MIE 243 Group Design Project
Project - 3D Printer
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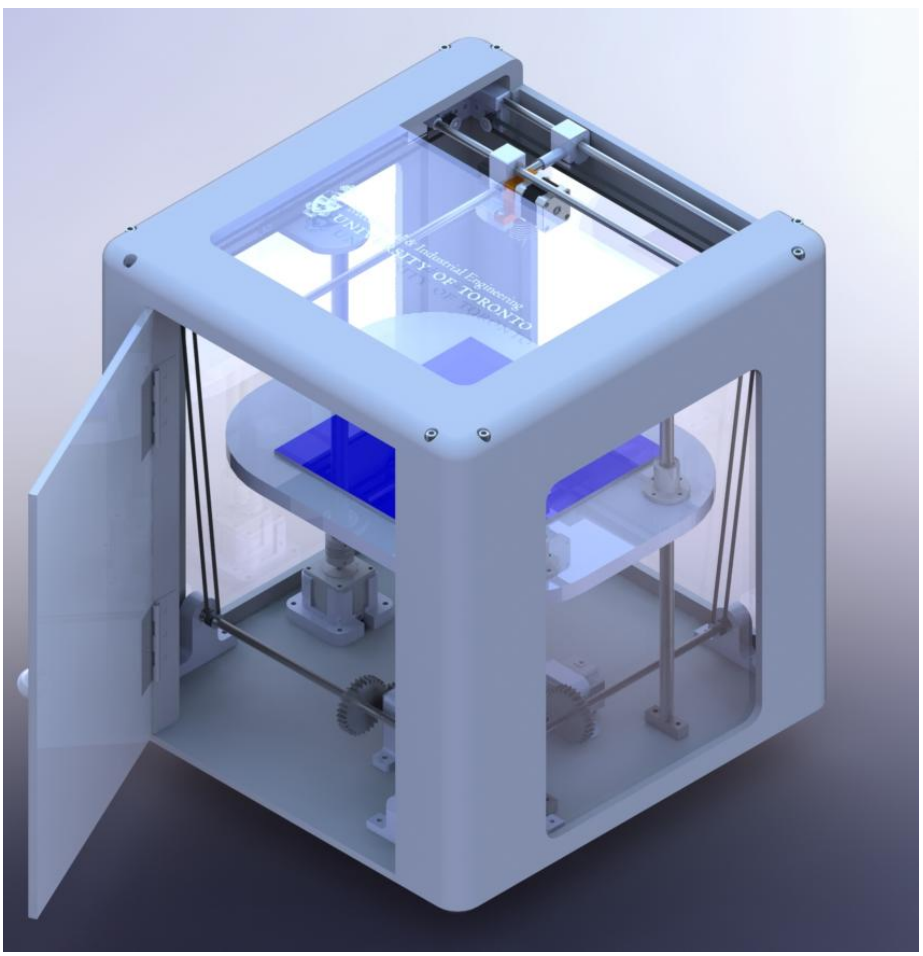

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1. Introduction and Research

1.1 Introduction

3D printing, also known as additive manufacturing, in contrast with reductive manufacturing, refers to a process that generates 3 dimensional objects by successively building upon layers of print material[1]. These layers can be viewed as many thin cross sections of an object, when layered together then they form the entirety. The technology of 3D printing was earliest developed during the 1980s[2]. However, due to limited technological ability and rather narrow applications,early 3D printers focused on the Rapid Prototyping - generating rough visualization and proof of concept models. Advances since then have greatly increases the print speed and accuracy of these printers. And with the development of computer aided design (CAD) software, bringing streamlined processes for converting 3D models to print instructions, 3D printing became much more accessible and received wider end-use applications [3]. Recent times have seen the emergence of 3D printing hobbyists and widespread adoption of the method in professional industries not only for prototyping, but also manufacturing of market ready parts. Today, 3D printing is used to manufacture parts in aerospace, medical implants and other complex components which can now be produced quickly and inexpensively using 3D printing compared traditional machining methods.

Understanding the basics of how 3D printer prints is not complex. All printers are simply the combination of a 3D positioning system with a printer technology capable of printing in the material desired. The characteristics of a printer is directly determined by the characteristics of the mechanisms within.

The objective of the project is to develop a well argued conceptual design for an entry level professional 3D printer, to be used in print farms which may consists 30 or more printers, operated by a minimum (one or two) of human operators. The major application of the design will be rapid prototyping for businesses, allowing them to quickly produce potentially market ready parts which can be applicable to their projects. The report will first begin by contextualizing the current market of all printers from hobbyist to professional. Trends in the market of printer parameters such as accuracy, speed, and cost are outlined, which leads into our 3D printer design.

1.2 Research

1.2.1 Classification of 3D printer

This section is aimed to explain the features in which current printers are categorized by.

(1) Based on Degrees of Freedom (DOF)

The most common way to distinguish one printer from the other is through the degrees of freedom the machine is able to achieve. For example, a 3 DOF system may be able to move a block linearly in the coordinate axis With an increase in DOF, the system is able to move in more complex curves and with higher efficiency. Most 3D printers follow a 3 DOF design where movement is defined in direction by the unit vectors of the Cartesian coordinate system. Some printers have up to 6 DOF. These additional DOFs are generally map to additional movement (pivoting/rotating) of the printhead mechanism. These additional DOFs generally increase print efficiency for high-very high complexity geometries, but increase cost and do not give significant advantages in efficiency for non-complex geometries.

(2) Based on printing coordinate

There are three types of printing coordinates in the market currently, Cartesian, Polar , Delta, or some combination of the three[4].

1. Cartesian

The most common coordinate type is cartesian 3D printer. Printer divides the printing volume into X, Y, Z coordinate. Printing objects are then converted into 3D printing file and coordinates are sent to the printer which then move the extruder into the desired position and start extruding filament onto desired position. In Cartesian printer, the X,Y,Z printing directions are independent.

Advantages

1. Easy to produce software for (as X, Y, Z independant).
2. Flexibility it allow in designs in terms of how the motion is achieved. For example some printers may move the print base and keep printhead still, or the printhead moves about a resting base, or some combination of the two.

Disadvantage

1. May not be space efficient depending on how motion is achieved.
   Ex: If the print base moves in X & Y thus the product size must be significantly increase to accommodate this movement.

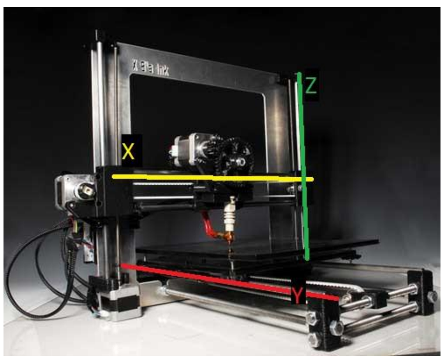


Figure 1 Cartesian Printer[5]

2. Delta

Delta printer usually consists of a circular print bed. The cumulative up and down motions components linked to the printhead allows complex curves as movements.

Advantage

1. Faster prints for complex geometries.

Disadvantages

1. Not vertically space efficient, linkages which move the printhead forces the inclusion of unusable print space.
2. Harder to develop software for (movements are more complex functions of control parameters) .

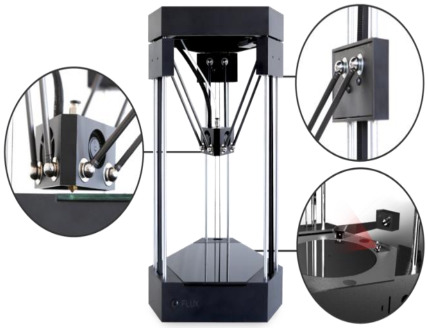


Figure 2 Delta Printer[6]

3. Polar[7]

In polar coordination system, the position of the printhead is fixed and only able to move up and down in the Z-axis. The rotation of one or more surfaces generate X & Y motion relative to the printhead. As this method is the least X & Y space efficient, little to no products use a polar only system.

Advantage
1. Faster prints for some simple curves.

Disadvantage
1. Not space efficient in XY plane if system uses only polar systems to achieve X & Y motion.

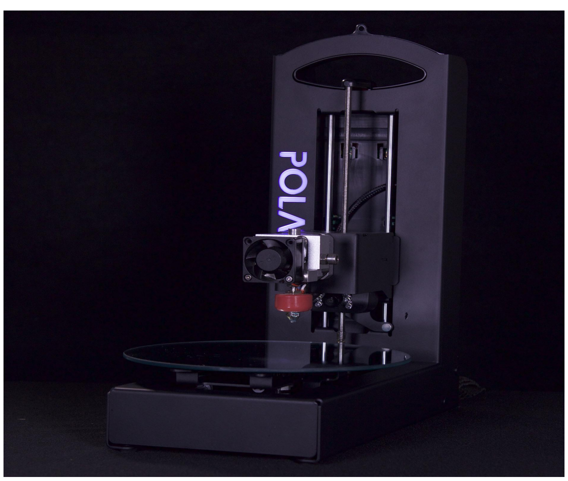


Figure 3 Polar Printer[8]

(3) Based on printing method/technology

There are 7 type of commonly used printing method available on the market. They mainly differ in material printing capabilities.

1. Material Jetting

The technology used in material jetting is called Polyjet. In which UV sensitive liquid polymer is jet onto the platform and then quickly solidified by being exposed under UV light. It is similar to a traditional inkjet printer except that the process is done repeatedly layer by layer to create a 3D object[9].

2. Binder Jetting

Powder based material is spread evenly onto the plate, the nozzle then sprays special liquid material to “glue” powder together in order to make a solid object, layer by layer.

3. Fused Deposition Modeling (FDM)

In FDM processes, plastic filament is heated and extruded through a nozzle onto a plate. A CAD model is being associated with the process which being sliced into layers. Once the process is complete, the object will cools down to solid state. Supporting material is needed in order to prevent sagging or part integrity[10].

4. Powder Bed Fusion

The powder bed fusion process involves either a laser or electron beam to melt and fuse the powder together. The electron beam will trace out the shape of the object that needs to be printed layer by layer, once a layer is complete, new powder will be replated onto the previous one by a metal bar, and the plate drops a little. The whole process repeats until the model is complete[11].

5. Sheet lamination

Sheet lamination processes are commonly refer to laminated object manufacturing (LOM). It apply a layer by layer approach to build the 3D object, which uses paper as the main source of raw material, and adds layer by layer adhesively instead of welding. It uses a cross hatching method to utilize efficient removal of post build object. Laminated models are best suited for aesthetic and visual purposes, not adequate for structural use.

6. Vat Photopolymerisation[12]

Vat Photopolymerisation uses liquid resin as the major raw material. The object is constructed layer by layer with a direct contact with ultraviolet (UV) light to harden the resin when is necessary. The plate holds the model will be lowered after every new layer is solidified.

(4) Base on printing materials

While this is a valid way of categorizing printers, it is generally a function of printing technology used. However this is an important parameter for anyone buying a printer to find a printer able to print specific materials for their needs. For example a hobbyist may only need non-structural plastics, while an industrial printer may need metal structural prints, and an engineer may need flexibility in materials to produce more specific prototypes.

Current market print materials

1. Metals: Stainless Steel in powder form, Silver
2. Ceramics : Porcelain
3. Paper
4. Thermoplastics: ABS (Acrylonitrile butadiene styrene) and PLA (Polylactic acid)

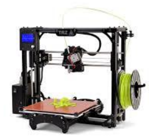
Give the previously stated research, we decided to focus on printers using Cartesian and Delta motion systems, and a simple extrusion type of printing technology (ex: FDM & Material Jetting) as these systems dominate to the entry level and much of the general printer market due to their lower cost and simpler operation. Suitable for non heavy industrial application (ex: rapid prototyping).

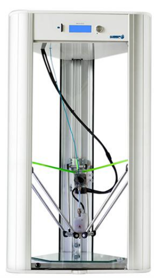
1.2.2 Commercially Available 3D Printers

In order to produce an engineering specification which is feasible from modern technology, research of existing 3D printers was performed.
Factors that determine the price and performance of a 3D printer are resolution, printing volume and number of extruders. The entries below provide all relevant information available from printers' manufacturers.

