1. Machine must be safe to use

Specification Justification:

4.3.3 Primary Function Justification:

The milling machine is supposed to hold a variety of sizes of circuit board to make the signal traces on the board. Generally, the maximum size of the common circuit board is about $165.5 \times 145.5(L \times W)$ [3] which is a surface area of 24080.25 mm^2 . In our design, the dimensions of our platform is about $180 \times 160(mm)(L \times W)$ and the maximum size of circuit board that our entry-level PCB milling machine can hold is about $180 \times 160 \times 2.5(mm)(X \times Y \times Z)$. The maximum total volume of circuit board that our PCB milling machine can make is about 72000 mm^3. Therefore, a large patform is necessarily required and our design meets this requirement.

4.3.4 Objective Justification:

Effiecient and Controllable:

Currently,most PCB milling cutters are required to move in three sets of directions to efficiently and conveniently produce the signal traces on the un-finished circuit borad. Aside from this, the speed of cutting is also an essential factor to produce the circuit board quickly. In our design, the drilling speed, milling spindle rotational speed, and diagonal travel speed is maximized within entry-level PCB milling machine standards.

The reason why we predominantly use computer programming to control the milling machine is that it allows users to utilize it more feasibly and reduces chance of errors, which in turns increases safety, an important parameter in our design.

Accurate:

The accuracy of cut is related to the quality of the circuit board when producing signal traces. Since the quality of circuit board is paramount in existing solutions, mechanisms that support higher resolution and accuracy will be preferred in the deisgn. To make the tolerance as small as possible, the addition of a suitable type of motor can be a great complement to improve the accuracy as well.

Inexpensive:

In our design, the entry-level PCB milling machine consists of eight main parts: Milling Cutter, Motor, Platform, Tool Holder, Base, Lead Screws, Knobs, and Slides. The detailed information of cost will be explained later. The total cost of the assembled entry-level PCB milling machine is approximately 2000 dollars by our evaluation. Compared with existing PCB milling machines in market, this price is relatively low[4]. The cost should be minimized while achieving all of the engineering specifications.

Durable and Sustainable:

These two objectives both depend on the materials of the machine. We will choose the most sustainable and durable materials to make the milling machine, the materials parts will be justified in later. However, if better materials are too expensive and cannot be justified as completely necessary versus worse materials, then they will not be selected. Whichever materials are chosen, the engineering specifications will be satisfied.

Portable:
Theoretically, the dimensions and weight of the entry-level PCB milling machine should be kept as small as possible, because unnecessary size is a waste of money. However, the size does not directly correlate with the function of the design, granted that it is large enough to hold standard circuit boards. Thus, this objective will be the least accounted for.
Add-in:
We should make sure that whoever uses it is safe and secure.

4.4 Explanation of Device Operation

4.4.1 Basic introduction of mechanism:

The milling machine is predominantly coordinated through computer numerical control (CNC), a type of milling that has become increasingly popular since the 1980s. A program is coded to control this complex process because it is difficult to manually move a precise cutter in three axial directions. It is simply more efficient for some type of computer to control the cutter rather than a human.
There will be a control panel designed in the front of the milling machine. This is designed in such a way that it eases user interaction - as an entry-level design, it should not be difficult to understand how to start the milling machine. With the use of a few dials/buttons, the input from the user should be relatively simple. The panel will have a power button that the user can press to either turn the machine on or off. There should also be an emergency stop button to shut down the machine for safety precautions.

4.4.2 Input Mechanism:

The milling cutter must be able to move in all three axial directions, the x-,y-, and z-directions. The team eventually determined that having any manual human input to control any axial direction would be cumbersome for the user. The milling machine is entry level, and should allow trained users to operate it without having advanced experience. As a result, all directions are controllable by a computer program, with the physical design of the machine allowing the cutter to move as so. To allow such motion, we will now examine how the design is able to move in all three directions. For all of the analysis below, see the hand drawings and/or CAD models for a reference and overall better understanding.
<u>x-direction:</u>
The milling cutter is linked together to the spindle and tool holder, and various other materials, but it will be referred to as a cutter for simplicity. The cutter moves in the x-direction on two attached shafts. This is the most basic movement method of the cutter that has been accounted for. These shafts, which range across horizontally above the platform, are supported at both ends by two vertical shafts. In our design, we chose to use the lead screw attached with a coupling to hold both the tool holder and the spindle. At the end of the lead screw, a motor will be installed that rotates

the lead screw to drive the both tool holder and spindle moving in the x direction. This lead screw will also be supported with a press-fit bearing instead of a flange.

y-direction:

The vertical shafts mentioned in the explanation above are what enables y-direction movement. Basically, we design the bottom of two vertical shafts to mount on two lead screws which are separately located on two sides of the base. There are two identical motors that are installed at one end of each of the two lead screws respectively. As the same mechanism of a lead screw is used in the x-direction, the motor is able to transmit rotational motion to the y-direction-used lead screw as the motion transmission. These two lead screws are perpendicularly postioned to the x-direction-used lead screw.

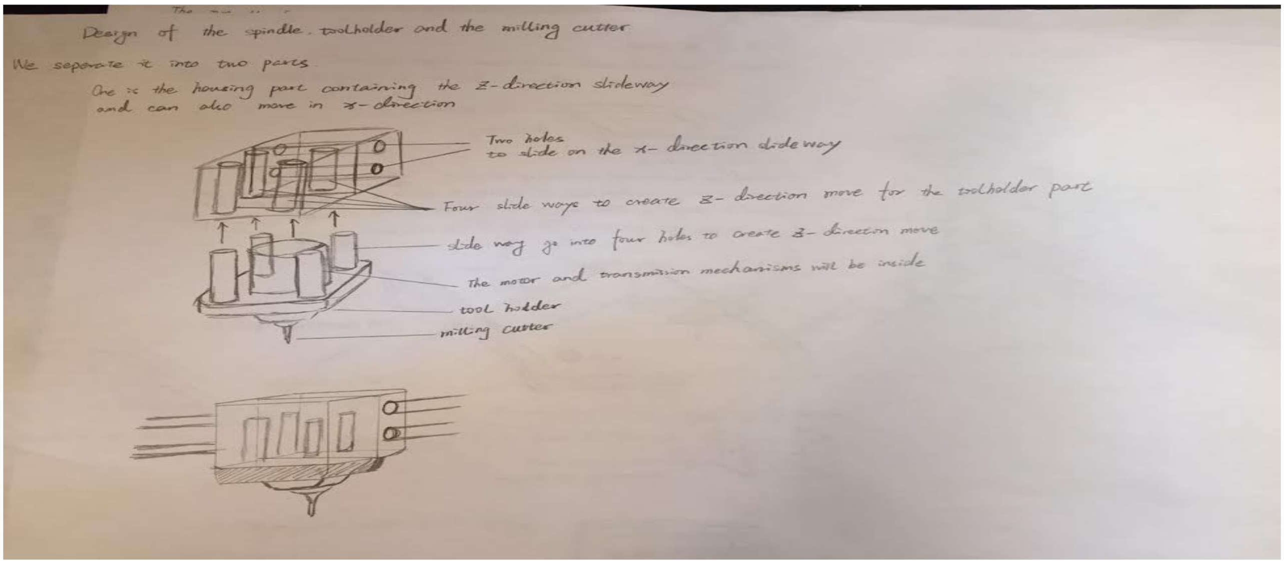
z-direction:

This axial direction was the most difficult to design because the team only wanted the cutter to move instead of other parts of the system as it would be rather difficult to implement a moving base/platform while retaining cutting accuracy. In the end, the team decided that the spindle was split into two segments. Thus, when z-direction motion was required, one half of the spindle would be able to move in the z-direction, while the other half was not. This half would contain the motor as well as moving the cutter itself. This solution allows the system to remain intact and retain precision and accuracy. As for how to move spindle, we still decide to use the lead screw which is installed in tool holder and the motor is mounted on the top of the tool holder which can drive the lead screw rotation. This mechanism would result in the moving of the spindle since tool holder is just connected behind the spindle that rotation of lead screw in tool holder can induce the moving of the spindle and milling cutter.

4.4.3 Output Mechanism:

All of the output is in regards to what happens with the milling cutter. After a series of input mechanisms ranging from belt drives, knobs, and computer numerical controlling, a series of output mechanisms occur. To understand these output mechanisms better, the entirety of the milling cutter has to be better understood.
As aforementiond in the analysis above for the z-direction input mechanism, the spindle was sectioned into two parts to allow for such motion. There are diagrams below to show the interior of the spindle/tool holder/milliing cutter. As illustrated, the front section has four slideways to allow for vertical z-direction, while the back section has two openings which allow the shafts to move horizontlaly in the x-direction. The motor and transmission mechanisms are neatly situated in the center of these four slideways.

The milling cutter extrudes out of the spindle, powered by a motor. All of this is encompassed within a tool holder for stability and protection. As these pieces are responsible for the output, it is essential that they are well protected from any hazards.



4.5 Component Selection and Justification

4.5.1 Introduction to Justification of Components

With each part of any design, the decision of how the part will be implemented is always a priority, but also what material or component used is critical. Choosing the wrong material will inevitably lead to failure, and ultimately be catastrophic. On a more minor scale, choosing the method of implementation seems less important, but when done correctly can save the design team time and money. This is where component selection becomes critical. To examine this, the design of an elevator will be used. The component selection, or method of implementation, is primarily a pulley system. In this pulley system, the type of materials can differ for the wires or pulley. However, using an inferior implementation or even simply wrong implementation will mean that material selection is irrelevant as the design is already destined to fail. Thus, in the following sections, the design team will justify the selection of components to each major part of the PCB milling machine.

4.5.2 Milling Cutter/Spindle:

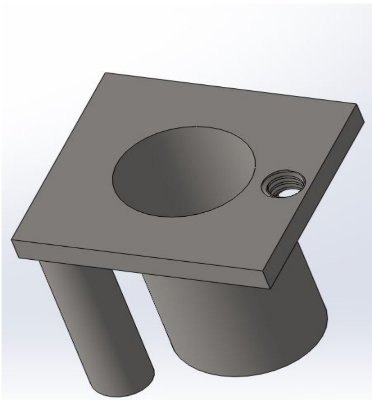
<u>Characteristic:</u>

The cutter is often producing a type of shear deformation. The cutter must be good in cutting different types of materials, from soft plastics to hard metals, as we are designing an “entry-level” milling machine. The machine isn’t designed for a certain material in particular, so it should generally be able to cut most typical materials well. With that being said, materials that it must cut are that of a printed circuit board. Printed circuit boards usually comprise mainly of copper layers, and thus the cutter must be able to at least cut through this copper.

The cutter we have designed in particular is encompassed within a tool holder that also holds the motor and spindle. This piece is segmented into two sections, as to allow for z-direction. This split of sections is justified because it ensures that a minimum amount of parts are actually moving. There are already sets of lead screws

that allow for x- and y- motion, so adding a set of shafts to allow for z- movement would make the design clunky and less able to fit within a small to moderate workshop as prescribed in the document requirements. Granted that vertical motion upwards is not as necessary as downwards, the requirements of shafts seemed unnecessary and thus justifies the idea of splitting the encompassed milling cutter into two parts. The split sections also neatly allows for the shafts to easily insert into one side of the milling cutter, avoiding any important features.
The front segment contains a motor which is connected to the spindle that drives the rotation of the milling cutter. Another motor is connected with the tool holder to drive the spindle and the lead screw for axial motion.

<u>Component:</u>

Component	Application	Justification
Spindle 	● Removing the area on circuit board to produce the signal traces ● Different sized milling cutters can produce varying sizes of signal traces based on personal requirement	● Providing different types of the cutter can meet different requirement of the circuit board[1][2]

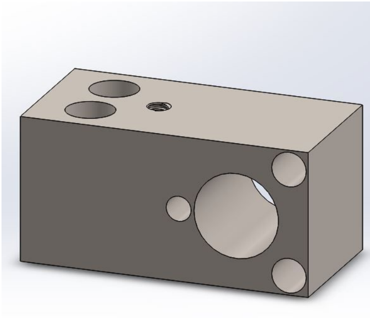
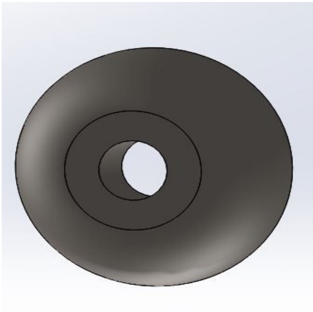
4.5.3 Tool Holder

<u>Characteristic:</u>

The tool holder is a device which includes the spindle by the lead screw. There is a lead screw that is vertically included in the tool holder. When we use the motor to drive the rotation of the lead screw as the input, the spindle could be driven to move upwardly or downwardly in z direction as the output. There is an another lead screw ，that controlling left-and-right motion of spindle， which is horizontally positioned at the bottom of the tool holder. As the same functional mechanism as z direction’s, the spindle would be driven to move in x direction by the tool holder due to rotation of the horizontally-placed lead screw.