Table 1 Commercially Available 3D Printers

Printer	Image	Size	Cost	Power	Resolution	Build Size
Cartesian Printer						
MakerBot Replicator [13]		528 x 442 x 411 mm	$2659	100W No heated bed	100 microns layers 11 micron XY 2.5 micron Z	251.46 x 198.12 x 149.86 mm
Ultimaker 2 Extended[14]		357 X 342 X 488 mm	$3030	Minimum 24V @9.2A (220.8W)	40 micron max layer resolution 12.5 micron	230 X 225 X 305 mm

					XYZ	
Lulzbot TAZ 5[15]		680 x 520 x 515 mm	$2200	Maximum 550W	75 micron XYZ	298 x 275 x 250 mm
CubePro[16]		578 x 591 x 578 mm	$2799.99		200 micron XY resolution 70 micron Z resolution	285 x 230 x 270 mm
Fusion3 F306[17]		606 x 645 x 560 mm	Single Extruder $3975 Double Extruder $4975	500W	21 micron XY 100-300 micron Z	304.8 x 304.8 x 304.8 mm
Stratasys uPrint SE[18]		635 x 660 x 787 mm	$15,900+	1905W Max Power Usage	254 micron layer thickness	203.2 x 152.4 x 152.4 mm
Type A Series 1[19]		766 x 572 x 459 mm	$2749	400 W maximum	50 micron layers 6.57 micron XY	305 x 305 x 305 mm

OneUp 3D Printer DIY printer[20]		368 x 305 x 76 mm	$199.99	100w - 150w Heated Bed	50 micron	100.08 x 100. 08x 124.97 mm
3D Systems ProJet 3500 HD Max[21]		825 x 1429 x 1740 mm	$70k- $90k	2400W Max Power Usage	32 micron XYZ	98.45 x 158.42 x 203.2 mm
Delta Printer						
DeltaWASP [22]		470 x 470 x 870 mm	$2550	300W	50 micron XYZ	200 x 200 x 400 mm
Rostock MAX [23]		152.4 x 482.6 x 812.8 mm	$999	N/A	20 micron layers	
Kossel [24]		350 x 350 x 700	$650	N/A	100 micron XYZ	

Detailed research conducted on trends and trade-offs

- Many printers have software setting for speeds, with high speed prints resulting in a tradeoff in quality (accuracy of print, material strength of finished print)
- Use of Fused Deposition Modeling (FDM) reduce the overall cost of the printed model, but trades off with surface finishes of the completed model.
- Larger print spaces correlates to significant increases in cost
- Cartesian printers generally have 3 DOF spread around the base and printhead

Price versus Printer characteristics

- Very cheap printers are generally sold as "DIY" where the user assembles the product. This introduces higher possibilities of error during assembly as it is "DIY"
- The most expensive printers do not generally have extremely high precision or print space. However these printer will have more advanced printing technologies that results in higher fidelity prints compared to simple FDM used by cheaper printers. These printers also have developed specific print material that have better mechanical properties, another reason for the high cost

Dual vs Single extruder

- Higher print speed due to continuously printing motion compare to single extruder, empty out the previous filament then feed from the alternative one. Motion can be continuous whenever you need a different type of material.
- Having spare melted filament material ready for use, reduce the amount of pause point, therefore saves time.
- Still having limitations in printing efficiency, because for some printer, dual extruder are mounted together and controlled by single step motor[25].

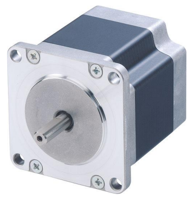
Delta versus Cartesian

- Delta printers have faster print speeds for more complex geometries
- Delta printers have significantly less vertical space efficiency compared to Cartesian
- Delta printers are generally not enclosed by a housing

1.2.3 Common Mechanisms Used in Positioning Systems

This section aims to provide background on strengths and weakness of mechanism used in positioning systems

Table 2 Common Mechanisms Used in Positioning Systems

Mechanism	description	advantages	disadvantages
 Step Motor [26]	Moves in discrete steps through open loop control of counting steps	More reproducible/reliable than conventional servo motor as steps are discrete	Costly compared conventional servo motor
 Serv o Motor [27]	Uses closed loop feedback to control angular position of output	Low cost No static loads High Peak torque Various types[28]	Brushes create dust once wear Poor thermal performance Current can result in demagnetized Low fidelity of motion[28]
 Lead Screw [29]	Converts rotational motion to linear motion	Self-locking, does not need braking mechanism High precision (depending on thread pitch) Moderately cheap	High wear becomes apparent when used in continuous power transmission applications Error increases as running length increases
 Ball Screw [29]	Converts rotational motion to linear motion.	Low wear, more efficient than lead screws Prefered over lead screw for continuous power transmission applications	Expensive Balls vibrate Requires braking system Error increases as running length increases
 Timi ng Belt [30]	Transmits and or modifies rotational motion	Maintains good precision through positive engagement of teeth at low speed and torque Inexpensive	May slip if used in high torque applications Requires tensioning Wearing parts, generally requires replacement within product lifetime

 Chains [31]	Transmits and or modifies rotational motion	Can never slip like belt Suitable for higher torque applications compared to belt	High noise and vibration, may use more expensive “silent chain” to reduce noise High inertia. Requires lubrication. More expensive than belt
 Rack and Pinion[32]	Converts rotational to linear motion	Always engagement between input and output Smooth motion if no reversing direction (backlash)	Motor need to be fixed on pinion. More expensive than belt Backlash (potentially noisy) Expensive Requires braking system if used for Z axis movement

2.0 Engineering Specification

We have decided to pursue a balanced design that maximizes overall performance for minimum cost, by leveraging the strengths of the mechanism outlined in the previous section. Our design will provide performance similar to other printers in the price range for a lower cost. The focus will be the printing of thermoplastics as they are the cheapest to print, and suitable for our focus of prototyping, and not structural components. The design should also provide flexibility for entry level user through a relatively large print size to allow for larger prints or multiple small prints to increase print farm efficiency. We also want to give entry level user the option to go more indepth with the printer, allowing them to remove or replace parts to their needs. And lastly low relative power consumption as the printer is to be used with many others

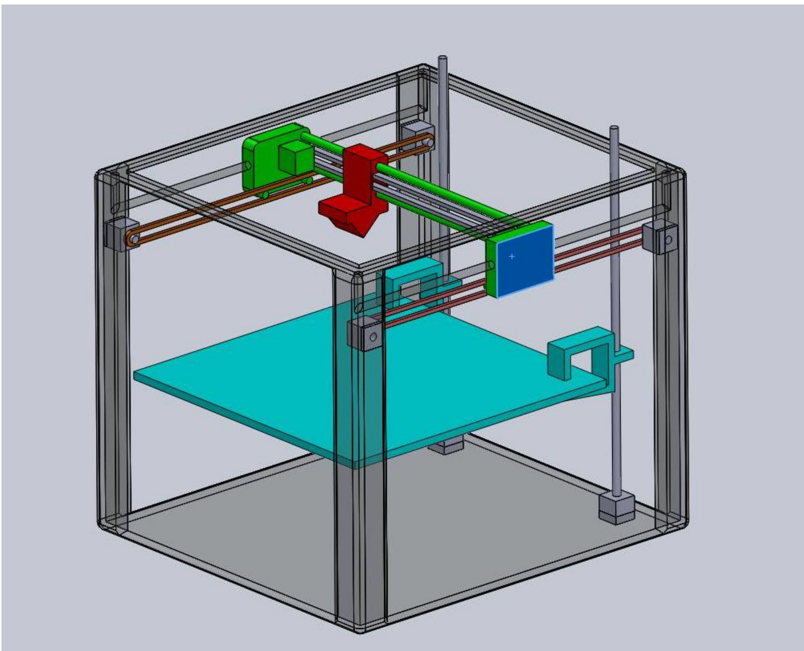
- Must be able to perform printing using an extrusion technology, with 3 degrees of freedom
- The design's overall size should within 60*60*60cm.
- Should have a minimum print space of 30*30*30cm.
- Layer resolution better than of 100 microns (less is better)
- XYZ resolution better than 100 microns (less is better)
- The design must not cost more than $2000.
- The design should print to two types of thermoplastics: ABS (Acrylonitrile butadiene styrene) and PLA (Polylactic acid)
- The design should print at least 30mm/s
- Design must not require human input while operating
- The design must not require more than 200W of power
- Design should operate with minimum vibration and noise
- Printing must occur within an enclosed space
- The design shall be easy to maintain, easy to remove/replace parts, and easy to clean
- Must secure and hold print mass while in operation

3.0 Candidate Designs

The two candidates developed are rather exploratory and contrast each other greatly not only in its method of achieving 3 degrees of freedom, but also the mechanisms used to convert rotational motor input to linear output motion. The candidates are then compared against each other and to the specifications, analyzing their strengths and weaknesses, then leading to the final design.

3.1 Candidate 1

This design is overall compact and similar with some of the existing 3D printers in the market. Its orthogonal geometry gives it a good packing factor if used in a print farm. Two step motors are connecting to two lead screws, in order to move the build plate up and down for Z axis motion. Two step motors are mounted on opposite ends of the housing drive belts moving a subassembly in the X direction. The subassembly has a step motor driving a belt to move the extruder in the Y direction.



Blue: Print Base

Green: Subassembly moving in X direction

Red: Extruder

Figure 4 *CAD model for Candidate 1*

3.2 Candidate 2

In this design, the extruder movement is driven by three rigid arms which slide along rails using rack and pinion mechanisms. Rigid links are connected to the extruder and pinions using ball or universal joints, such that the extruder can move in X Y directions as result of the combination of up and down motions of the rack and pinions.

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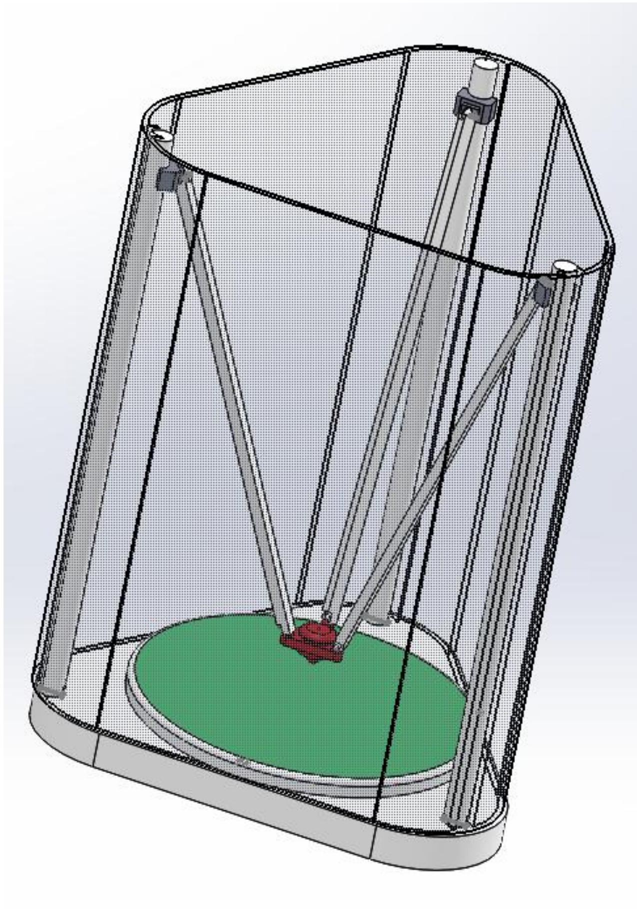


Figure 5: *CAD model for Candidate 2*

3.3 Comparison of Candidate Designs

Table 3 Comparison of Candidate Designs

	Candidate 1	Candidate 2	Advantage
Printing Approach	Cartesian	Delta	

Overall framing and axis set-up Space efficiency	• Independent driving systems for x, y and z axis • compact structure space efficiency	• Inter-related driving system for x, y and z axis • Less space efficiency, vertical space efficiency greatly reduced	Candidate 1
Mechanism	• Uses timing belt and lead screw to perform motion transmission and conversion	• Rack and pinion for motion conversion • Requires use of ball or universal joints to function	N/A
Built Size	• 30*30*30 cm	• 30*30*24 • Cylinder of 30 cm in base diameter and 24 cm in height	Candidate 1
Size	• 53*48*46 cm	• 75*36*36 cm	Candidate 1
Printing Quality speed and accuracy	• Faster and more accurate for orthogonal geometries	• Faster and more accurate for curved or round surface • Precision varies as at different heights	N/A
Power Consumption	• Requires 5 step motors • Z axis motors do not have to be on constantly	• Requires 4 step motors • All three motors must be running constantly	N/A
Maintenance	• Belts wear and needs replacement within product lifetime. However, generally a cheap repair • Lead screws may also require replacement over product lifetime	• Rack and pinion will wear slower than belt, but replacing will be difficult and more expensive	Candidate 1
Cost (done through comparison with market printers see section 1.2.2)	• At most $2000	• At most $1500	Candidate 2

3.4 Additional Analysis of Candidate Designs

- Both designs are constrained in precision by the minimum step size of the step motors -> possible inclusion of gear ratio to release constraint
- Both designs use step motors, as step motors have a higher fidelity of motion and very reproducible step size compared to servos (specific step motor types will be outlined later in Final Design section of report)

- Candidate one
    1. Uses two motors to achieve X axis motion -> possibly able to reduce to one
    2. Uses two lead screws for Z axis motion, could induce positioning errors if rotation of motors not align, making the base not level
    3. For Y axis motion, the subassembly carrying the motor is moved all together, creating more load for the X axis motors -> move Y axis motor such that it does not need to be moved
    4. Print base is only supported on one end -> possible errors if large deflection present
    5. How the belt will be attached to the subassembly and extruder to be able to pull it, also how the belts will be tensioned
    6. Methods/mechanism with regards to belt replacement and maintenance should be considered.