<u>Component:</u>

Component	Application	Justification

Tool Holder  	● Holding the spindle ● Driving spindle and milling cutter to move ● Protecting the motor and lead screw to some extents	● Tool holder is really light that does not negatively influcen on the total weight[3] ● Tool holder have a enough inner space to include a lead screw and motor[3] ● Tool holder does not have any affect in input and output mechanism although it includes a input lead screw[3]

4.5.4 Belt Drive vs. Lead Screw for y- motion

Characteristic:

Both a belt drive and lead screw are commonly used, and were both well justified for the use of our y-motion transmission. The main objective of this component is to transmit linear motion as we want the shaft to move in the y-direction to then move the cutter. This gives the lead screw an advantage because it converts rotational to linear motion, whereas a belt drive maintains rotational motion [4][5][6]. Although this does not rule out the belt drive, it signifies that the lead screw requires less additional componenets to complete the task. Lead screws have a very quiet operation and in general are less likely to slip compared to a belt drive. Lead screws are self-locking, meaning that if y-motion is unwanted, it is easier to halt this with this choice [6]. Granted that this is an entry-level design and that the milling machine is moderately small, the load on these components is not excessive. Lead screws are highly efficient at low loads [7]. Both the belt drive and lead screw are simple in design and cheap, as well as offering flexibility.

component	application	justification
Belt Drive	● Two angled guides to produce a drive that is continuously variable over a range of ratios ● Mainly industrial applications	● Transmission: can drive multiple output shafts; flexible; typically planar but does allow some out-of-plane offset.[8] ● Modification: can modify direction of rotation, and can

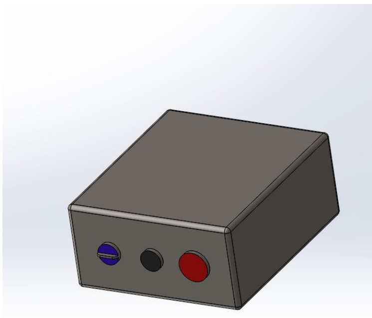
		realize a speed ratio input-output[8] ● Provides engineered point of failure[9] ● Low stored energy when moving[10] ● Alignment is much less critical than gears[11] At the end-of-life: ● Increasing noise (squeal sound), vibration[12] ● Increased chance of slippage[12] ● Decreasing efficiency[12] ● Creates debris[12]
Lead Screw 	● HELIX Linear Technologies—significantly increases lead screw accuracy. Using advanced thread-rolling processes and material composition technologies, HELIX offers precision engineering lead screws that makes the lead screw as accurate as possible[15] ● Lead screws use the helix angle of the thread to convert rotary motion to linear motion. The performance of a lead screw is heavily dependent on the coefficient of friction between the nut and the screw, which in turn depends upon the material used for the nut and screw. Lead screws typically use nuts made of internally lubricated plastic or bearing-grade bronze.	● Lead screws cost less[13] ● Lead screws are self-locking and do not require a braking system[13] ● Lead screws are better for vertical applications[14] ● Lead screws are generally more efficient, requiring greater torque and a larger motor and drive.[14] ● Lead screws have higher friction and run a hotter temperature.[14] ● Most lead screws are not well suited to high throughput, high speed applications or those with continuous or long cycle times.[14]

	Plastic nuts usually travel on stainless steel screws while bronze nuts often run on carbon steel screws.[16]	

4.5.5 Base and Platform

<u>Characteristic:</u>

Many industrialized milling machines are designed such that the cutter itself moves. However, it is completely viable that the base/platform is moving to coordinate the cut. The design team concluded that it was much easier and simplistic to have a moving cutter than a moving platform, based on how standardized it is. It was deemed not feasible to have a moving platform because this requires that the cutter, which is much smaller in size than the platform, be perfectly still to assure perfect accuracy. Although most of the function is computer controlled, this is slightly analagous to drawing on a piece of paper. It is easier to draw on a motionless paper than to have a motionless hand and a moving paper, even if it is computer automated.

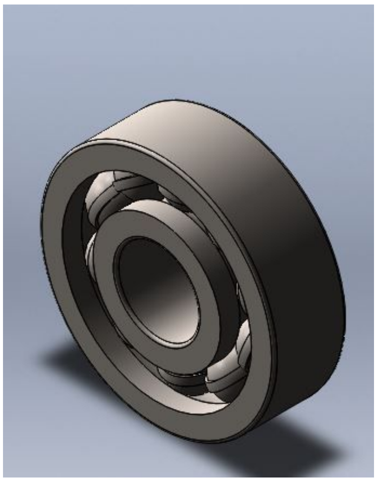
component	application	justification
Rectangular Steel Base 	• Provide a rigid and stationary working area for the cutter • Platform must be able to support workpiece being cut by the milling cutter, without damaging the cutter or workpiece • Allow for movement of lead screws and other components	• One of the most standardized choices for a PCB milling machine, as evident in [17][18][19] • Produces a sturdy base for a good price as steel is highly standardized

4.5.6 Supports for all components

<u>Characteristic:</u>

Supports are completely necessary in a plethora of engineering designs. Without supports, components are more susceptible to failure because they are more exposed and will not have a load to help support it against axial loads/forces, deteriorating more quickly over time.

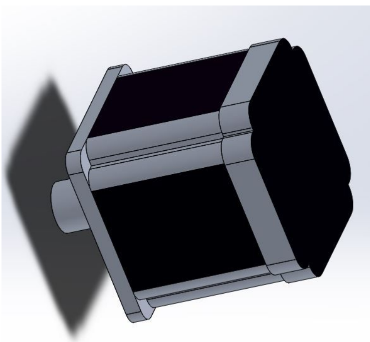
Determining which support to use differs based on what component we want to support. Thus, we will examine a variety of supports and justify why one support is better vs the other in certain applications.

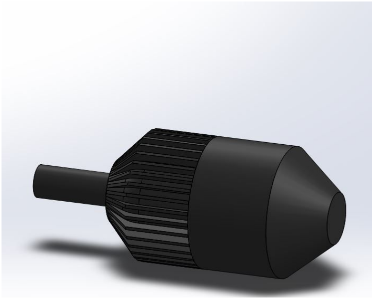
Component	Application	Justification
Ball Bearing 	● To provide sufficient support to all components, particular those that are directly related in the input-output motion transmission ● Reduce friction, heat, axial loads/forces, tension, wear, etc on components	Ball and rolling bearings are more suitable for high speed and high torque applications.Granted that the milling cutter's main applications are at high speeds, some form of a ball or roller bearing would be optimal for support. However, we need to be able to handle axial force loads. Thus, some type of angled ball will possibly the best method of support.

4.5.7 Motors

<u>Characteristic:</u>

The motor must be able to supply power to move the spindle so that it can then move the milling cutter to create cuts. For our design, we also require motors to rotate lead screws, as to allow for complementary x-, y-, and z- motions. Both DC and AC motors are possible to use in CNC milling machine applications [20]. It also has to be small enough so that it does not jam with any pieces of the milling machine. The motor should also not be overpowered (i.e., be efficient) as it is only required for an entry level milling machine.

Component	Application	Justification
DC Motor AC Motor 	- Power necessary parts, i.e spindle, lead screws, etc - Be efficient in power - Not overfill too much space, relatively small motor due to size of milling machine	- Use AC motor if we require constant change in directions [21] - Use DC motor if need flow of electrons in one direction [21] - Both are cost efficient, but AC has a higher power factor [22] - In general, if AC voltage is supported, use AC motor [22]

4.5.6 Buttons

Characteristic:

The addition of buttons on the milling machine allow primarily for user simplicity. By having a few amount of buttons on the machine, the user is able to turn the machine on or off, immediately stop the machine via an emergency stop button, and adjust the speed on the milling cutter via a dial. This adheres to our engineering specifications and team goals of making the machine as user-friendly as possible.

On our design, there will be one dial and two buttons. The two buttons include an on/off mechanism and an emergency stop button. These two differ because the emergency stop button will halt the machine under any circumstances, whereas the on/off button may not work in certain situations.

The dial on the other hand adjusts speed of the milling cutter. Although this can also be done through CNC, it may speed up the milling process if accuracy is not as important as time spent.

The on/off button will be a small green button, and the emergency stop button will be a large red button, because it is what humans intuitively perceive as on/off and ‘danger’ buttons, respectively.

4.6 Materials Analysis

Component	Materials	Properties
Lead Screw	Stainless Steel	Prevents corrosion and is more resistant than typical steel due to chromium content present [6]
Base	A36 Steel [1] Structural Steel Tubing [1]	Easy to machine, and has good strength and corrosion resistant. Commonly used for plates [7]
Milling Cutter	Coated in polycrystalline diamond or titanium aluminum nitride [2]	- Hard Coating that protects milling cutter against wear, important as cutter comes into contact with metals such as copper
Spindle	Titanium Stainless Steel	- Need to choose a material that is highly resistant [4] - Also choose a material that has a high tensile strength [4] - Titanium is rather expensive, but has the highest tensile strength. Stainless Steel is more corrosive resistant than normal steel, cheaper than titanium[5]
Tool Holder	Hot Rolled C1018 [8][9]	-Must be able to hold spindle/motor/milling cutter, and be highly resistant and light/durable - This material acts as good casing material since it has higher manganese contents

		making it more uniform and harder [4]
Shafts	Aluminum Alloy	- Offers a wide variety of beneficial material properties, including "tensile strength, density, ductility, formability, workability, weldability, and corrosion resistance" [10]
Supports (Bearings)	Chromium Steel [3]	Must be very strong, durable, aid in friction, wear The addition of chromium content in steel (i.e., stainless steel) helps with these properties.

4.7 Basic Calculation - Reasoning for Dimensions

Base: 200 x 400 x 450 mm (chosen from researching entry level designs, small-moderate workspaces)

These set of dimensions are slightly larger (in terms of material layout area, as our layout area is relatively large compared to the base) than this industrialized machine [1] to compensate for the "moderate" sized upper boundary of workspace. Although the dimensions do not exactly resemble a square surface area or cubic volume, they are similar enough as to allow for more symmetry in the cut. Due to the placement of other components, a rectangular surface was more feasible.

Milling Cutter: Works approximately within the volume of the dimensions (length,width) of the base with an approximate height of 0-100mm (with 0 mm at the surface of the platform) above in the z-direction, (relative to the base/platform) depending on the time of operation. The height above the platform is not critical in exactness, but provides a good reference/range to where the milling cutter is at any given point.

Lead Screw calculations: Equations from [2]

$L = \frac{1}{360} * \theta * p$ $\qquad\qquad$ $V = \omega * p * 1\ minute/\ 60\ seconds$

L = *Length of screw travel* $\qquad$ V = *linear velocity of travel*

θ = *angle of rotation* $\qquad$ ω = *angular velocity*

p = *pitch* (*mm per revolution*) $\qquad$ $[m/s] = [rad/minute * m/rad * 1\ minute\ /\ 60\ seconds]$

$[mm] = [rad * mm/rad] = [mm]$

4.8 Evaluation with Engineering Specification

As we mentioned above, our final design is to choose the PCB milling machine which has a stationary platform with a moving milling cutter(x-y-z). The main benefits of this type of PCB milling machine are that we are able to efficiently make the printed circuit board due to a triple-directional motion of the milling cutter with a fixed platform and relatively high speed of milling tools, as well as producing highly accurate signal traces on the board because of the low tolerance level of the milling system.

As for the milling system of our entry-level PCB milling machine, the speed of the milling spindle has maximum 30000 revolutions per minute. Also, the drilling speed is 100 holes per minute which can ensure a high efficiency of producing signal traces in upward-and-downward direction. We believe that this is the most essential factor for the function of a PCB milling machine.

For the accuracy and resolution of our design, two main types of measurements to determine the repeatability and mechanical resolution are involved. The acceptable tolerances of repeatability and mechanical resolution are $\pm 5\ \mu m$ and $\pm 0.8\ \mu m$ respectively. Beyond that, the high accuracy in the fitting hold system also can improve our quality of finished circuit board because the position of every tiny part can affect the final precision of moving parts.

Since the PCB milling machine is targeted at making printed circuit board, the space for holding the original circuit board is very significant. Therefore, we design to allow for about 350000 cubic millimeter for holding the original material. We believe that this volume of circuit board is enough based on our research and engineering specification justification.

Overall, we contemplated lots of aspects to ensure our final design meets our engineering specification.

5.Price of Components

Component	Materials	Cost Justification
Lead Screw	Stainless Steel	The price for a 32 mm shaft diameter lead screw seems to be dozens of dollars [2], and the design requires 4-6, so a range of $50-80 seems adequate [3]
Base	A36 Steel Structural Steel Tubing	A 1 foot by 1 foot (300 mm by 300mm) plate at a thickness of 3 inches (75mm) is a little over $200. If we extrapolate this data to the size of our plate (not with the recommended thickness as a lot of it will be either hollow or empty space) we are approximating around $300. (Slight increase in thickness/width/length)[4]
Milling Cutter	Coated in polycrystalline diamond or titanium aluminum nitride	Tungsten Carbide milling cutter from company proxxon sells for approximately $20-$30 [5][6]
Spindle	Titanium Stainless Steel	Typical spindles seem to vary from $50-$500. Granted that we are using an entry level design, it is more likely that the spindle will cost approximately $200. [7]
Tool Holder	Hot Rolled C1018	CNC Tool Holders appear to range anywhere from $10-$100. Using the same logic as for the spindle, we are approximately looking at a tool holder costing $40.

		[8]
Shafts	Aluminum Alloy	One foot sized aluminum alloys at one inch diameters are approximately $8. There are multiple shafts in the design, so approximating for 4-8 shafts of the same size it will approximately be $32-$64 [9]
Supports (Bearings)	Chromium Steel	Standard ball bearings are a few dollars each [10]. Granted that angled roller bearings are more complex, they should cost more, and in combination with a higher quality material we can approximate each angled roller bearing to be around $10. Depending on how many we need, say any amount from 8-16, we can approximate about $80-$160[10]
Motor	-	According to [1], small motors seem to be in the hundreds range. Thus, we need 4 small motors, so approximately we are looking at 4x$150 = $600 in motor parts

Total:
Our total sums up to less than $3000. Thus, we can either increase the material quality on certain components or use the extra money to add more components (like bearings).

6.Conclusion

Through research, collaboration, and understanding of fundamental principles, the design team was able to expand a simple engineering specifications writeup into an implementable and practical design for an entry level PCB milling machine. Although there are no perfect methods to solving this design problem, we believe that throughout the project we were able to produce a coherant explanation to our personal methodology. This includes the overall structure of the milling machine, the materials selected, and cost versus function analysis, amongst many other critical aspects into designing a milling machine. It is common that designers will input a bias into what they deem best suitable for any given application, simply because it is natural to have a voiced opinion about something. There was an emphasis that the design team remained as objective as possible, figuring out what choice was best in the overall function of the milling machine, rather than relying on intuition or personal experiences. The design team strongly believes that the final design is fully suitable for the next step, and hopes that the reader shares the same beliefs.

7. 2-D Engineering Drawing

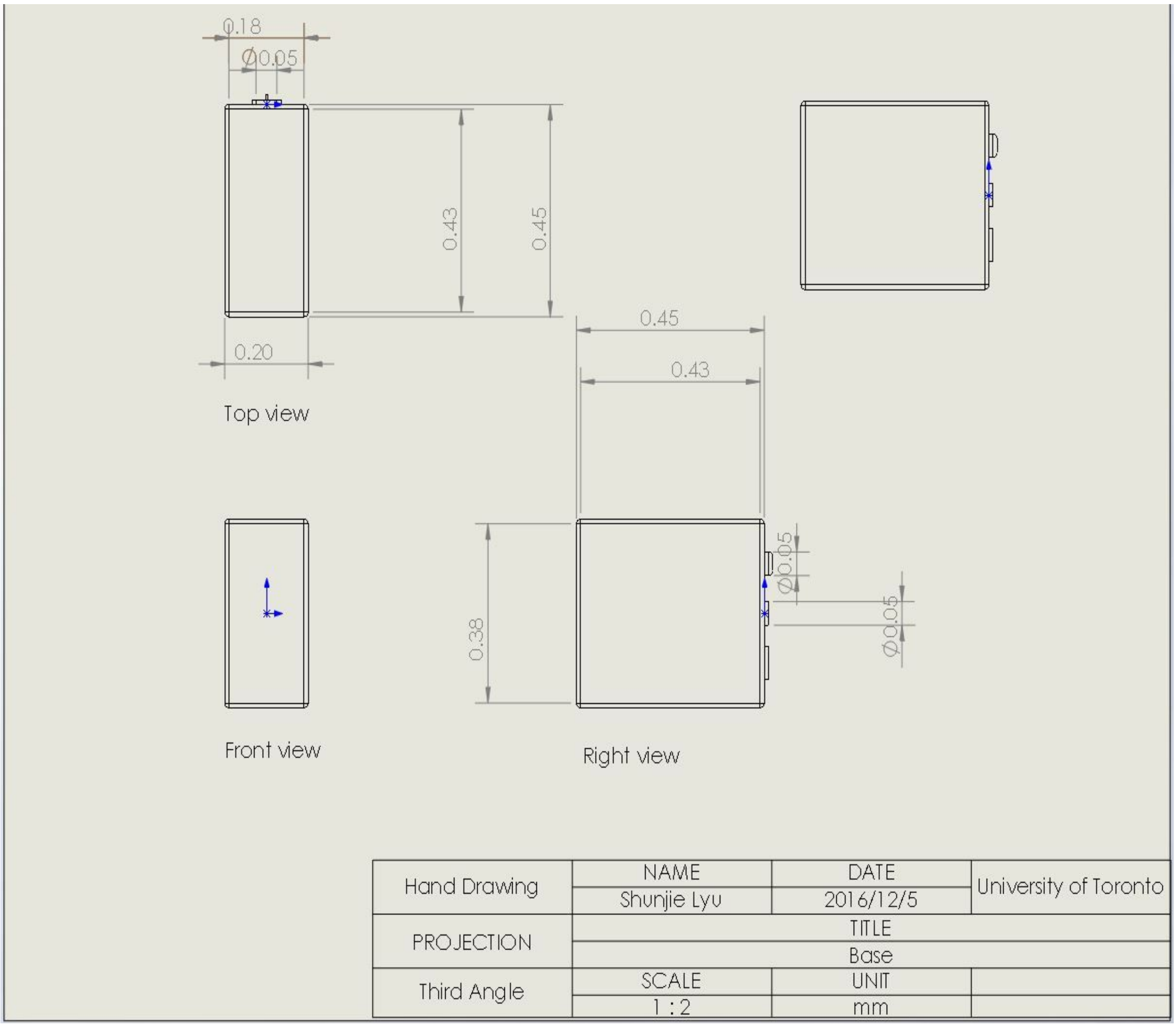


Figure 1. Base

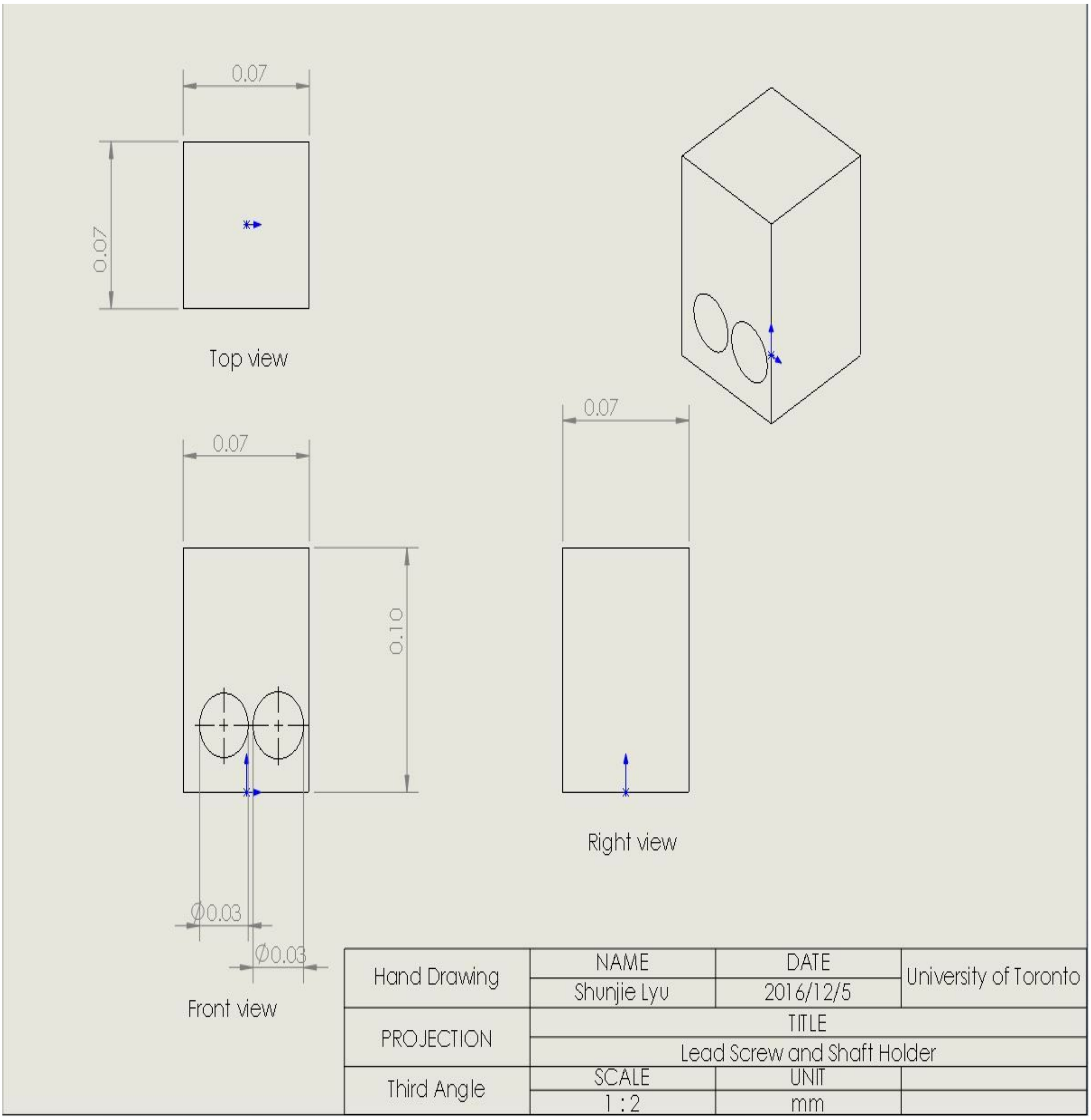


Figure 2. Lead Screw and Shaft Holder

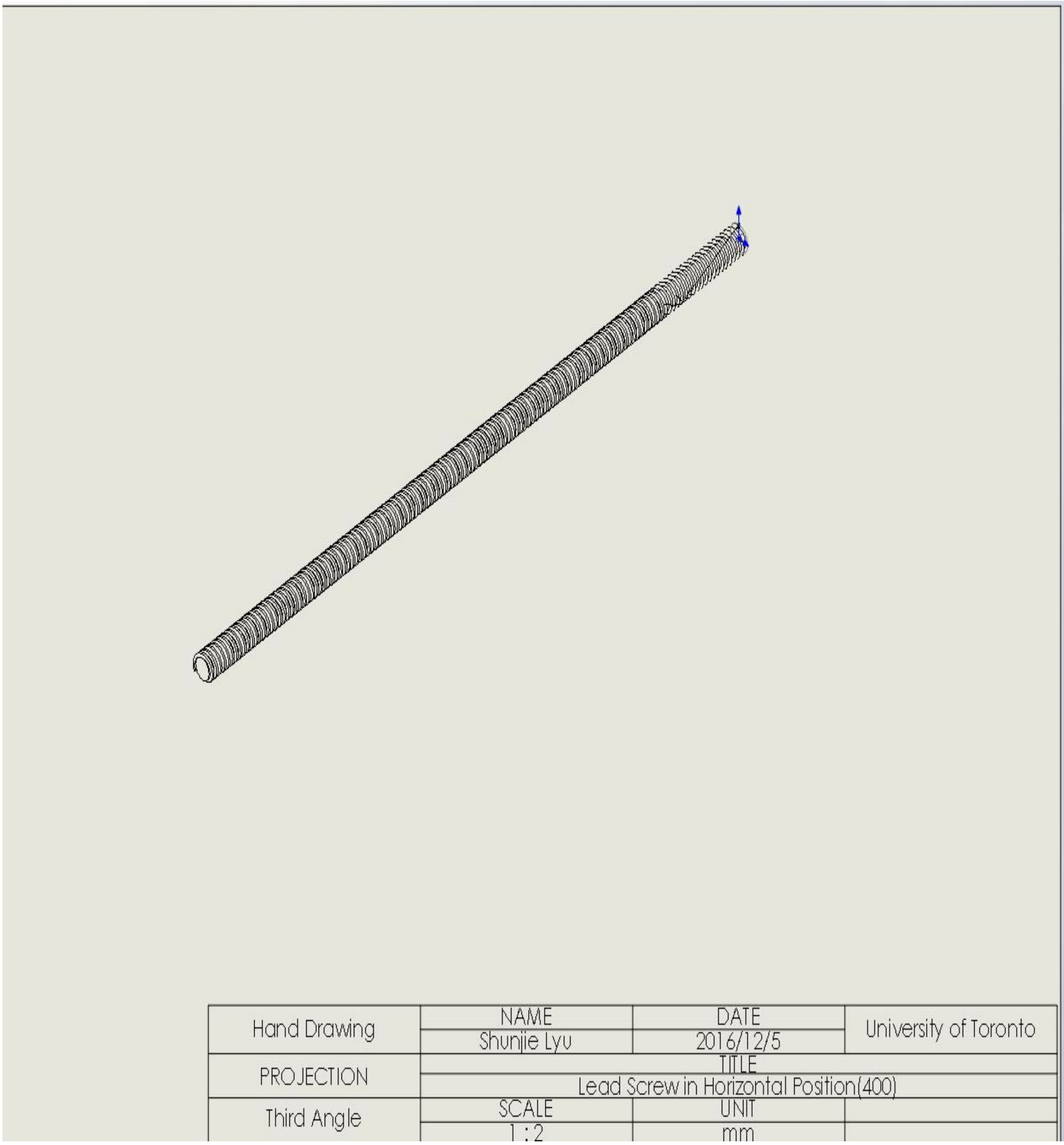


Figure 3. Lead Screw in Horizontal positon(400)