- Candidate two
    1. The precision changes depend on the height printer is currently printing at. A change in height of the rack and pinion drive will result in different changes in X & Y distance as different heights of the print
    2. As the design uses a rack and pinion, gravity always acts on it as it move vertically, thus motor needs to continuously run or requires a braking mechanism
    3. Also as it uses a rack and pinion, the power of the motor must also be used to move the motor itself -> Consider using other mechanism
    4. The design has very low vertical space efficiency, given the current height of 74 cm, it is only able to print a max height of 24cm
    5. Design has a rounded triangular shape, harder to pack many together
    6. Has a high center of mass (design is very tall), thus vibration caused by the mechanisms are amplified
    7. Long and slender structural members -> possibility must use higher strength materials

4. Design Analysis and Description

4.1 Final Design Overview

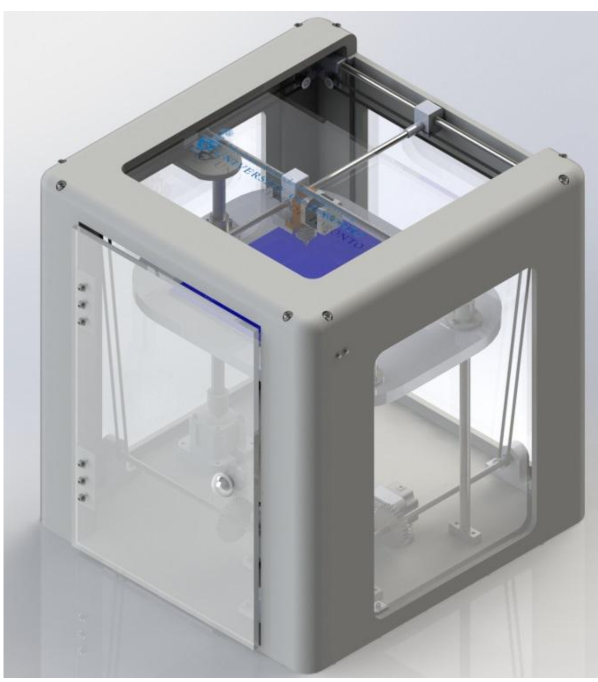
Our final design is an refinement of Candidate 1. Our analysis of the candidates found that the main issue with Candidate 1 was the redundant number of motors. This issue was resolved by redesigning/reorganizing the mechanism. The main issue of Candidate 2 is the lack of space efficiency inherent to a delta positioning system; this issue conflicts with one of the goals of the design of giving entry level users flexibility in allowing for larger prints. Also, our specified 30cm print height can not be done in Candidate 2 without greatly exceeding the specified height of 60cm (as in Candidate 2, a 24cm print height accounted to a total height of 74cm). The much higher center of gravity of the Candidate 2 would also amplify vibrations making it noisier. Although the delta print becomes significantly faster for prints with curves and is estimated to be cheaper, its disadvantages prevent it from meeting the specification.

The candidate design stage also allowed us to have a direct comparison between positioning mechanisms. It showed the major weakness of rack and pinion drive when used for vertical motion. Additionally, the rack and pinion drive requires the motor to also move its own weight, possibly making it slower and less power efficient. On the other hand, belt drive system for x and y axis movement also shows disadvantages in maintenances such as tensioning and frequent replacement.

The following section will walk through how our design achieves 3DOF printing

Then, the next section will be detailed mechanism/part selection and justification

We will state the specifications of our final design and list sample calculations for some specifications



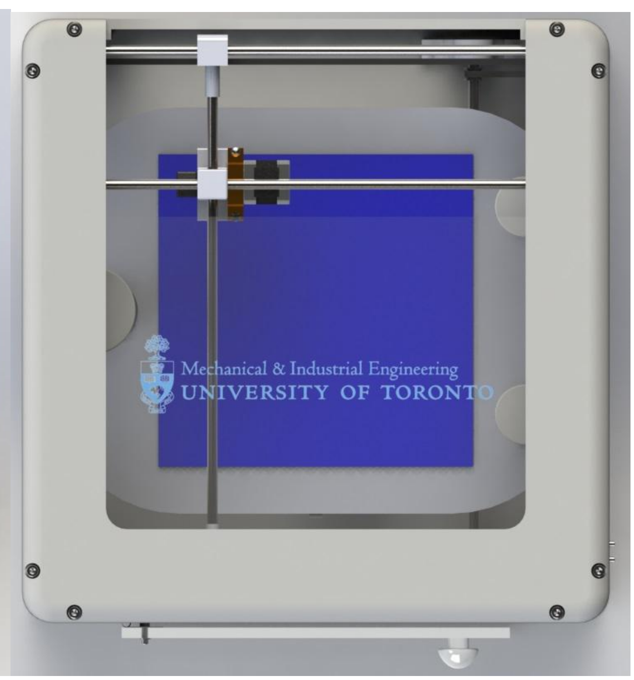


Figure 6: *Rendered Isometric View of Final Design* **Figure 7:** *Rendered Top View*

The top is semi open to allow filament into the extruder

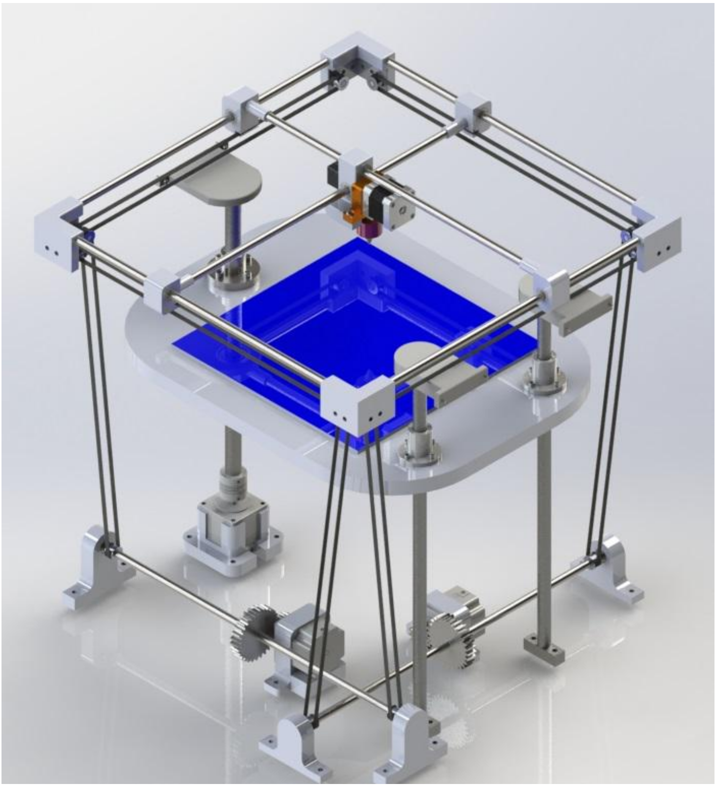


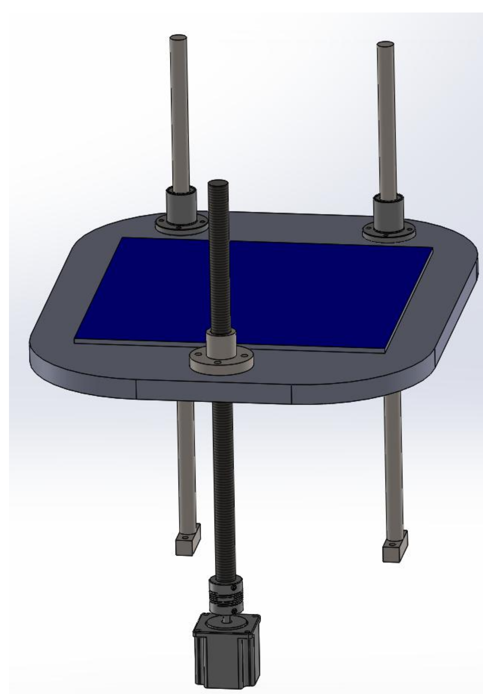
Figure 8: *Rendered Isometric View (without housing)*

Blue: Represents 30cm x 30cm print space

4.2 Explanation of Operation

4.2.1 Z Axis Motion

The final design achieves Z axis motion similar to Candidate 1. However, the significant change is that the motion is now created by only one lead screw, and the print base is supported on both sides. As stated in section 3.4, having two lead screws may actually be to the detriment of the design, as if the rotation of the screws are improperly synced then the print base will no longer be level.



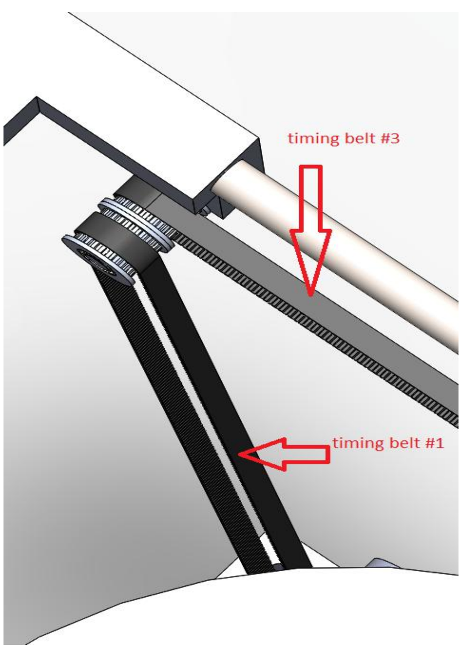
The final design is arranged such that motion is created by the lead screw on one end of the base, while two rods on the opposite ends provide additional support through their connection to linear bearings screwed onto the base. The system is powered by one step motor connected the lead screw through a helical flexible coupling. The coupling does two things. Firstly, it connect the motor shaft and lead screw which have different diameters. Moreover, it allows one to one rotation even when angular misalignment is present (up to an extent), this allows for a controlled output motion and thus reduces errors by diminishing the effect of misalignments. **Figure 9**

Figure 9 *above shows Solidworks subassembly of lead screw and support rods connect to the print base*

4.2.2 X and Y Motion

As the same mechanism and layout is used for both X and Y direction motion, the explanation of operation is combined into one section.