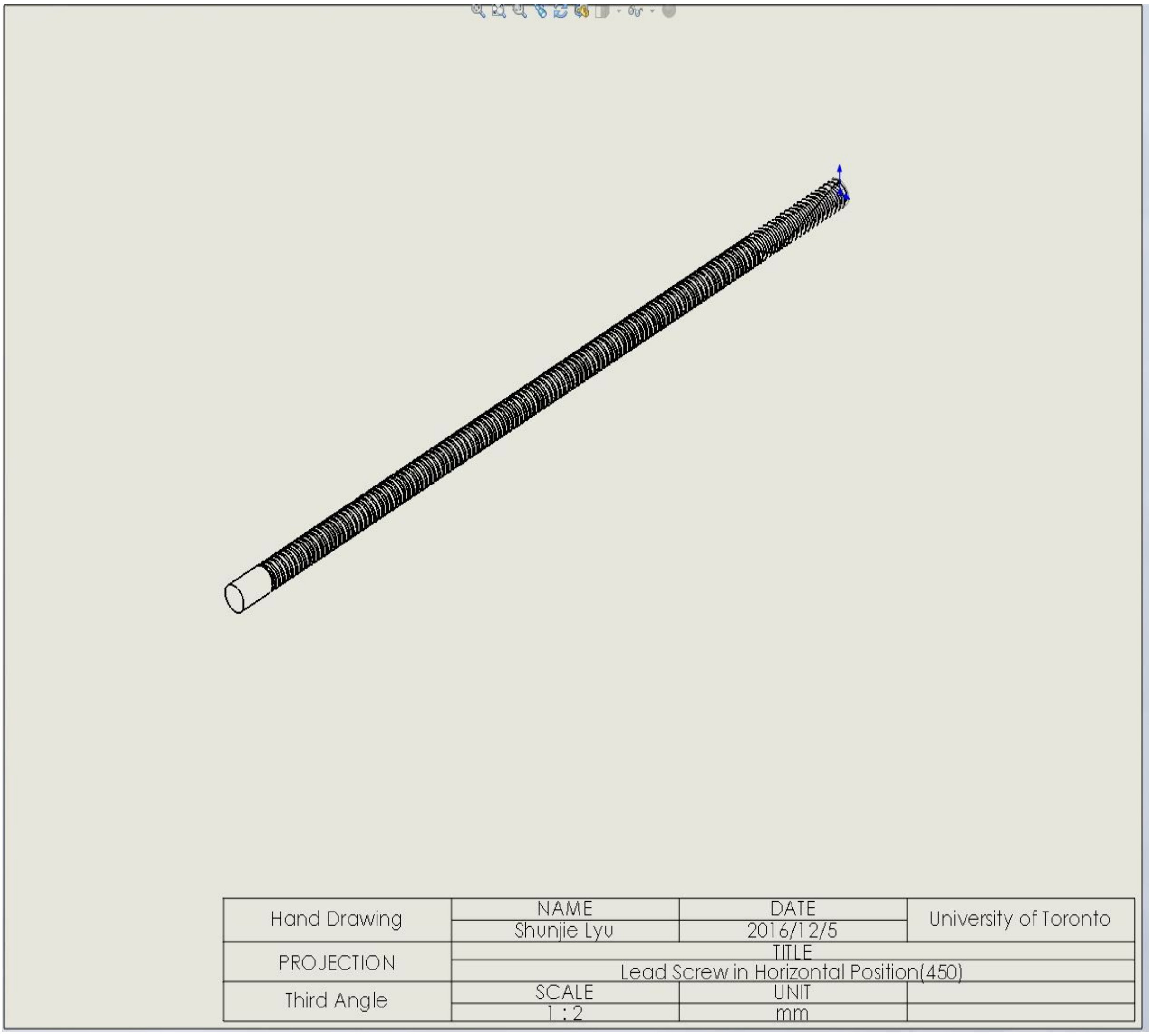


Figure 4. Lead Screw in Horizontal Positon(450)

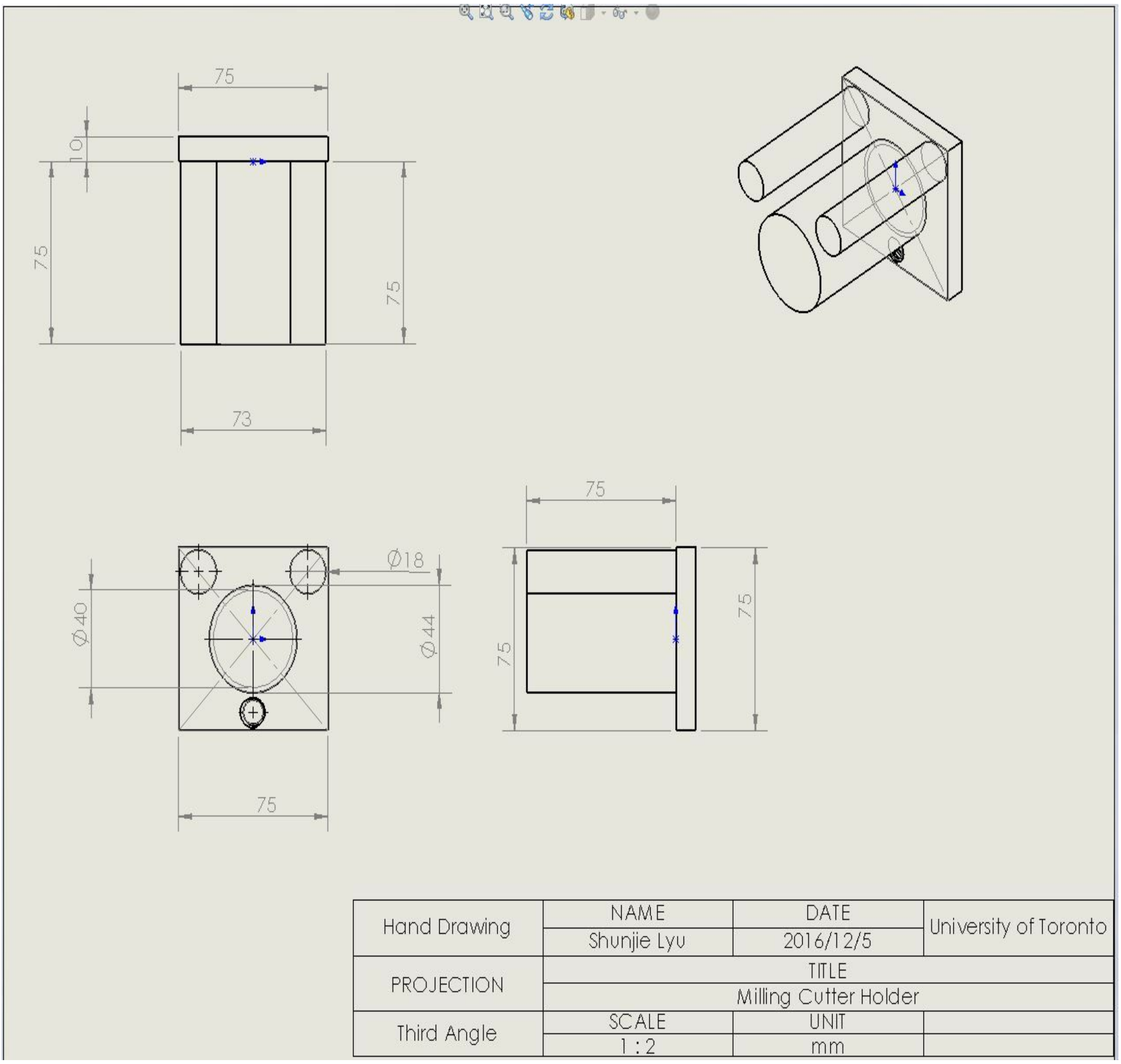


Figure 5. Milling Cuter Holder(Spindle)

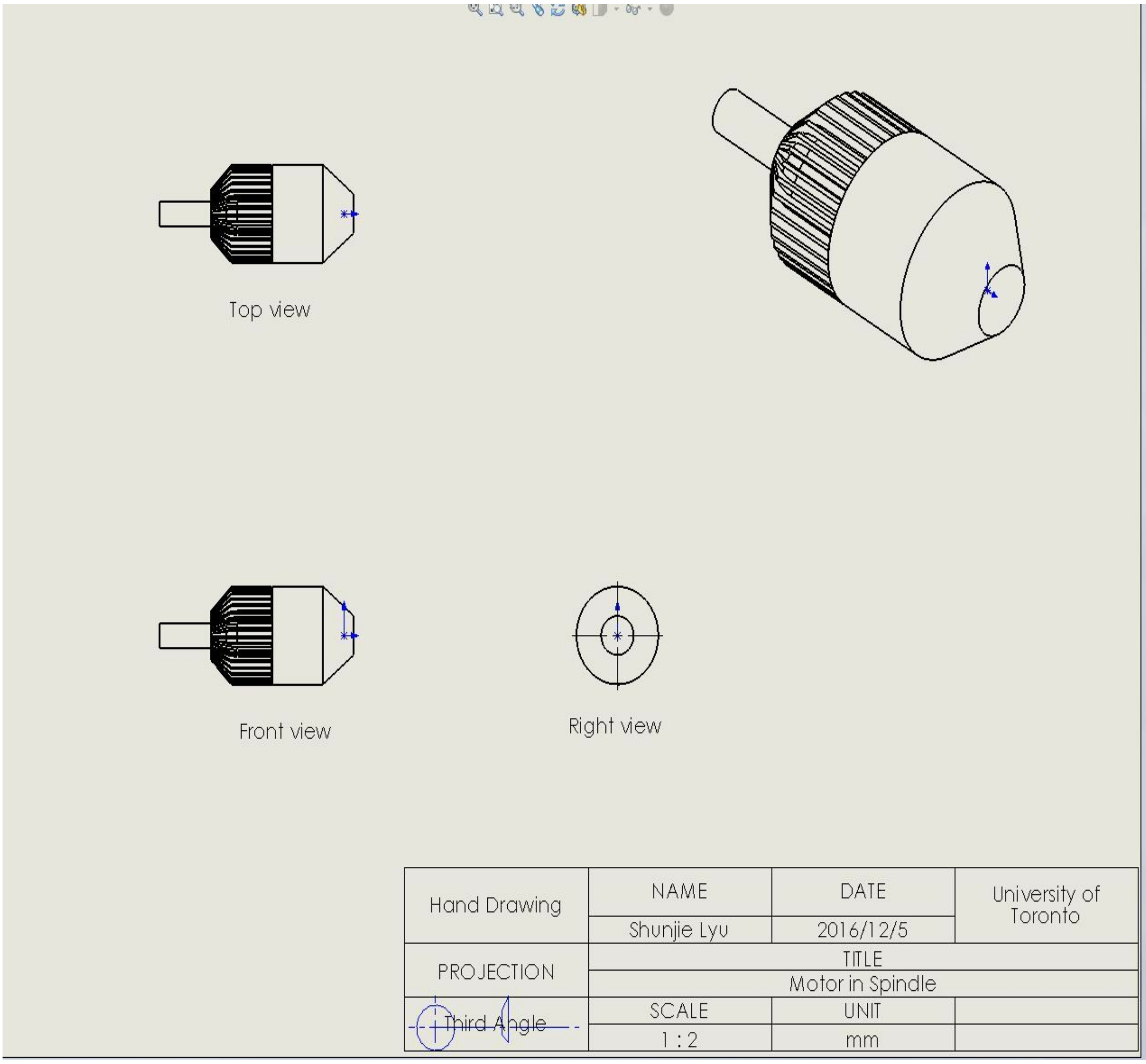


Figure 6. Motor In Spindle(rotation-drived motor for Milling cutter)