Both X and Y are controlled by their own step motors located at the base of the housing of the printer. The step motor shaft is connected to a gear pair that gears up to decrease effective step size of the motor (increase precision), but also transmits the rotation to a shaft. On either end of the shaft is a timing belt pulley which rotates at the same speed as the shaft. The timing belts connect to these pulleys transmit rotation up to the pulleys at the top of the printer. These top pulleys then are connected to belts that run in the XY plane and subsequently connected to blocks which are move in either the X or Y direction as the pulleys rotate pulling the block with the belt. Opposite sides have a pair complement blocks that move together similar to the X direction subassembly in Candidate 1. Complement blocks are connected by a support rod which the extruder assembly is able to freely slide along through the use of linear bearings. Thus the extruder is able to move in X and Y directions



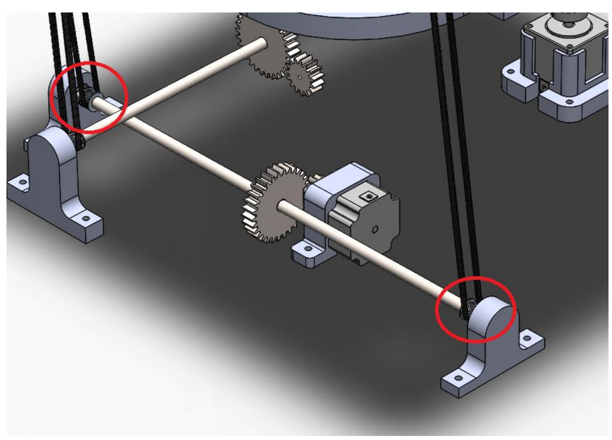


Figure 11 *Motor input to pulleys transmitting motion upwards*

Figure 10 *Timing belt 1 transmits motion into the X Y direction through timing belt 3*

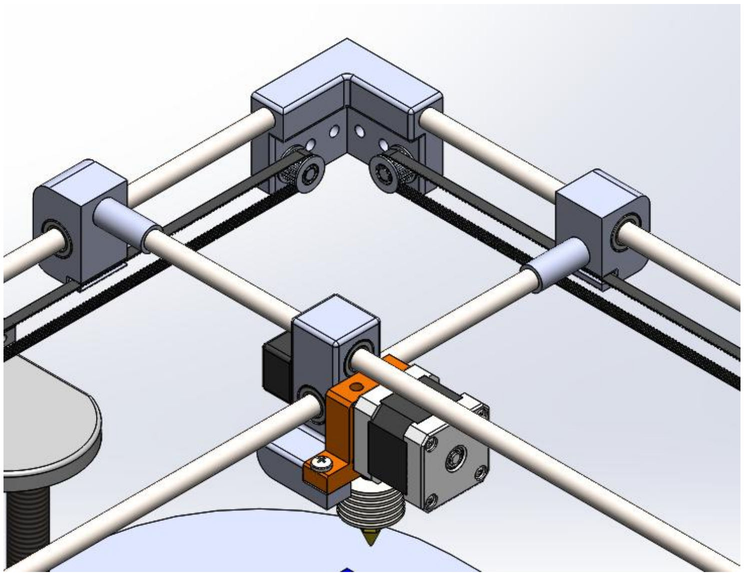


Figure 12 *Shows timing belts attached to blocks which slide in either X or Y direction along support rods. The extruder is then able to move in X and Y direction by sliding along support rods from aforementioned blocks*

4.2.3 Supports

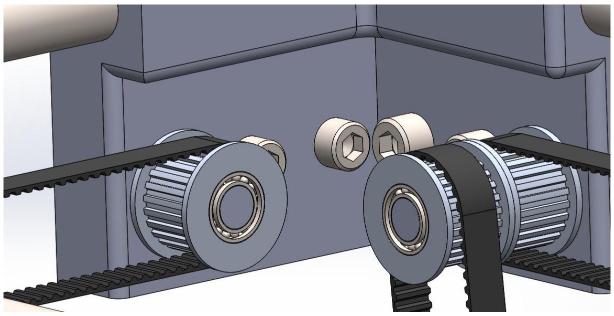
Z axis

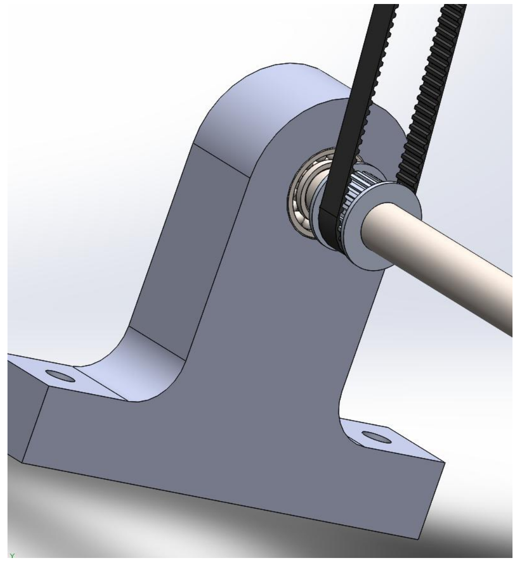
- Motor is mounted to metal block which is then mounted to the base of the housing
- The top of the lead screw is press fit into a ball bearing that is within a block mounted which is bolted to the housing
- The top of the two support rods are supported in similar fashion to the lead screw, however there is no bearing as the rods do not rotate
- The bottom of the support rods have threaded holes which mount to the base of the housing
- The two supporting rods are supported by linear bearings which are press fit into mounts. Mounts are then bolted onto the build plate

X and Y axis

- Motors are mounted to base of housing through mounting blocks
- Gear and pulley shafts are supported on both ends by ball bearings on both side, press fit into mounting blocks which then mount to base of housing
- Top pulleys and all motion elements are supported by L shaped corner blocks with threaded holes that mount to the housing
- Top pulleys are supported by a shaft connected to the corner blocks, and

its rotation supported by ball bearings
- Any sliding elements such as the extruder block require linear bearings





F

igure 14 *Bottom pulley mount*

Figure 13 *Timing pulleys rotate attached to shafts in the corner blocks*

4.3 Detailed Mechanism and Parts Selection/Justification

4.3.1 Z axis

We chose to use the lead screw as in this specific application of vertical positioning, its strengths become very pronounced, while the effect of its weakness are diminished. Two supporting rods are located on the opposite side of the build plate, constraining the vertical movement of the the build plate.

- First the lead screw is self locking, implying we would not need a breaking mechanism that would be required for a rack and pinion or ball screw drive.
- Secondly the print base will only move discretely for very short distances at a time as layers are printed. Meaning the lead screw is not continuously transmitting power, significantly lowering wear on the lead screw.
- The lead screw is also a cheaper option to the rack and pinion and ball screw, while still having a high precision (dependent of thread pitch) compared to other mechanisms when paired with a step motor, and low error (± 0.009" per foot of travel for Precision Acme Rods) [33].

Compared to Candidate 1, the change is the use of only one lead screw. This removes the other redundant motor in Candidate 1. And as mention before, this configuration removes the possibility of print base becoming not level due to asynchronous rotation of more than one lead screw.

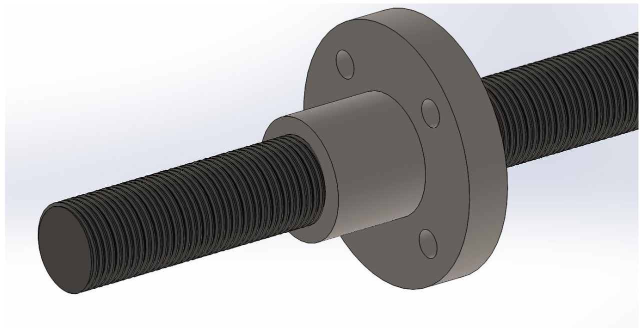


Figure 15 *Lead screw and matching nut which mounts to print base*

4.3.2 X and Y axis

The final design employs a refined version of the timing belts design from Candidate 1
We chose to use the timing belt because:

1. Timing belt forces positive engagement, necessary for accuracy in positioning
2. This is a low speed and torque application, meaning a well tensioned timing belts has a extremely low possibility of slip which is the main weakness of belts compared to other mechanism
3. A belt drive does not require the motor to move like a rack and pinion drive, and thus more efficient and faster (if motor is running at same speed and torque)
4. Lead/ball screws for require more supports to run compared to belt
5. Lead/ball screws also present a tradeoff between precision to speed. As thread pitch of lead screw (precision) increases, more turns of the motor are required to create the same amount of linear motion. This is not a problem with the Z axis as the print base only moves for small distances periodically. However, in X Y the extruder is must constantly move during operation. This constant motion also greatly increases the wear in a lead screw if used
6. Ball screws require an additional braking mechanism
7. Chains will never slip, but are heavy and noisy(low noise was one of the specifications)

This positioning application makes the timing belt a very good option as it is the cheapest option, while maintaining. good precision.

The main disadvantage of the timing belts is that it has worst wear compared to other mechanism and thus needs replacement during the product's lifetime, belt replacement considerations will be discussed in section 4.3.5.

Belts also require tensioning. This is done through passive tensioning at point where the belt attaches to the block which slide in either X or Y direction. As the picture shows, screws screw the belt to the block, but there are large tapered holes on the inside face such that the belt will be pushed into these holes by the screw. This localized strain imposes tensile forces, tensioning the belt.

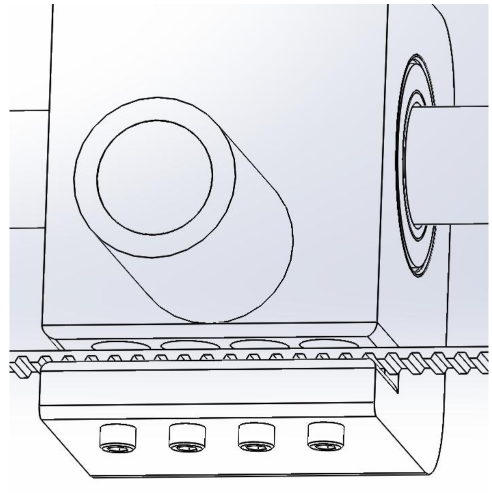


Figure 16

We also choose to add a gear pair to increase torque of the motor, to ensure it is able to move the extruder, but to also decrease the effective step motor step size without buying a more expensive motor which would be more expensive[34]. We choose to use anti-backlash spur gears, as any backlash would resulting in a compounding error in X Y position during the print as the extruder will very often change direction of motion.

Figure 17 *Anti Backlash Gear*

A planetary gear train would be a compact method of greatly reducing effective step size, however it would be more expensive and have backlash

Note: Anti-backlash gears are depicted as regular spur gears in CAD model

4.3.3 Support

The main support components for our designs are the housing, ball bearings, linear bearings, rods and mounting brackets. The attachment mechanisms are mechanical fasteners and press fit.

Importance of the housing:

- All parts are connected to the housing directly or through mounting brackets. This allows easy replacement and maintenance of parts.
- The housing is made out of 6061 T6 Aluminum which reduce the overall weight of the design while keeping modules and stress factors within desired range [Appendix B]
- Most parts are mounted onto the bottom of the housing allowing our design to have low overall center of mass which prevents safety hazard during operation
- X and Y axis components are mounts to four corners of the housing allowing weight to be evenly across the housing
- Three sides of the housing are hollowed in the middle decreasing cost and weight of the housing. The sides are not hollow completely due to the overall strength of the housing structure

Choice of ball bearings:

- All rotating parts are supported by plastic ball bearings on both ends and then press fit into supporting elements
- Ball bearings have the lowest cost comparing with roller and angle bearings. Also there are little to no axial forces, making ball a good choice
- In our design, the movement of components will be low speed, low torque, suitable for ball
- The printer can print plastic bearings for future replacement

Choice of linear bearings:

- Linear bearings are used in sliding elements to allow for low friction (smooth) motion
- While much more expensive than bushings, the frequent sliding motion would quickly wear down bushing. Additionally the frictional contact of bushing would reduce the power efficiency of the system

Choice of support rods:

- Steel, as it has one of the highest modulus of elasticity, meaning very little structural deflection

Choice of press fit:

- All bearings are press fit into the supporting elements
- Press fit is the easiest and cheapest way to fit two part together
- Our design is expected to operate under low axial force, press fit is strong enough to secure parts into mounts

Choice of mechanical fasteners:

- Allows for easy removal for maintenance as attachment is non permanent. See section 4.3.5

4.3.4 Motor Selection[35]

In this design , we select step motors for xy and z axis as well as extruder drive. This is due to the fact that step motors have a reproducible and high fidelity motion. Only very expensive servos can achieve similar performance.
For all motors we are choosing NEMA 17 size motors, as they are the cheapest among NEMA standardized motors
Motor selection for motion elements:

- As our motion mechanism are relatively inexpensive, more of the cost can be allocated to motor with smaller step sizes. Step motors are standardized with the largest step size of 1.8 degrees, moving down by half at each price tier. Four our design we will use a motor with step size 0.9 degrees

4.3.5 Maintenance Considerations

As mentioned before, the cheaper mechanism selections such as ball bearings and timing belts are wearing parts and require replacement throughout the product’s lifetime. The roof and door are removable by screw to allow user to easily access the design interior. All support elements, such as mounting brackets are also removable. The removal of bottom pulley supports and corner blocks by screw releases tension in the belts allowing for easy removal.

4.3.6 Heated Base Plate

Most higher end plastic printers will include a heated print base. The heat keeps the print warm during the print and prevents warping due to the plastic cooling down at an uneven rate. User looking to printing large prints must use a heated, as warping becomes more of an issue for longer (larger) prints.

- The bed will be heated by Polyamide (Kapton) film heater[36].
    - Polyamide has high heat resistance and smooth finish on the surface which helps with removing the product from the bed. Polyamide heater heats up faster and more evenly when compared to PCB heater, especially when used with another surface. Although Aluminium clad heaters are efficient and inexpensive however it requires more complicated installation steps than other heaters. Thus, Polyamide heater is the optimal solution for the heater choice.

- Print surface: 2mm of Tempered glass to have a smooth surface, also to protect the heater from damage by external force such as contact with the extruder.

- Adhesive material: An adhesive material is usually ideal to ensure material will stick properly to a bed. Common choices are painters' & Kapton tape and gules. However those choices are not reusable after each print. Our choices is preinstalled 1mm thick PEI (Polyetherimide) sheet. PEI sheet is reusable and only requires limited cleaning. PEI can stick to both ABS and PLA when heated to proper temperatures. User can change the sheet when the preinstalled sheet reaches it service life[37].

4.3.7 Extruder

In this design, we decided to use a single screw extruder[Appendix C] because it's cost efficient and compact in size.

- The step motor is mounted using bolt and nut onto the extruder block
- A counter weight is added on the opposite of the extruder to balance the moment
- A fin heat sink is attached near to the extruder head to diffuse excessive amount of heat when melting the printing filament
- The extruder will use a NEMA 17 step motor with a high step size to reduce cost as precision is not of importance

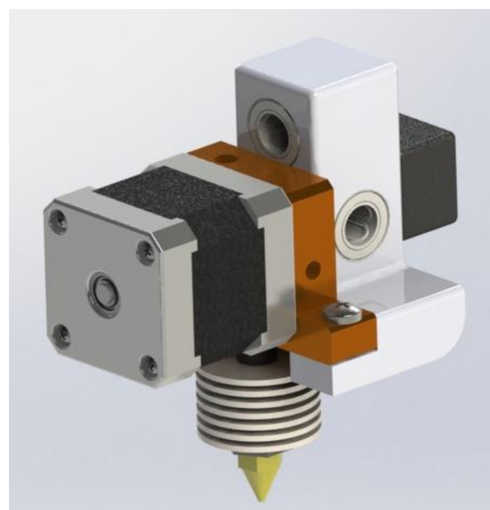


Figure 18

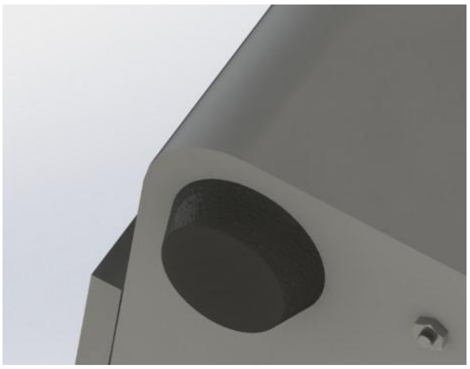
Note: In Bill of Materials, extruder cost includes cost of step motor used to feed extruder

4.3.8 Additional Features

- The printer sits on four rubber feet. This is to dampen the vibration caused by internal motion during operation, making the printer quieter. This could have a noticeable impact in print farm as a large number of printers are operating at once
- The design features a hinged door to keep the print space enclosed, and allow for removal

of printed parts

- The roof is left partially open to allow print filament and control circuit for extruder stepper motor to reach the extruder
- 3 side and the roof feature transparent acrylic



windows to allow monitoring of the print progress

Figure 19 & 20 *Rendered images of rubber feet (left) and an open door (right)*

4.4 Final Design Specifications

- X Y precision
  Since the motor moves in 0.9 degree increments and there is a 2:1 speed reduction gear, the axles will rotate in 0.45 degree increment and takes 800 step to complete one turn. The diameter of the pulleys are 11 mm, therefore each step from the motor results a 42.5 microns (0.0425 mm) movement along X & Y axis and satisfies the specification for X & Y resolution of 100 microns (0.1mm).

- Z precision
  NEMA-17 motor has 0.9 degree increment, which takes 400 increments to complete one rotation. The lead screw used has 1/16 in pitch, thus 1.5875 mm of travel per rotation.

Each increment will results in 4 microns (0.004mm) movement along Z-axis. The layer resolution satisfies the specification of 50 microns (0.05mm).

- Fastest possible X Y movement speed
  450 rpm/60*2*pi*0.01=235.6mm/second
  Actually print speed much lower than this, this is the upper bound estimate

- Power Consumption
  Estimated consumption of each motor (assuming 80% efficiency) is approximately 5W
  Estimated extruder consumption 40W
  Estimated heated bed consumption 100W
  Total consumption 160W which is less than the specified value of 200W

- Overall Size: 56.0cm(L) x 58.0cm(W) x 61.3mm(H)

- Build Space: 30.0cm(L) x 30.0cm(W) x 32.4cm(H)

- Plastic print type: Single Extruder, PLA or ABS

- Features
  - Includes polyamide film heated print base
  - Includes vibration and and noise reducing rubber feet

- Cost: Refer to Section 5 Bill of Materials

5.0 Bill of Materials

The housing is constructed with 6061 T6 aluminum alloy , with the volume estimate of 0.027 in Solidworks,

Table 4 Bill of Materials

Part	**Description**	**Cost (USD per unit)**	**Quantity**	**Total Cost (USD)**
NEMA-17 4209	Connect to lead screws to perform plate movement.	91.50[38]	3	274.5

Step Motor Drivers	Relays signal to motors	99.43[38]	3	298.29
Step Motor Controller	Send signal to drivers from central controller	368.57[38]	1	368.57
Motor mount	To stabilize motors	6.5[39]	3	19.5
Bearing Mount	To stabilize and connect bearings with housing	5[40]	7	35
¾"-16 Precision Acme Threaded Rod 3ft Length	Carry out vertical motion in z-axis, accomplish higher accuracy.	64[41]	1	64
Anti-backlash spur gear	Connect and transmit motion between motor and rotating rod	20[40]	4	80
Helical Flexible Coupling	Connection and prevention of misalignment	5[42]	1	5
Metal support rods (steel)	Restraint vertical Motion.	16[43]	2	32
Top support rod	support top rod	1[44]	3	3
Corner block	Connection corners of rods from different directions	0.168[45]	4	0.67
Corner pulley shaft	supports of timing belt pulley	0.1[46]	8	0.8
Timing Belts	Confine extruder movement in x	1.8/meter[47]	approx. 1.5-2m	2.7-3.6

	and y axis, enhance printing efficiency.			
Timing Belt Pulley	Support of timing belts	1[48]	10	10
Rail rider	sliding component provides movement of motion	1[44]	3	3
Extruder	Source of material extrusion.	59.99[49]	1	59.99
Base	Location of printing.	40[50]	1	40
Heater	Heat up the material.	20[51]	1	20
Linear roller bearing	Reduce the amount of friction of the motion and smooth the movement of the extruder rack.	15.9[52]	2	31.8
Ball bearing	Installed on top to support motion for lead screw and rods	5[53]	4	20
Housing(0.024)cubic meters of aluminum)	Housing is constructed with 6061 T6 Aluminum alloy	2300/ton [54]	0.024 cubic meters (with density of 2.5e3 kg/cubic meters)	138
Acrylic Window	Allows operator to monitor	5.3[55]	4	21.2

	progress of print			
Door Hinge	connection of the door and housing	0.67[56]	2	1.34
#10-32 Screws		0.15[57]	150	22.5
Rubber Feet	prevention of damage to floors/tables/etc.	0.3[58]	4	1.2

Total cost = $1553.96
Meets the specified cost of $2000

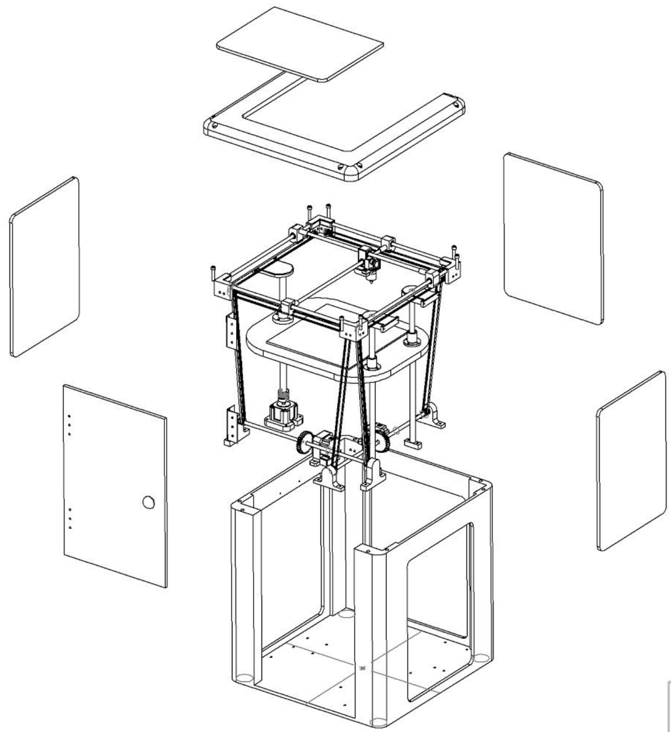
6.0 Conclusion and Next Steps

The major task of the design project was to devise an advanced conceptual design for an entry level 3D printer, used as part of a print farm, its main focus will be high-quality rapid prototyping for businesses. Through extensive research, the team is able to come up with our final design, based on a cartesian positioning system, using FDM printing technology. This design uses belts drive to control position in the X and Y axis and lead screw to control Z axis position. The design focuses on leveraging the strengths of various mechanisms to optimize performance in a lower cost. It also aims to have a relatively large print space, operate quietly, and be relatively power efficient. It also uses mostly standardized parts, hence cost-efficient for mass production in the long run and suitable for bulk sale to print farms.

Although this report outlines a fully designed 3D printer, this design has not been physically examined to be feasible. If time and resource permit, we will start building the model based on CAD drawings, and test out the data to see if we can implement the design in real life applications. There are a few other factors that have to be tested out, including safety and human factors.