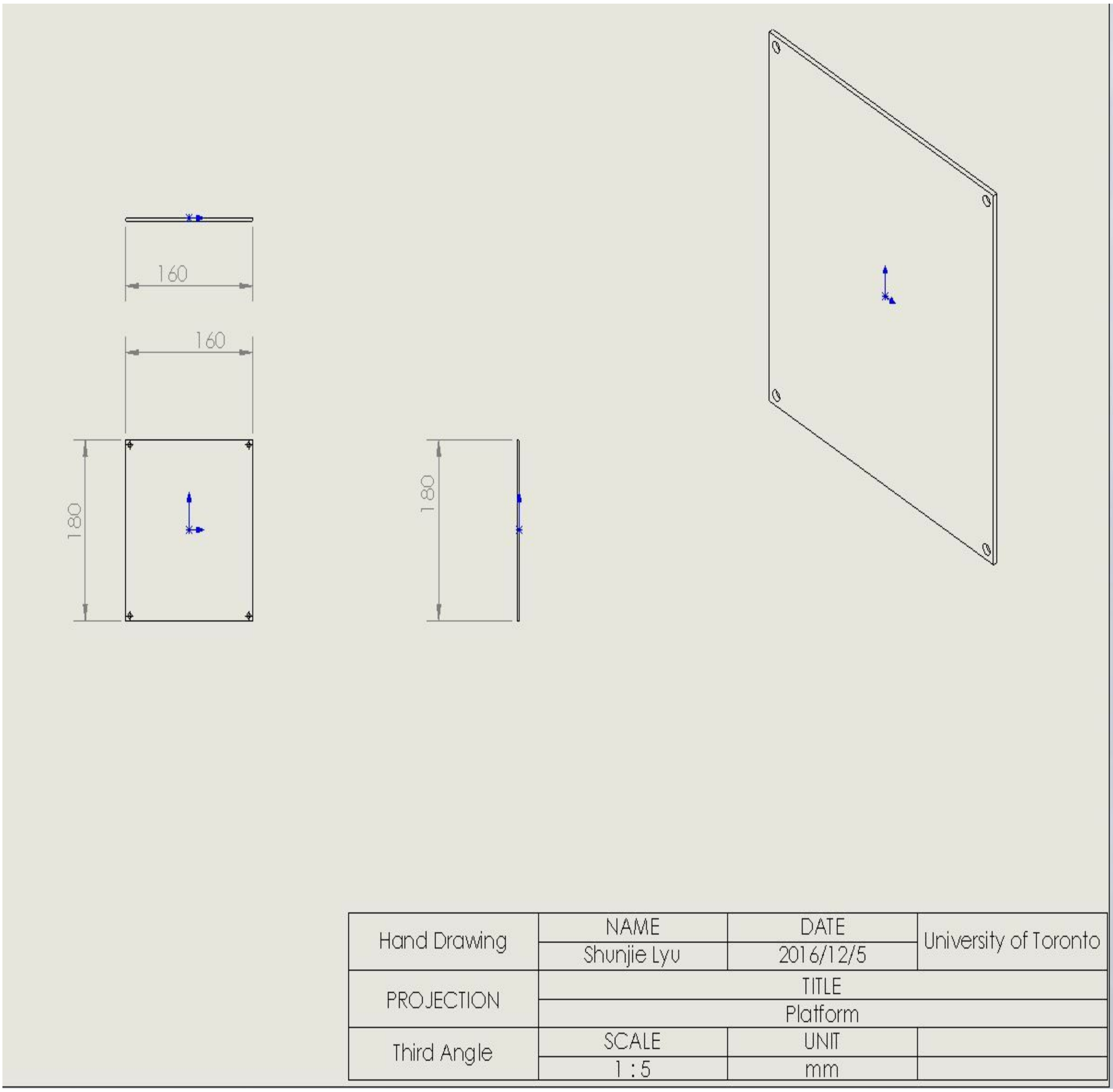


Figure 7. Platform

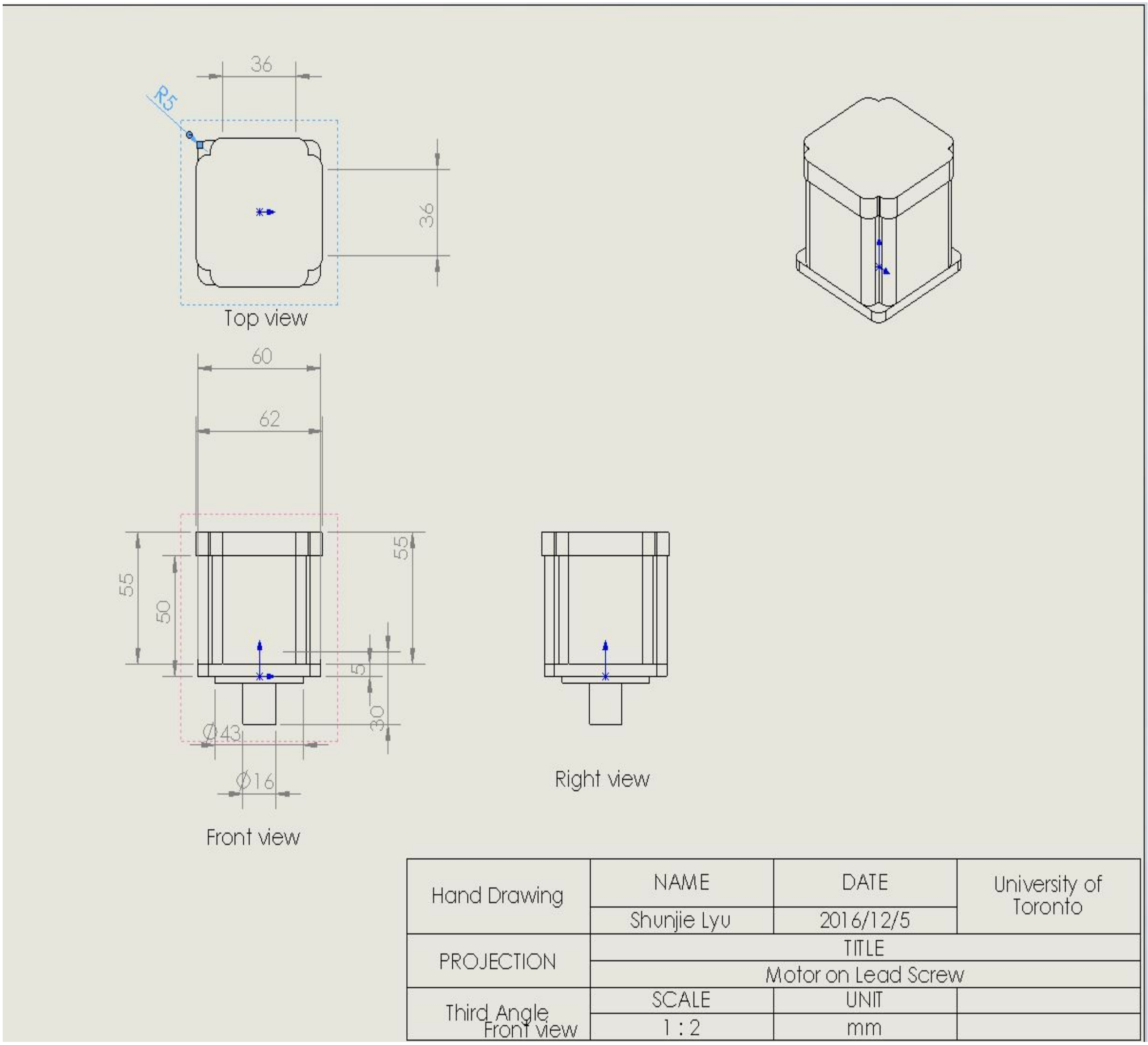


Figure 8. Rotation-drived Motor

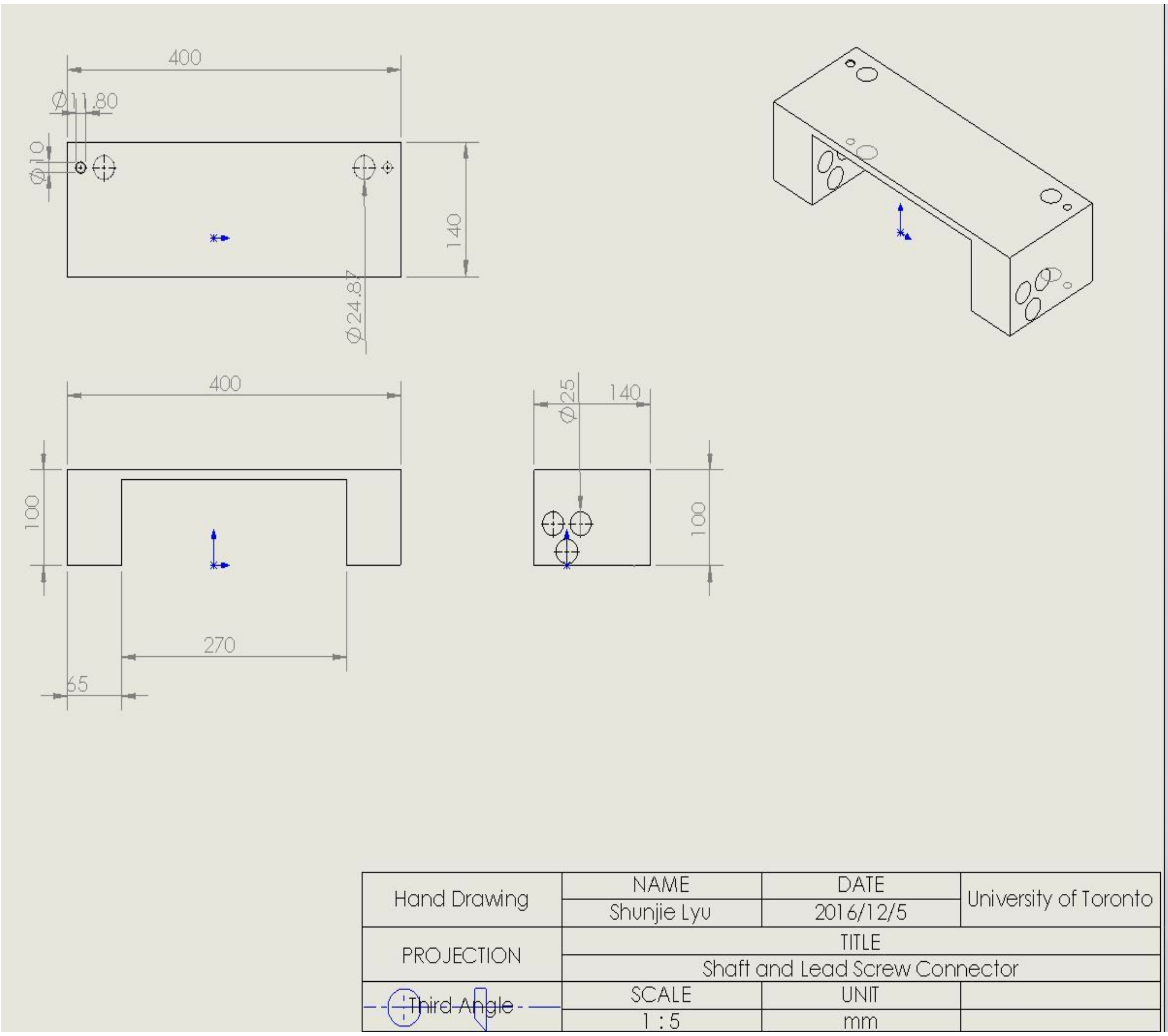


Figure 9. Shaft and Lead Screw Connector

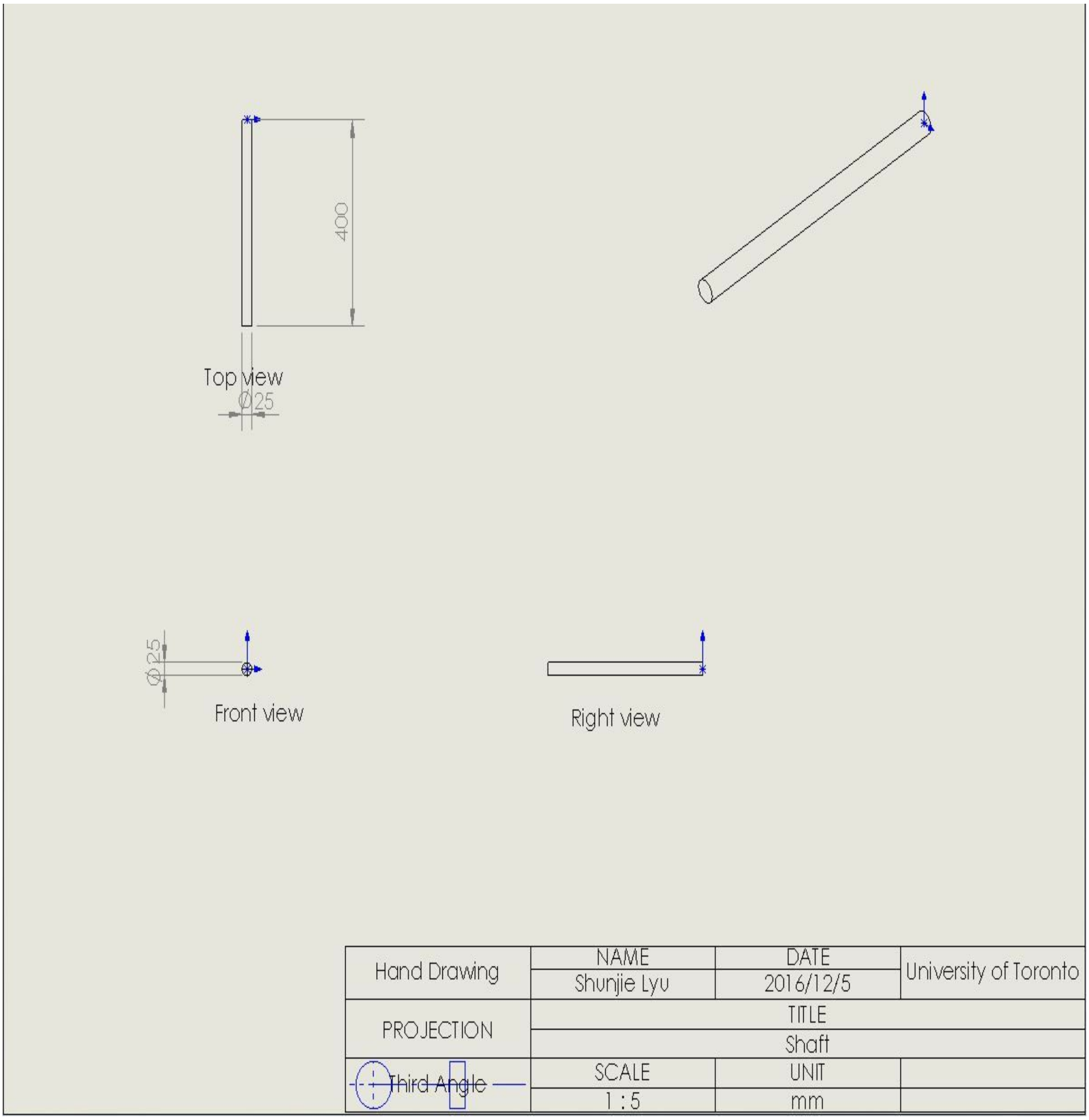


Figure 10. Shaft

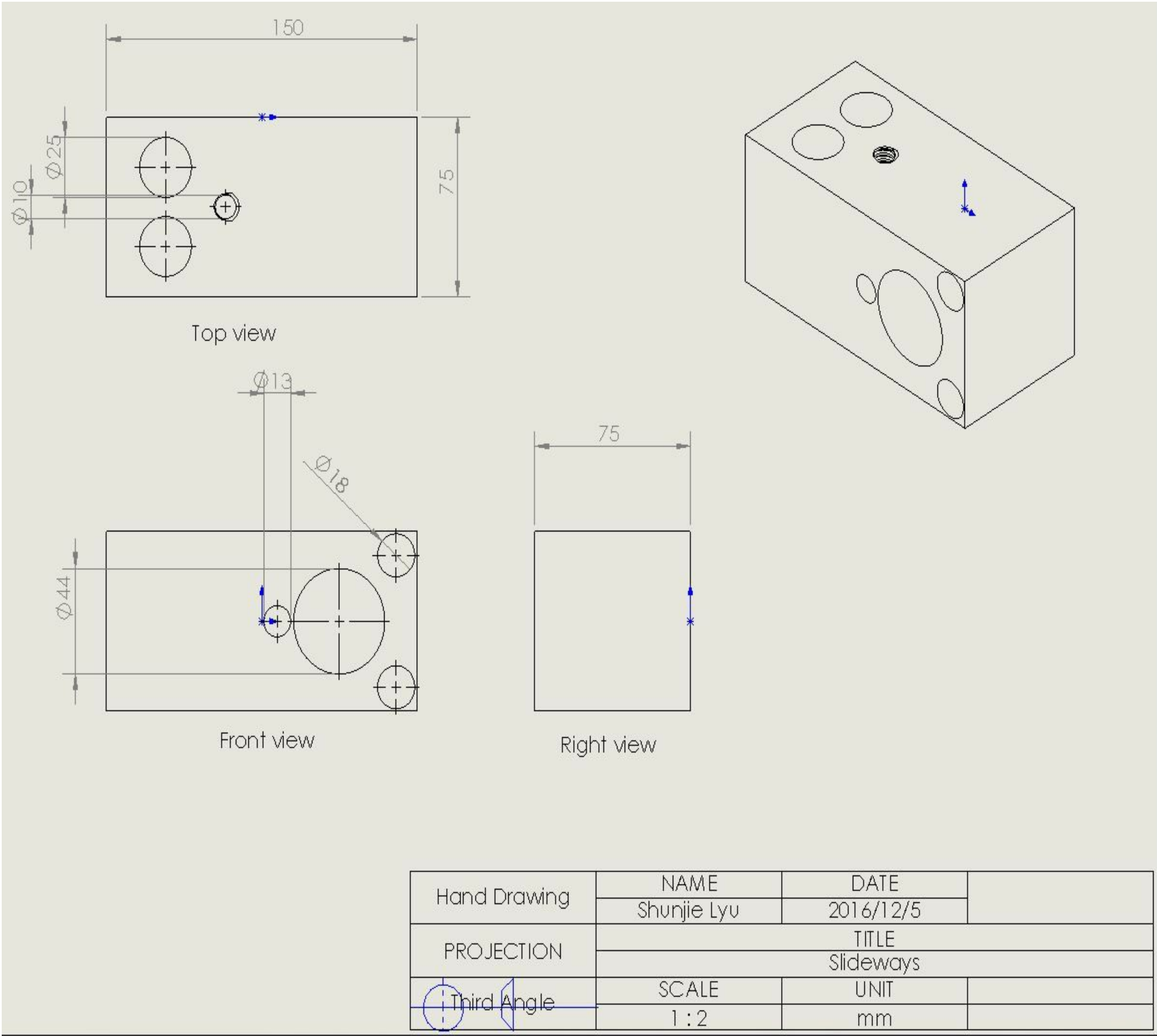


Figure 11. Slideways

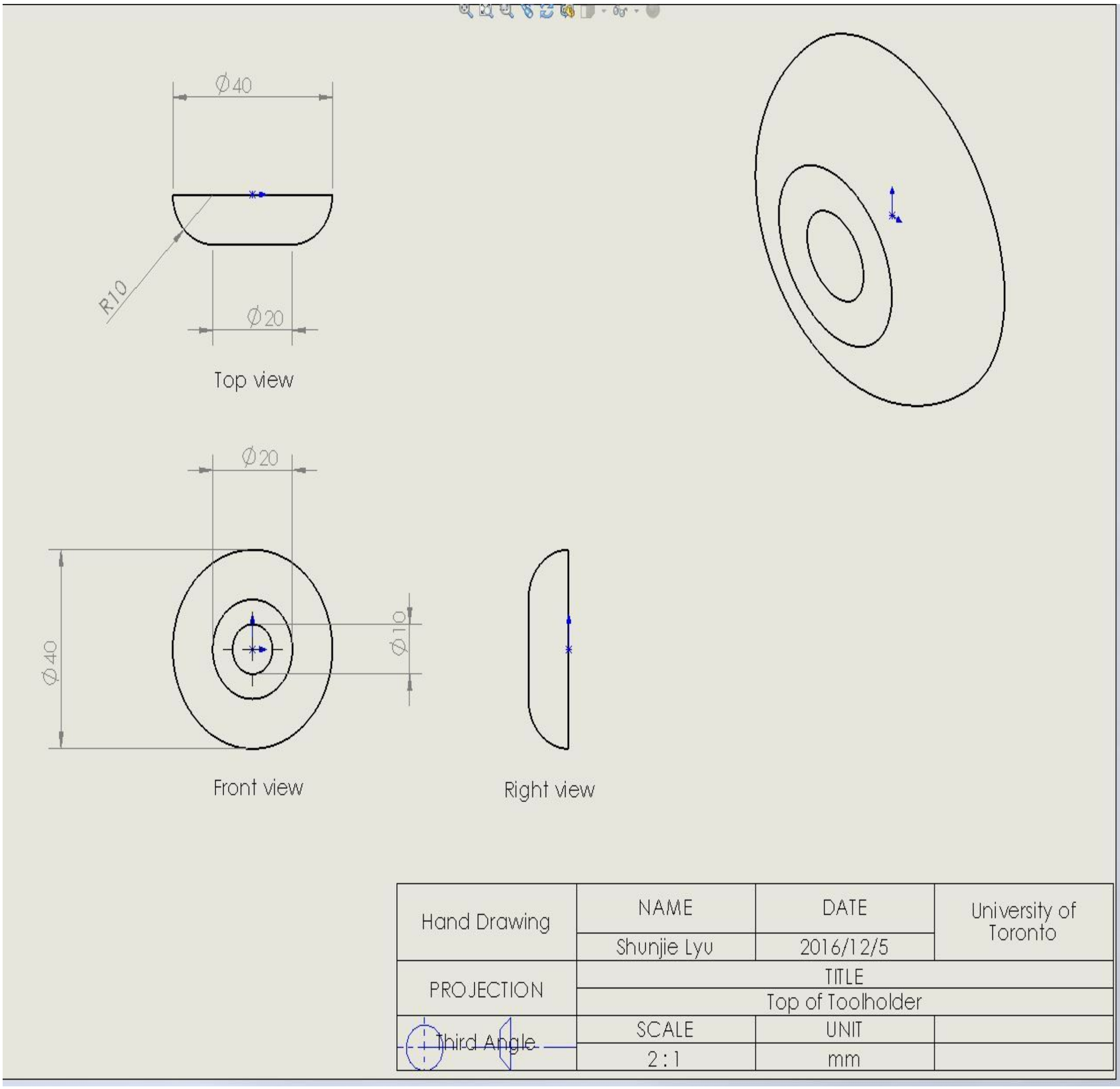


Figure 12. Top of Toolholder

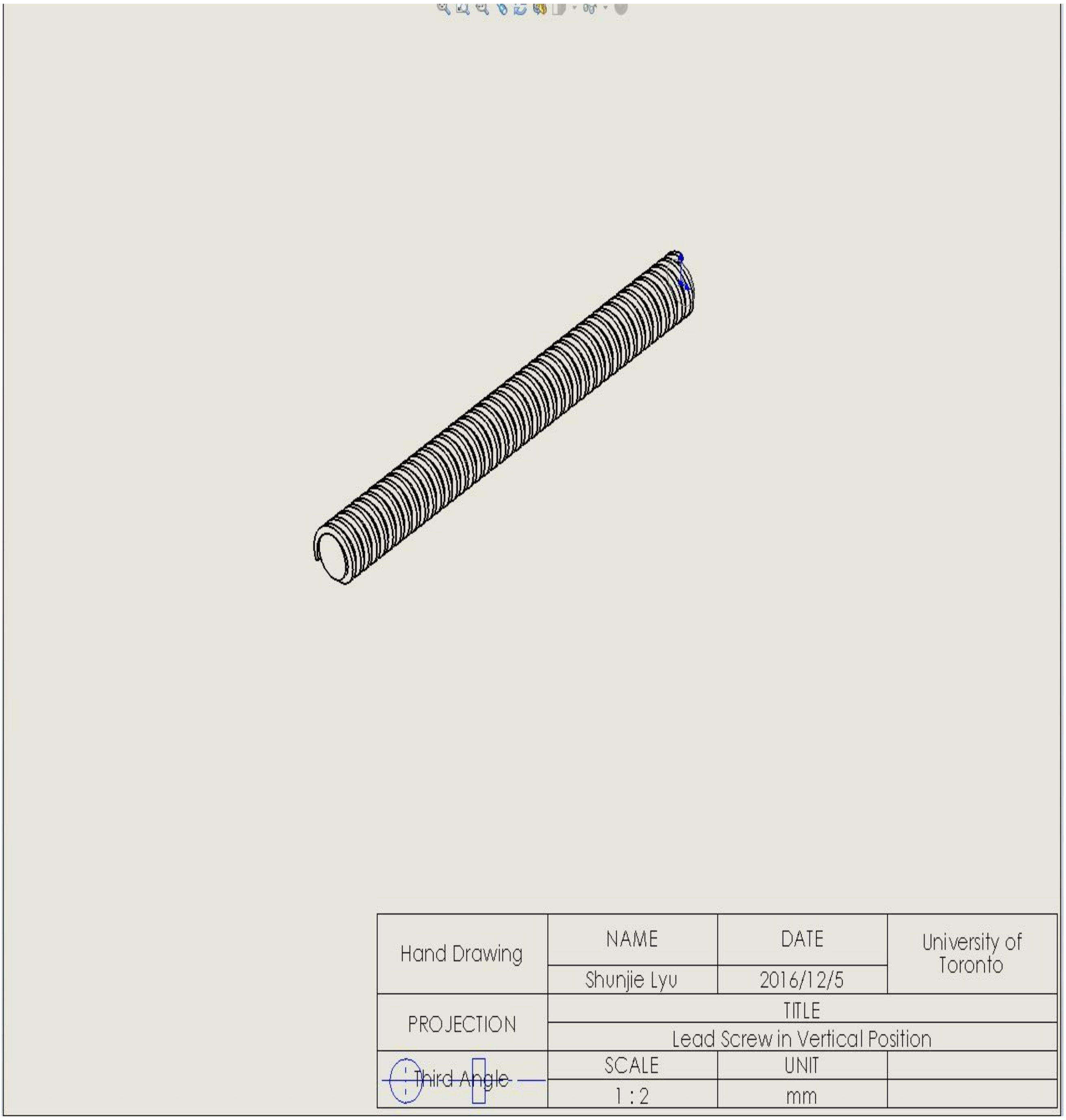


Figure 13. Lead Screw in Vertical Position

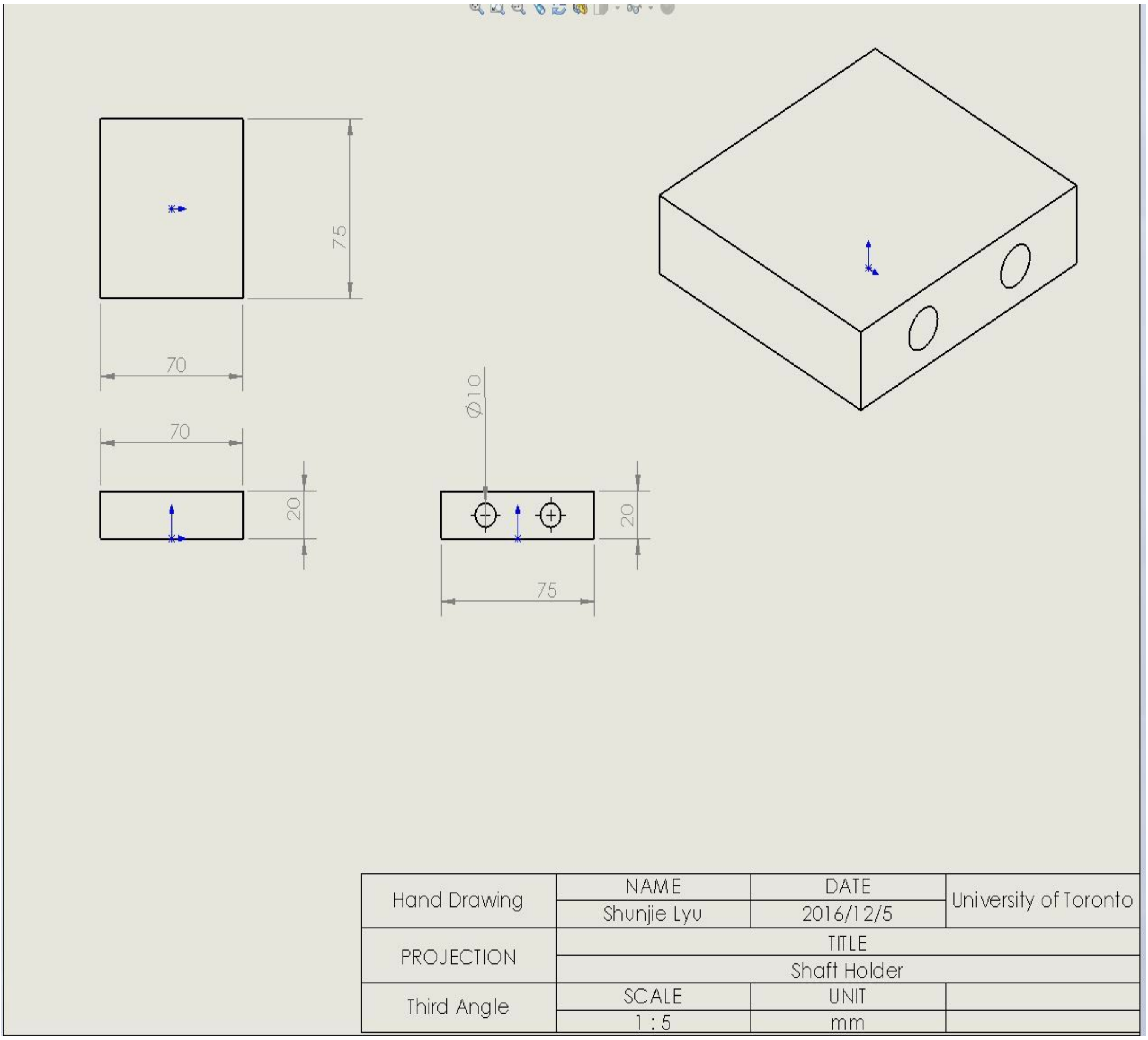


Figure 14. Shaft Holder

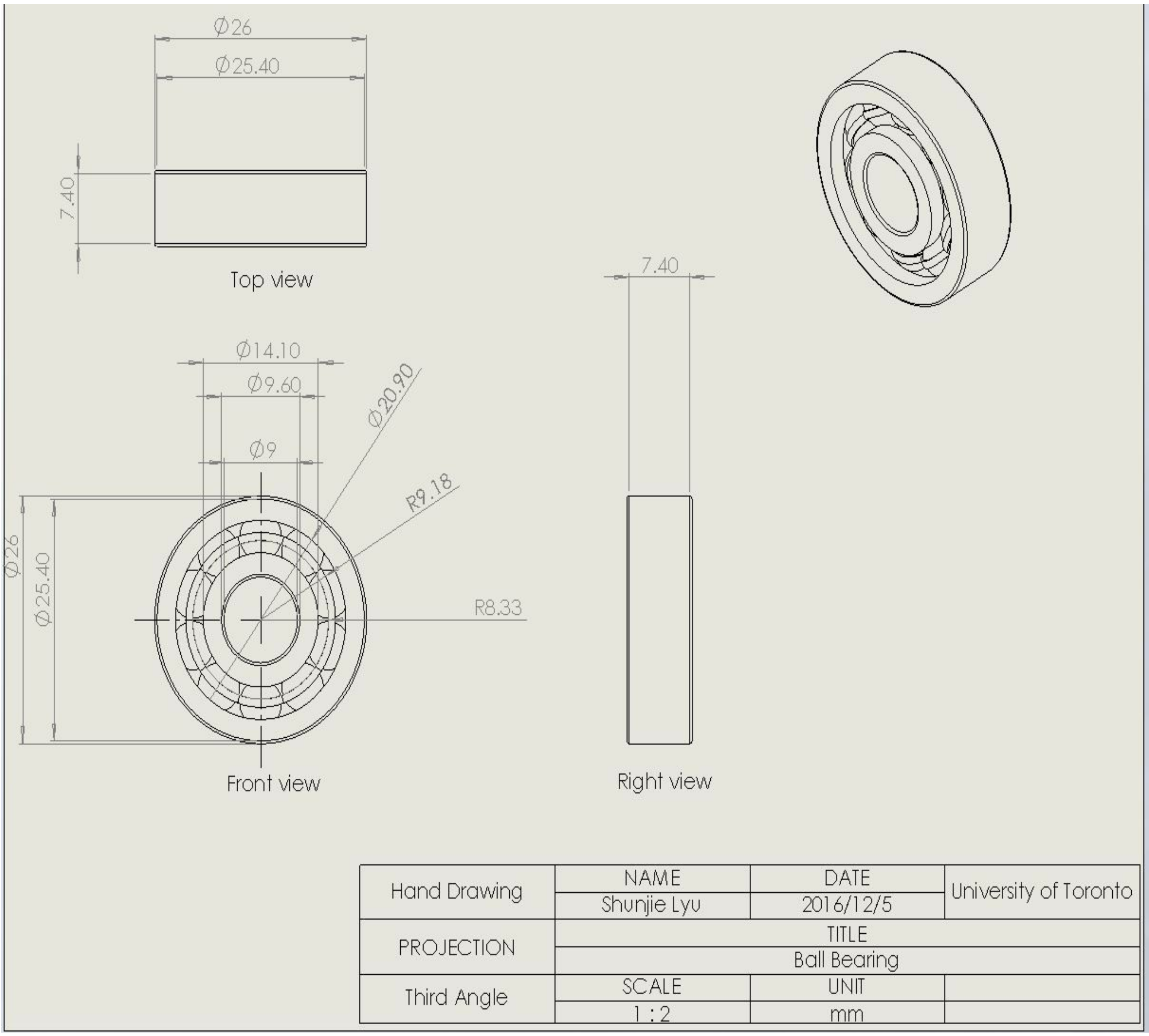