7.0 Drawings

7.1 Assembly Drawings



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DRAWN	Ziming Huang	2015.12.06

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Tolerance:0.05mm

University of Toronto

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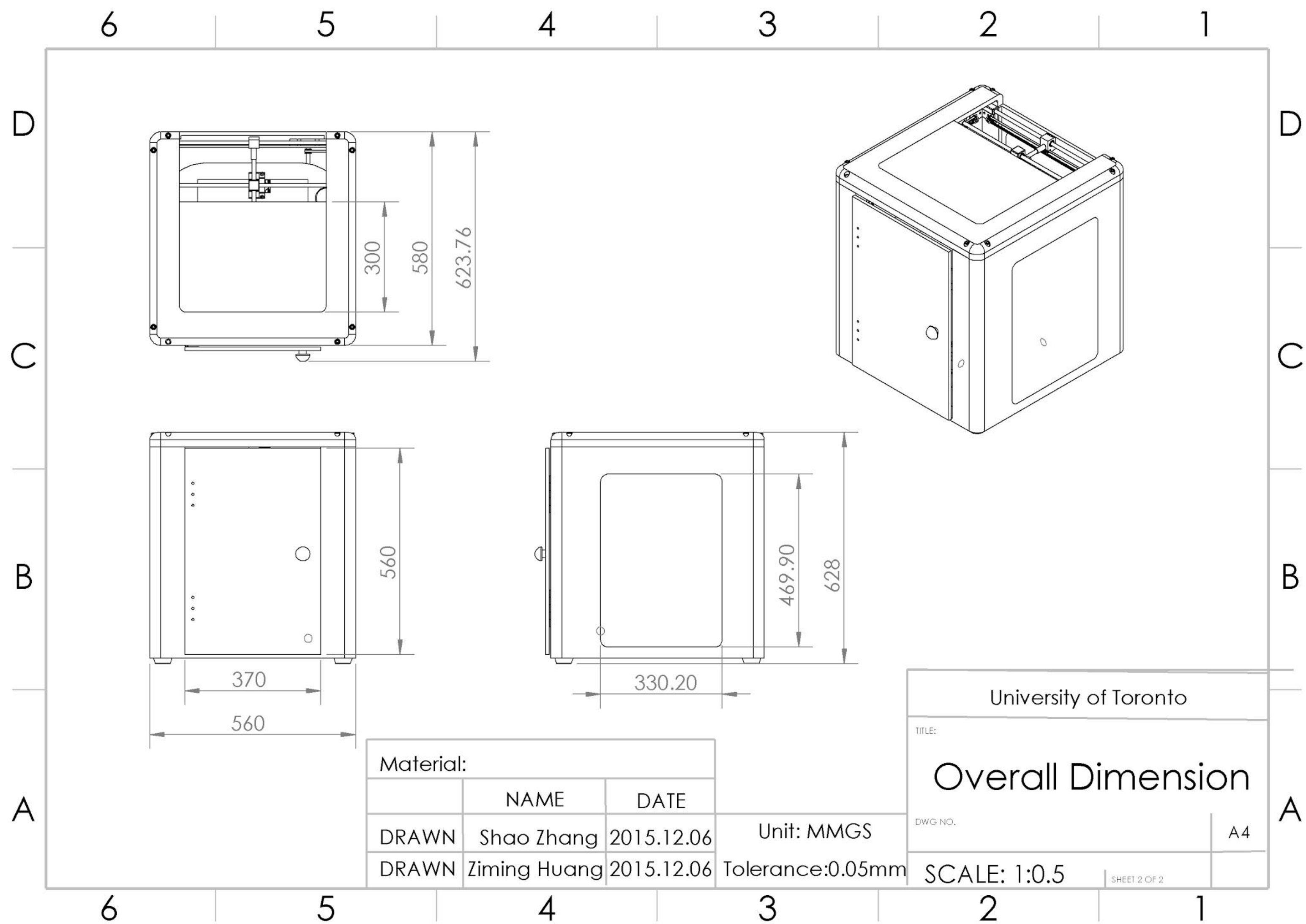
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University of Toronto
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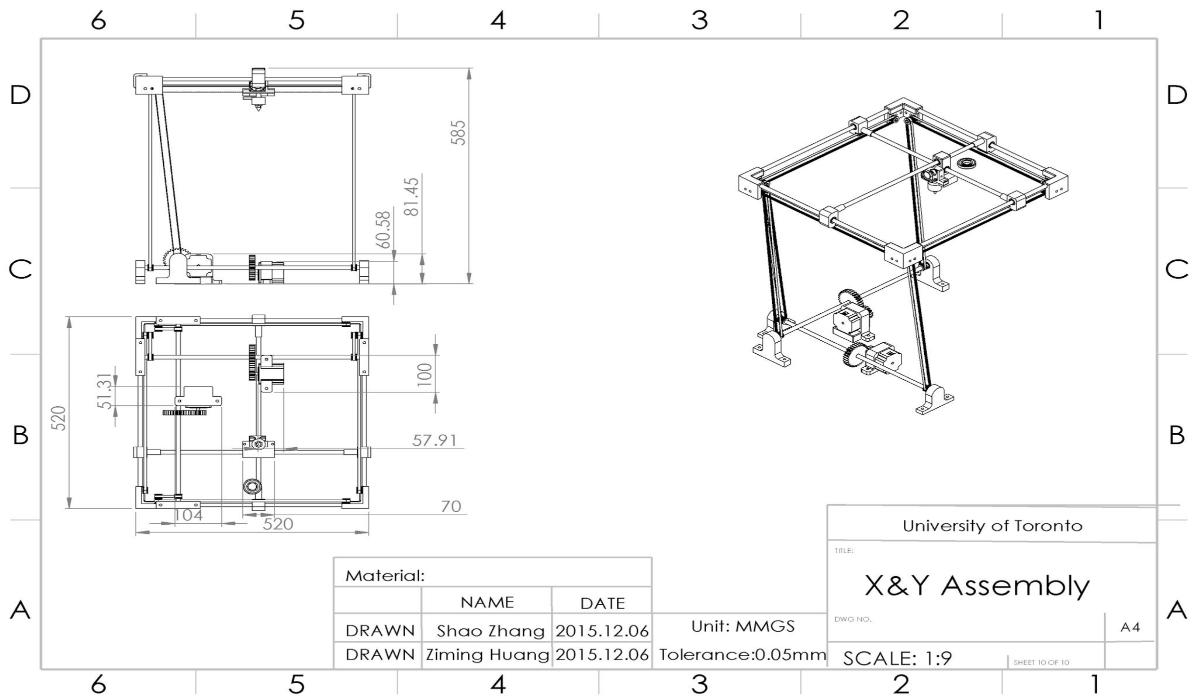
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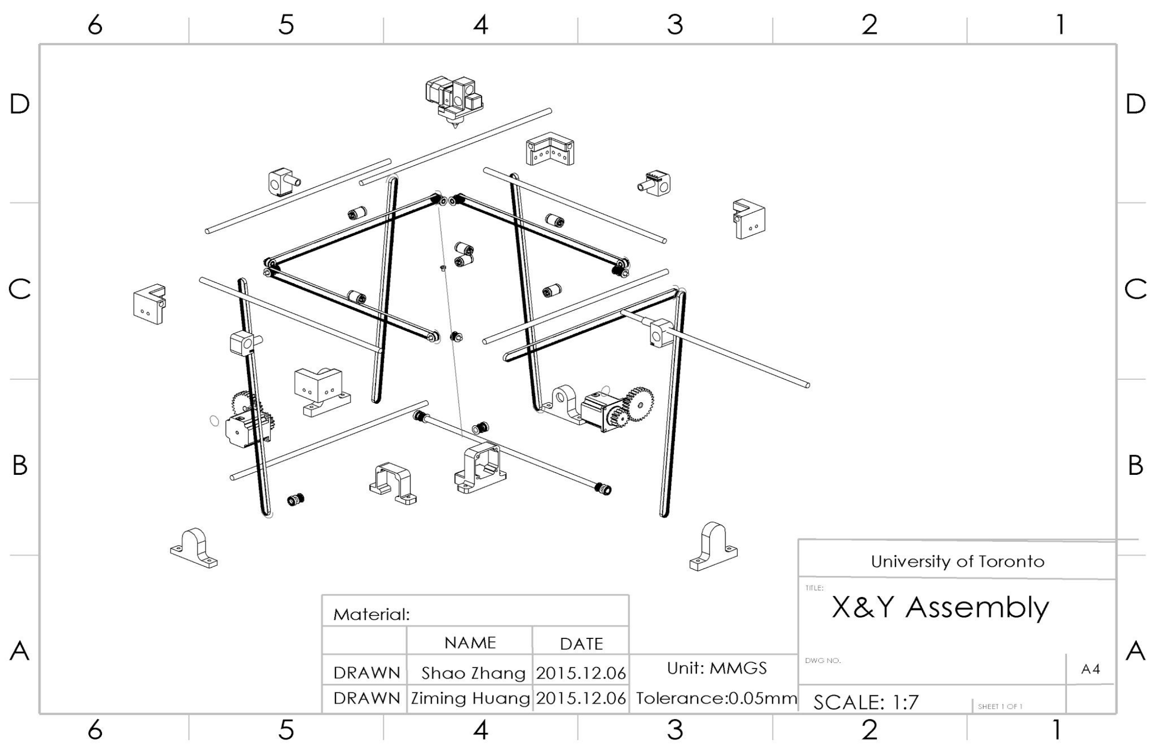
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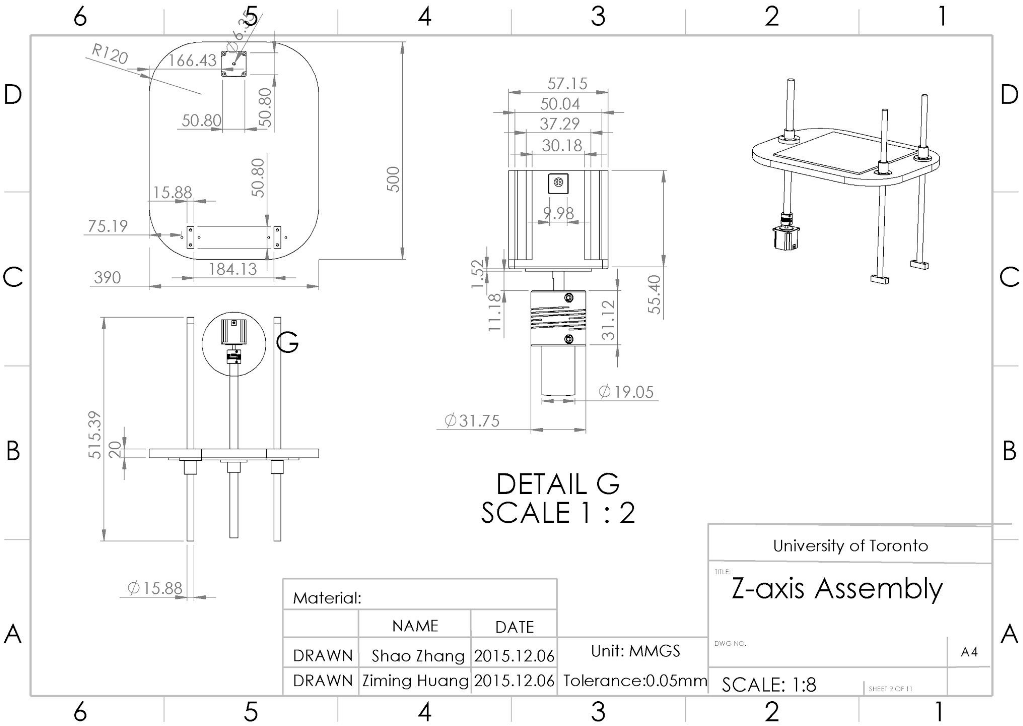
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University of Toronto
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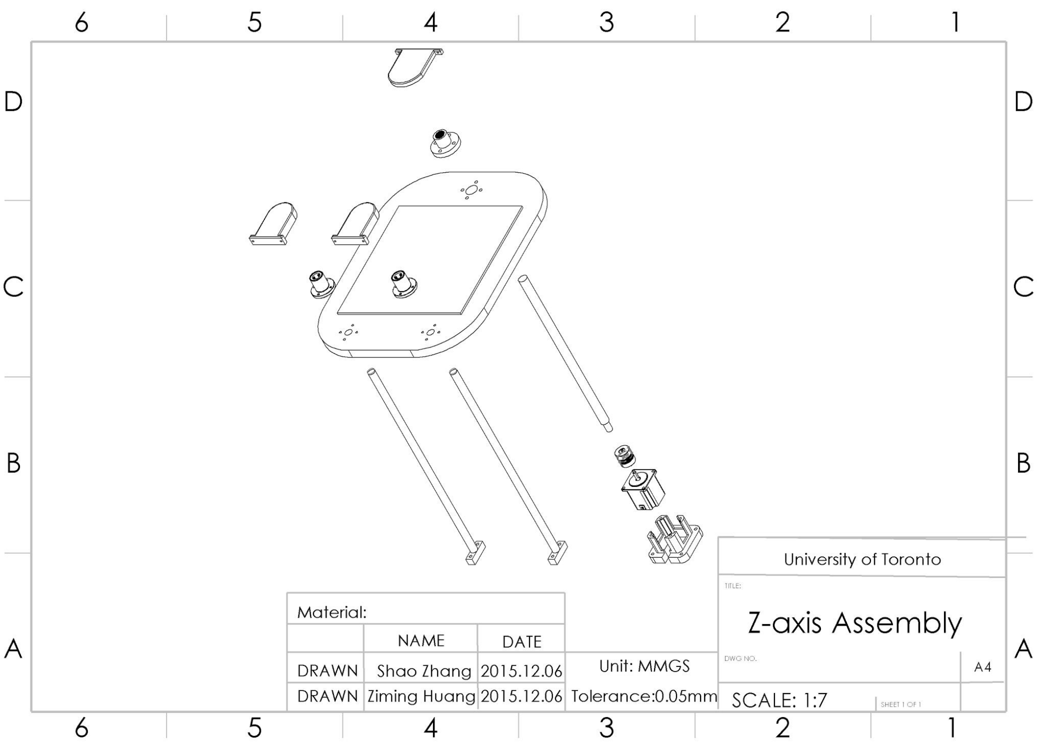
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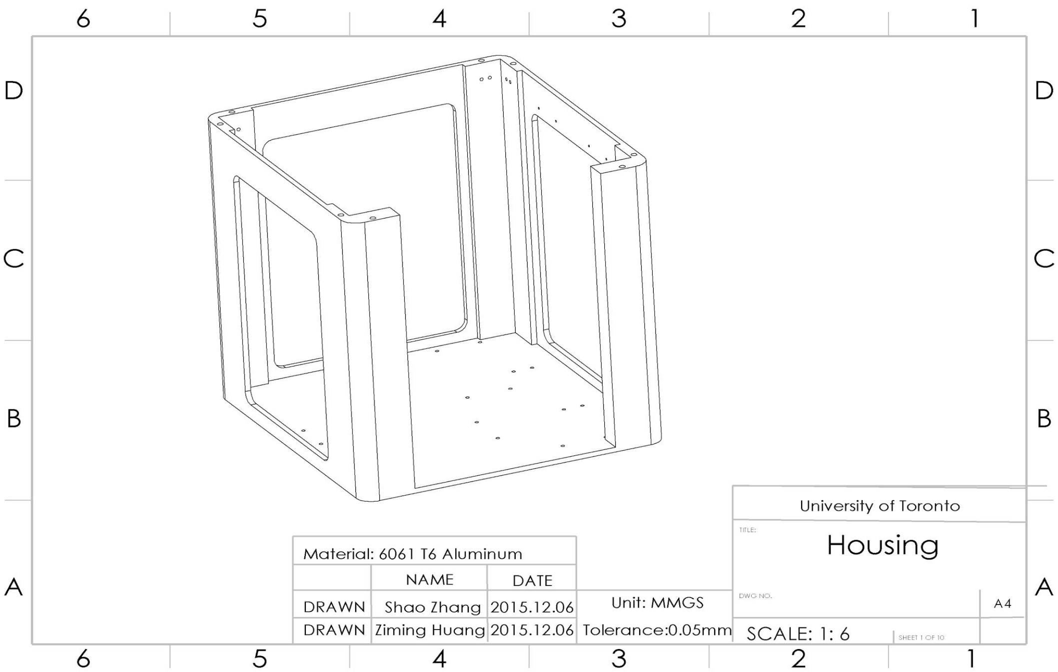
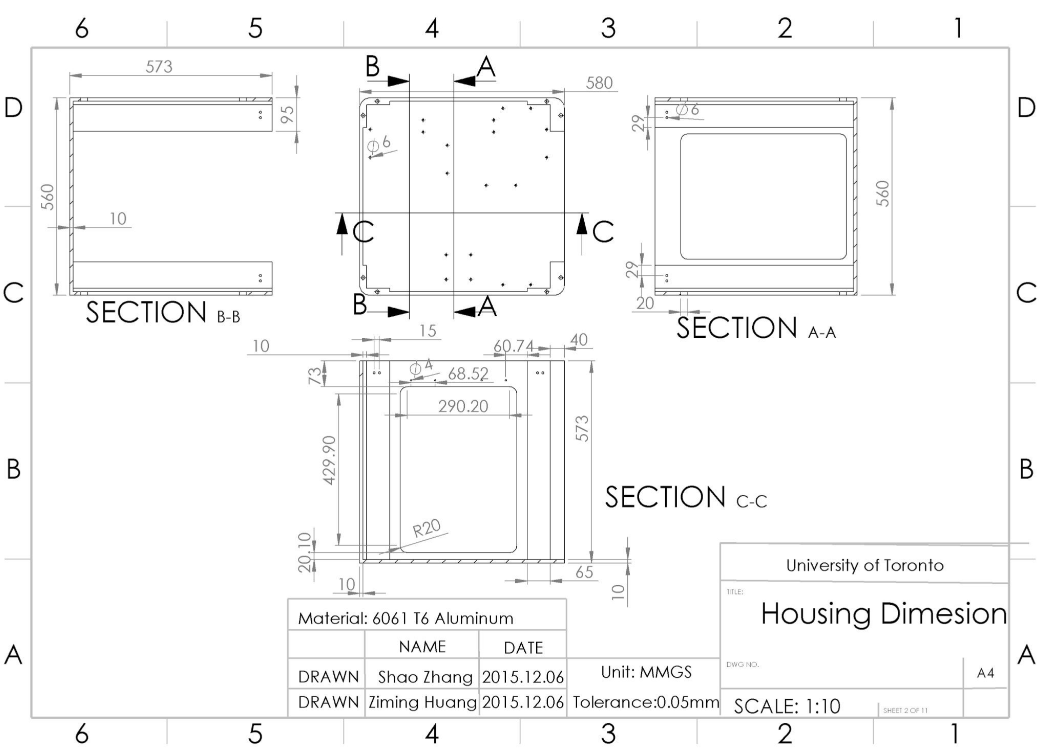
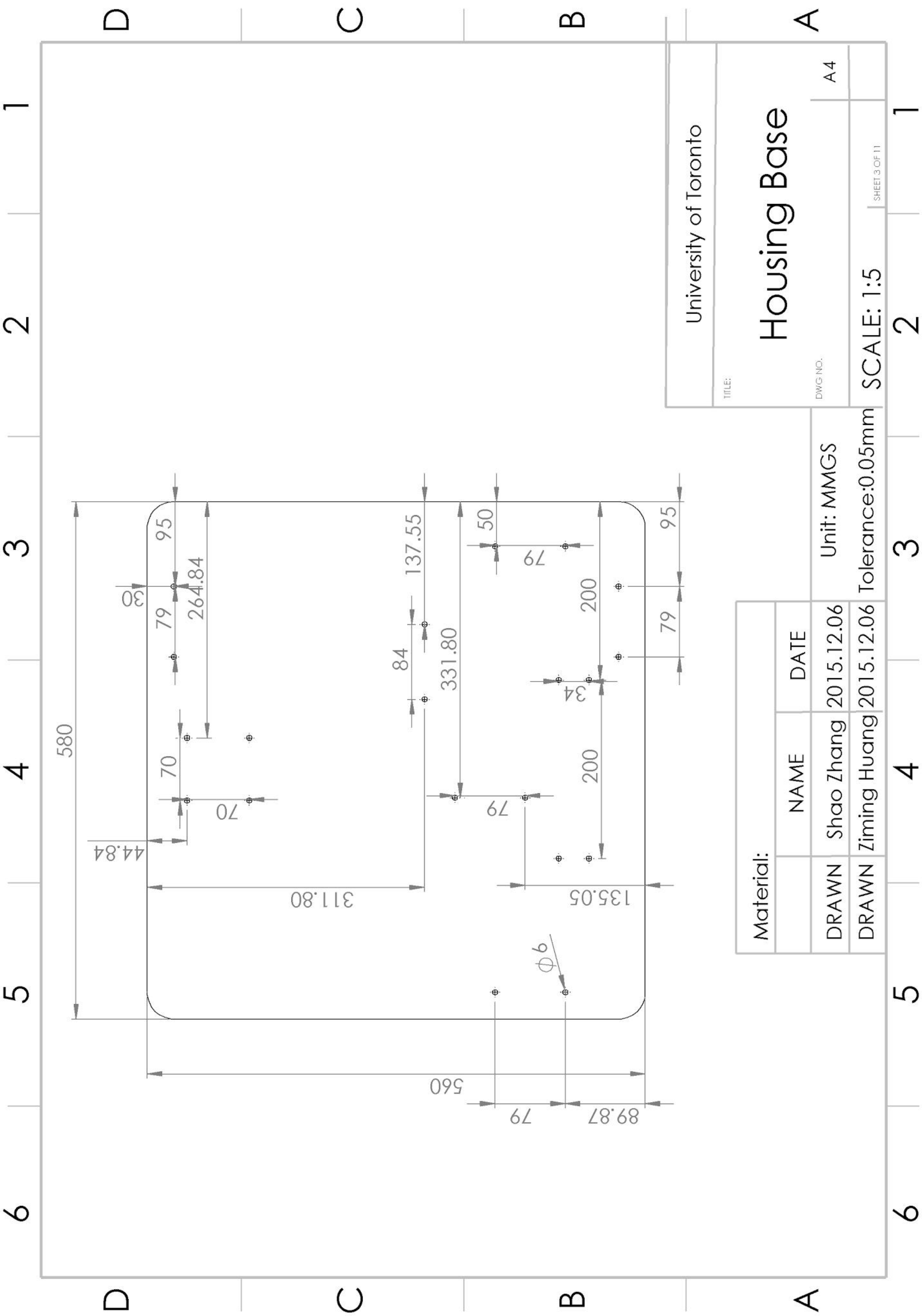
7.2 Supplementary Drawings