Figure 15. Ball Bearing

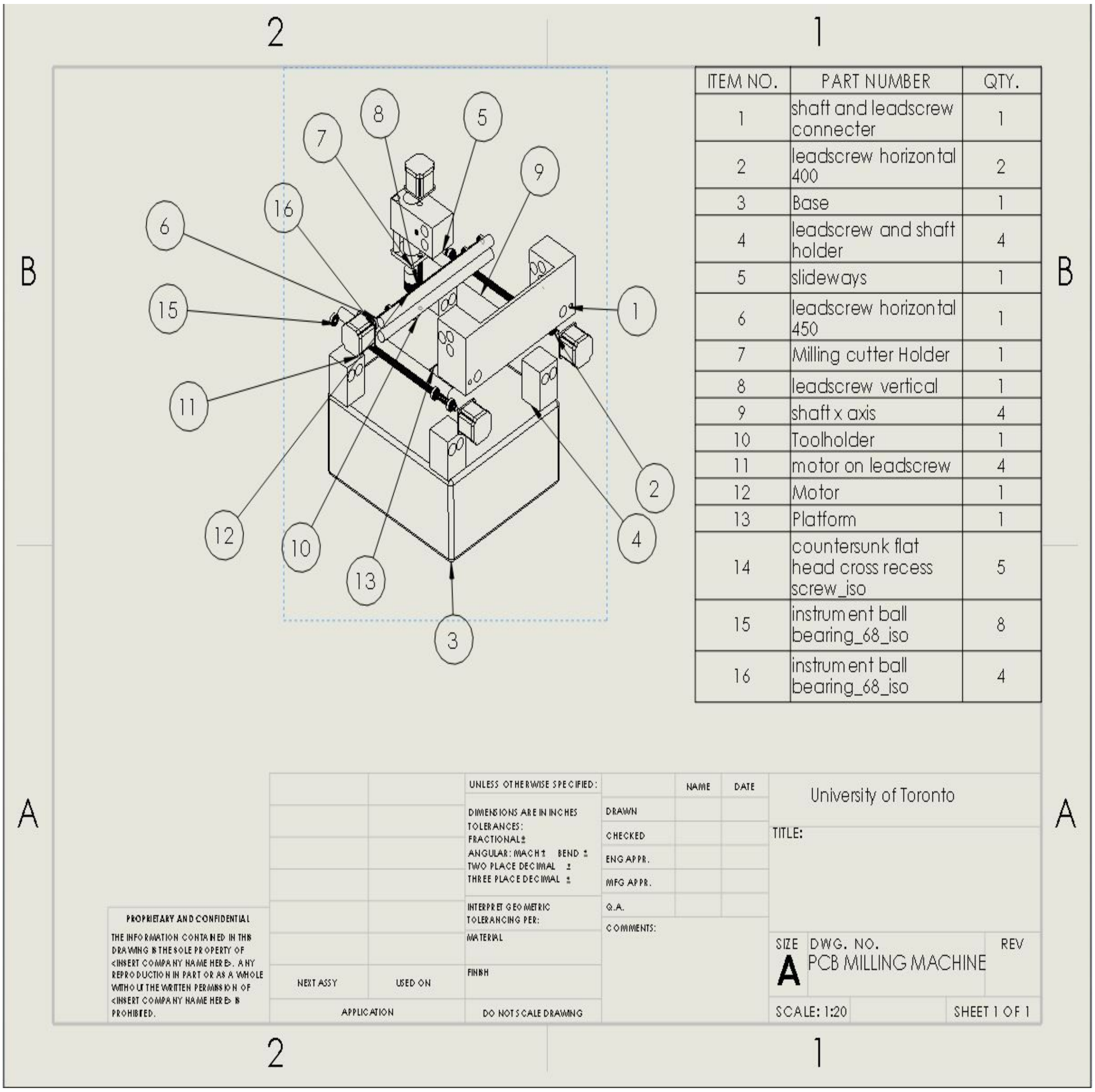


Figure 16. Exploded View Diagram

8. Final 3-D Drawing

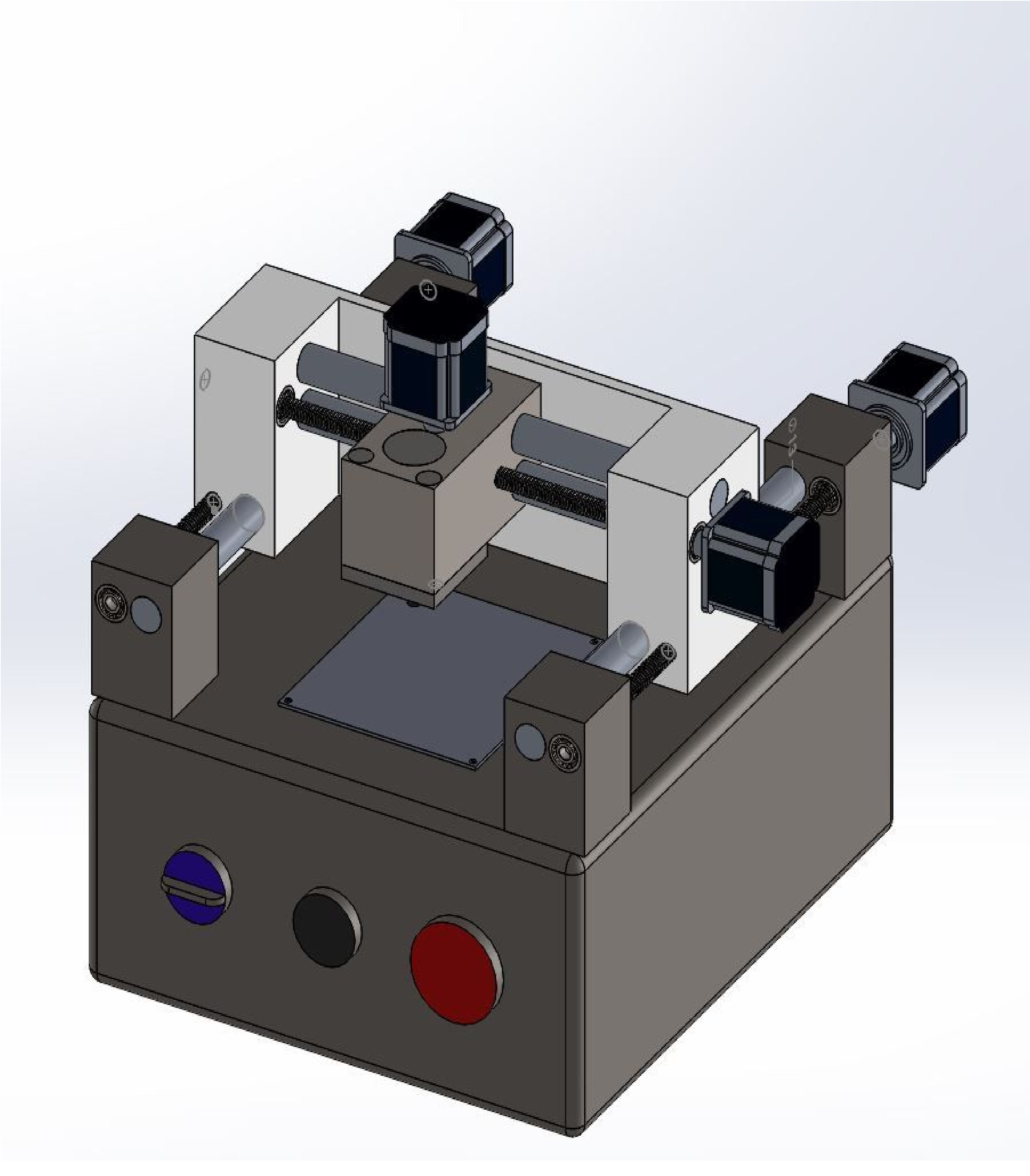


Figure 1. Assembly Drawing

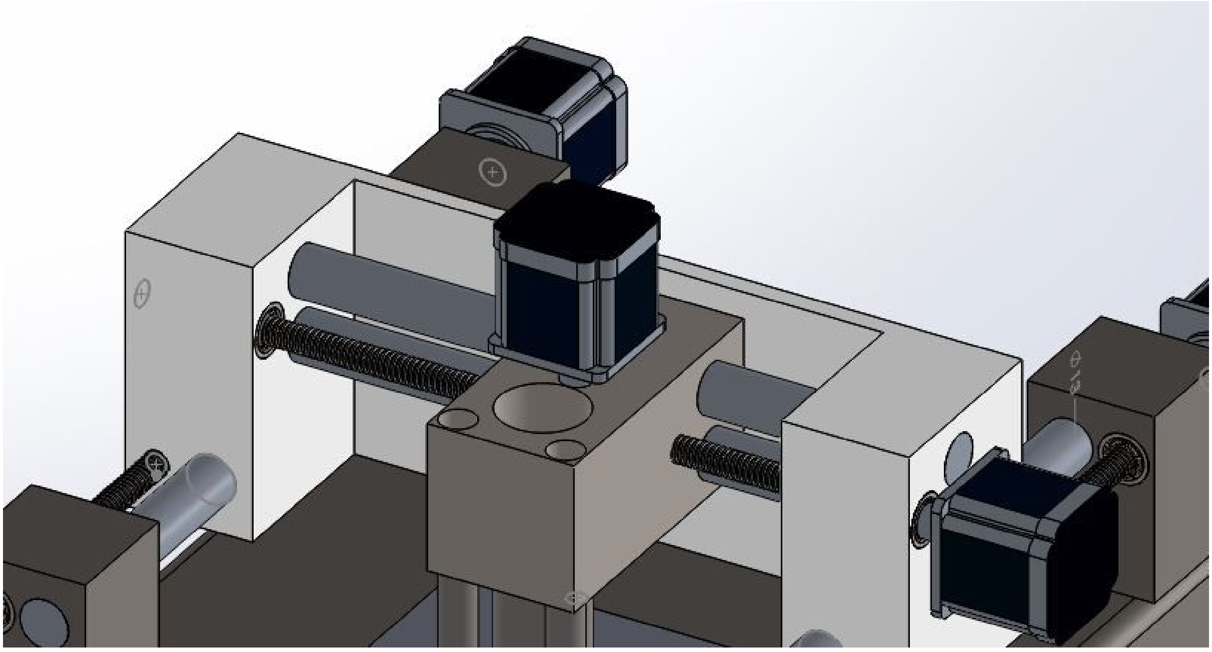


Figure 2. Left-and-right motion mechanism(X direction)

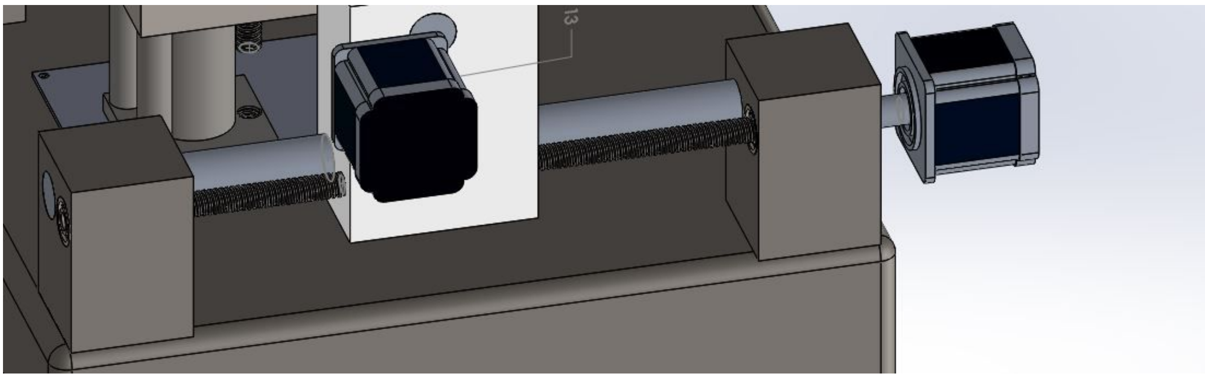


Figure 3. Forward-and-backwar motion mechanism(Y direction)

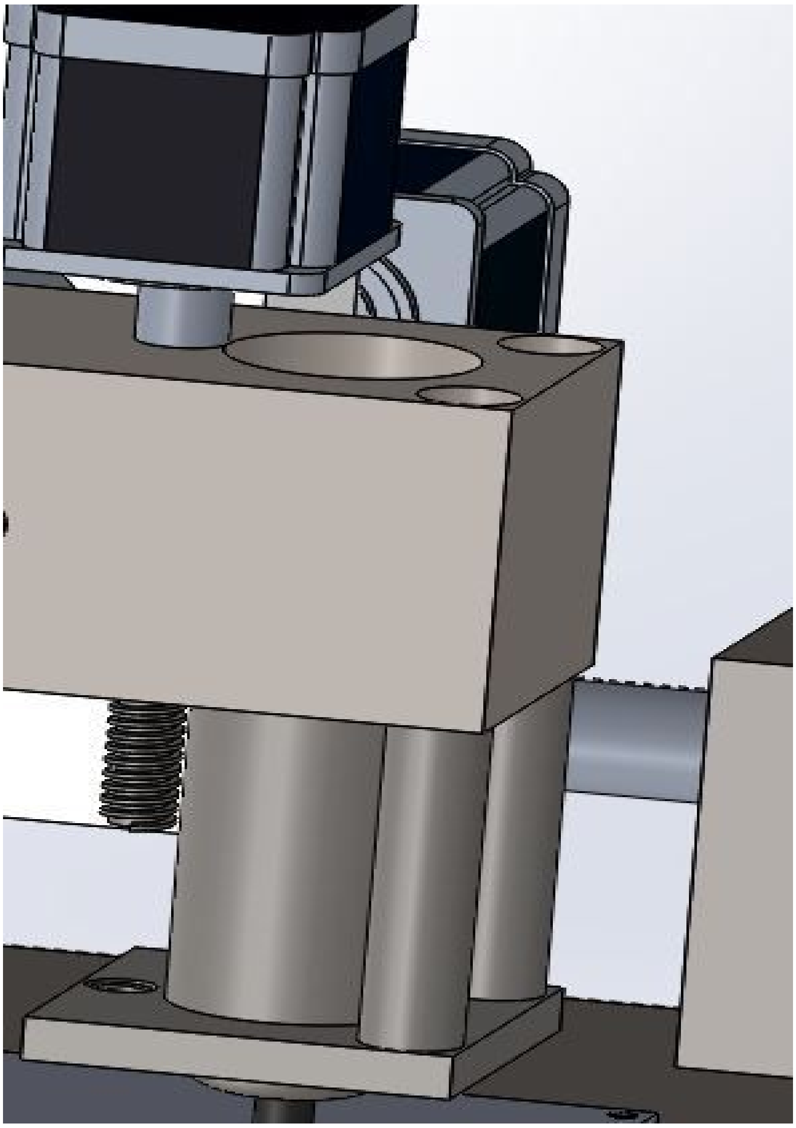


Figure 4. Downward-and-upward motion mechanism(Z direction)

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2.3 Constraints:

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