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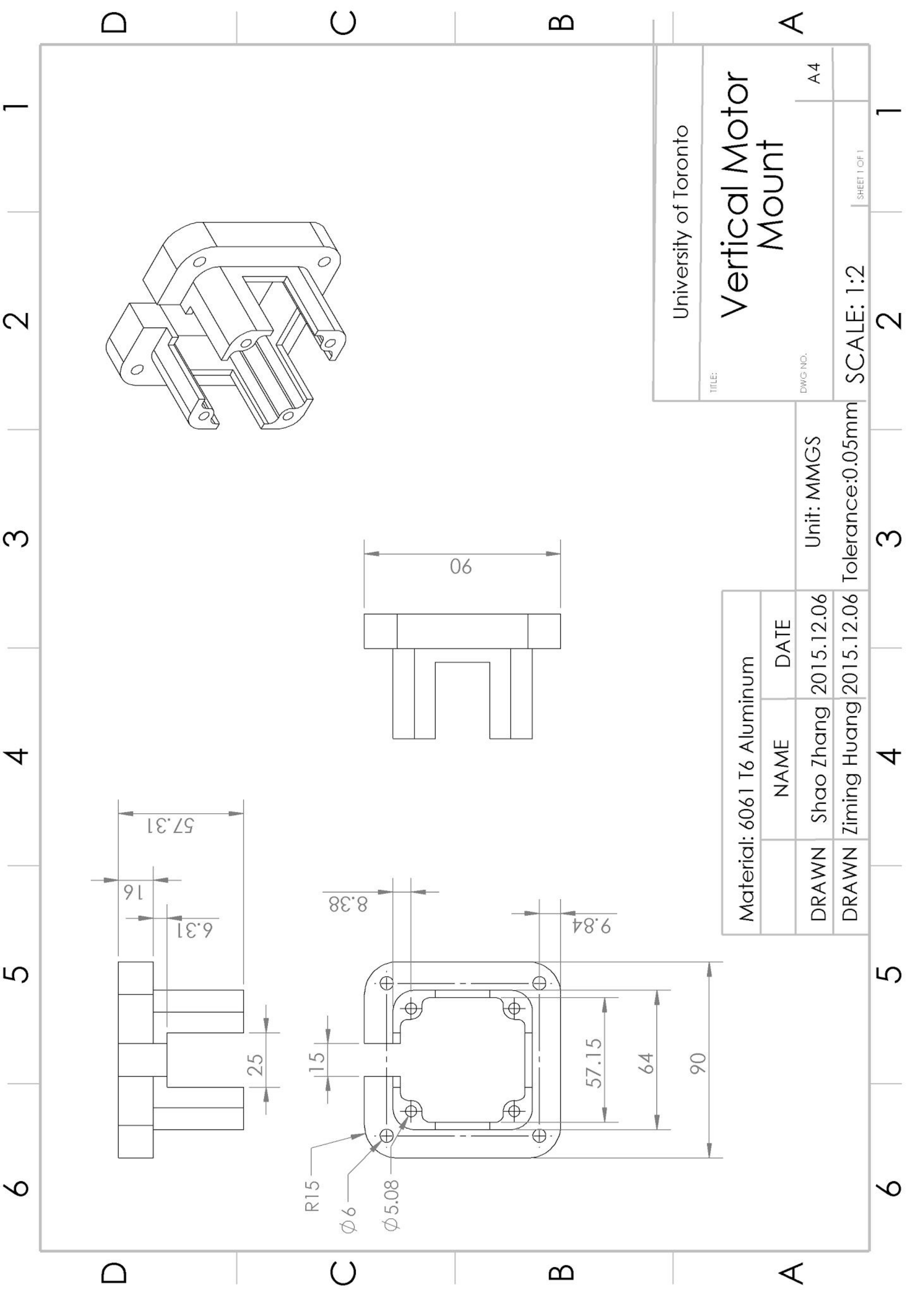
University of Toronto
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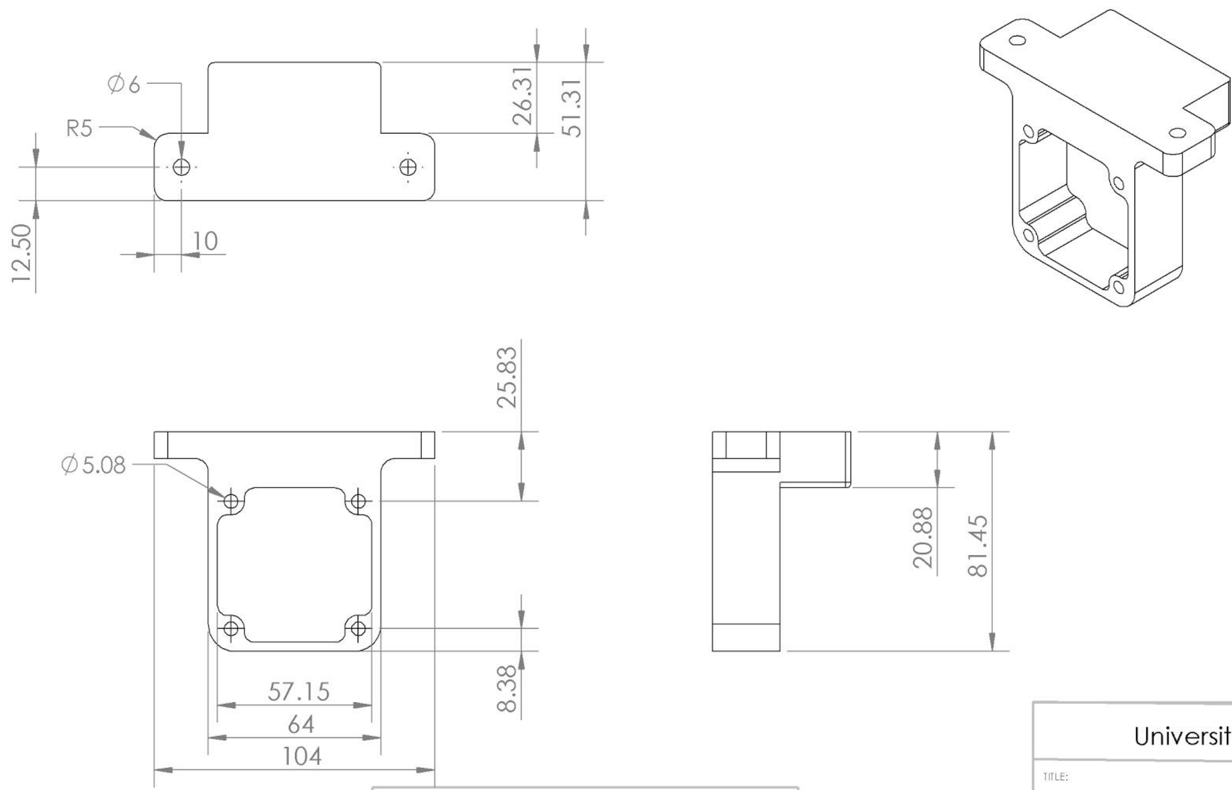

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DRAWN	Ziming Huang	2015.12.06

Unit: MMGS

Tolerance:0.05mm

University of Toronto

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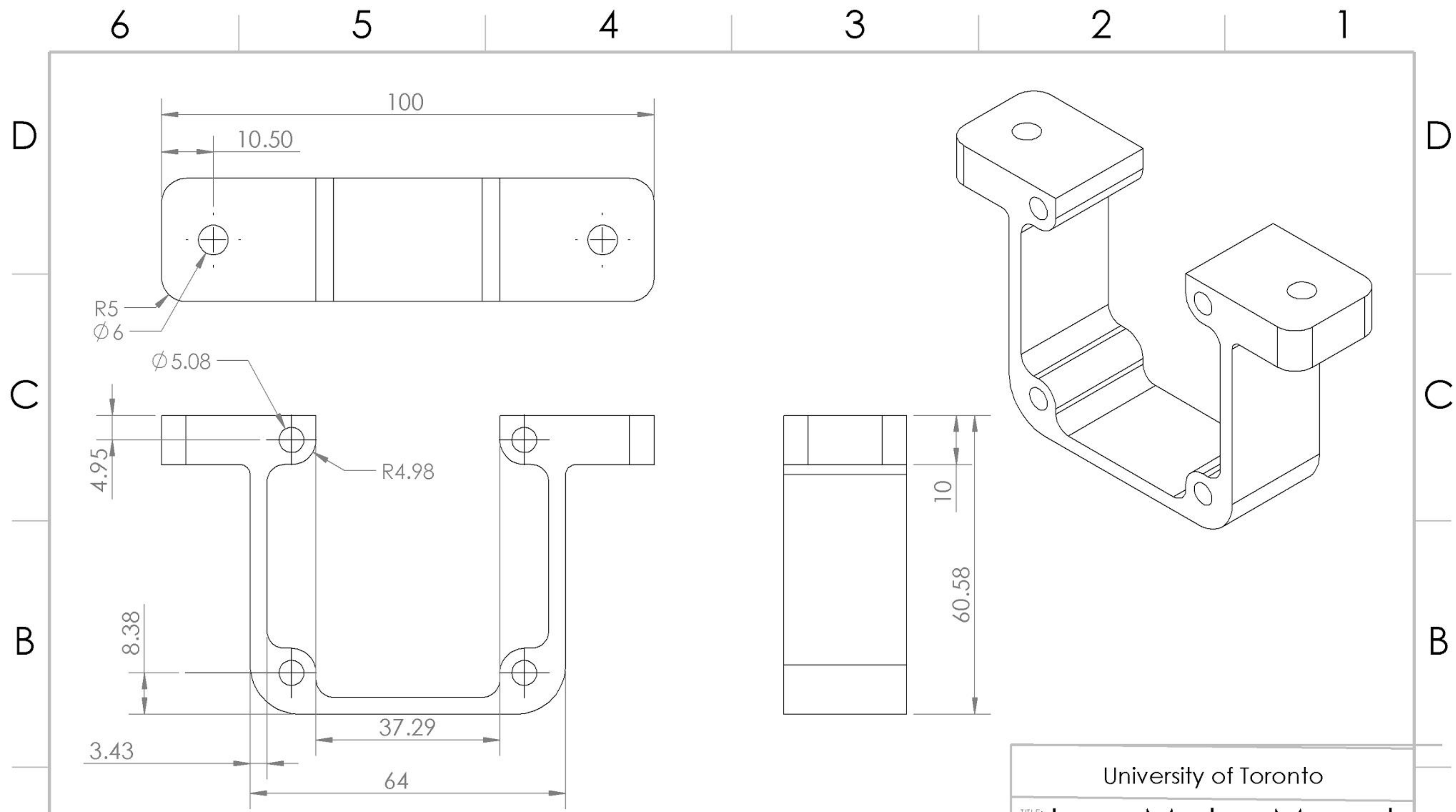

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DRAWN	Ziming Huang	2015.12.06

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University of Toronto

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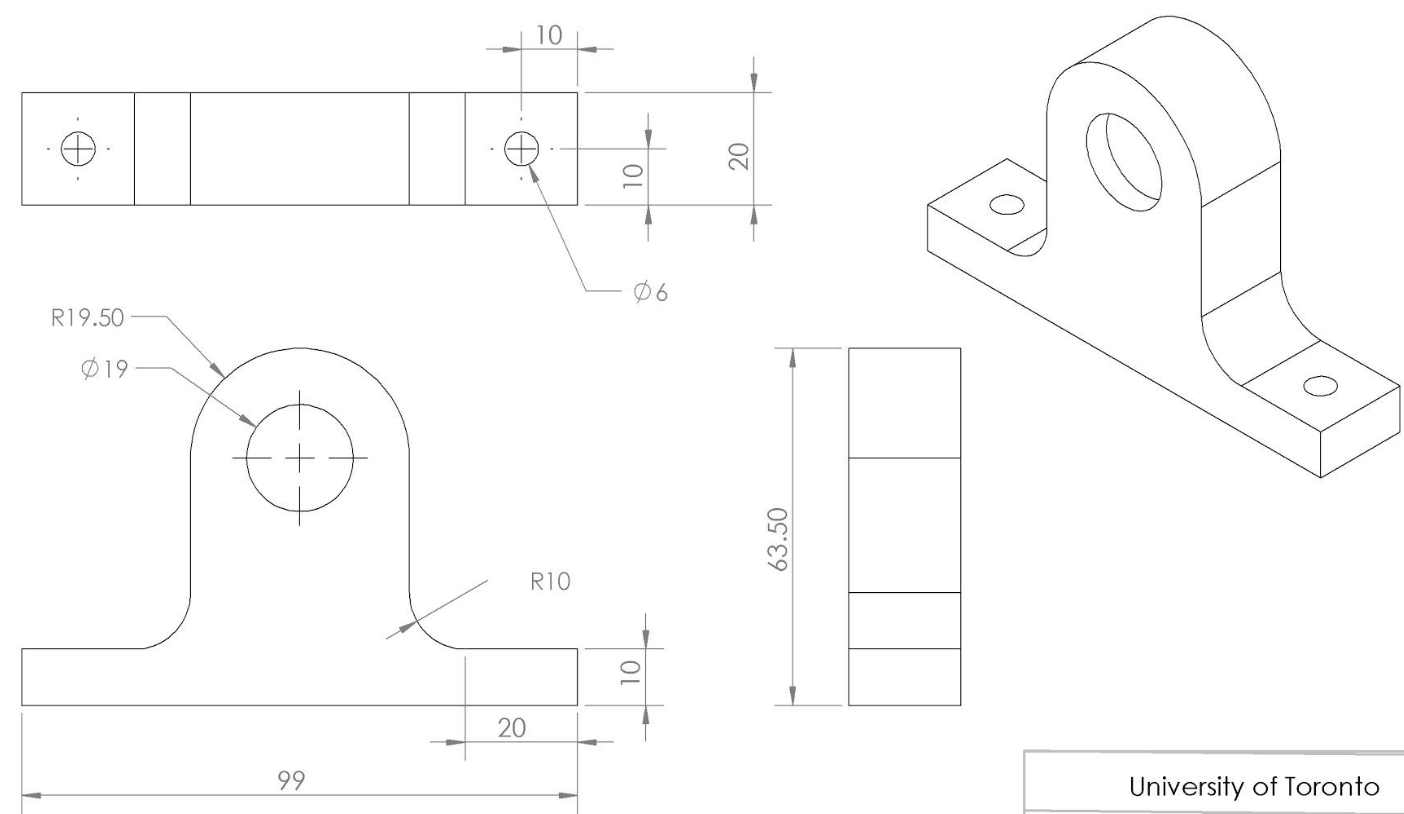

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University of Toronto

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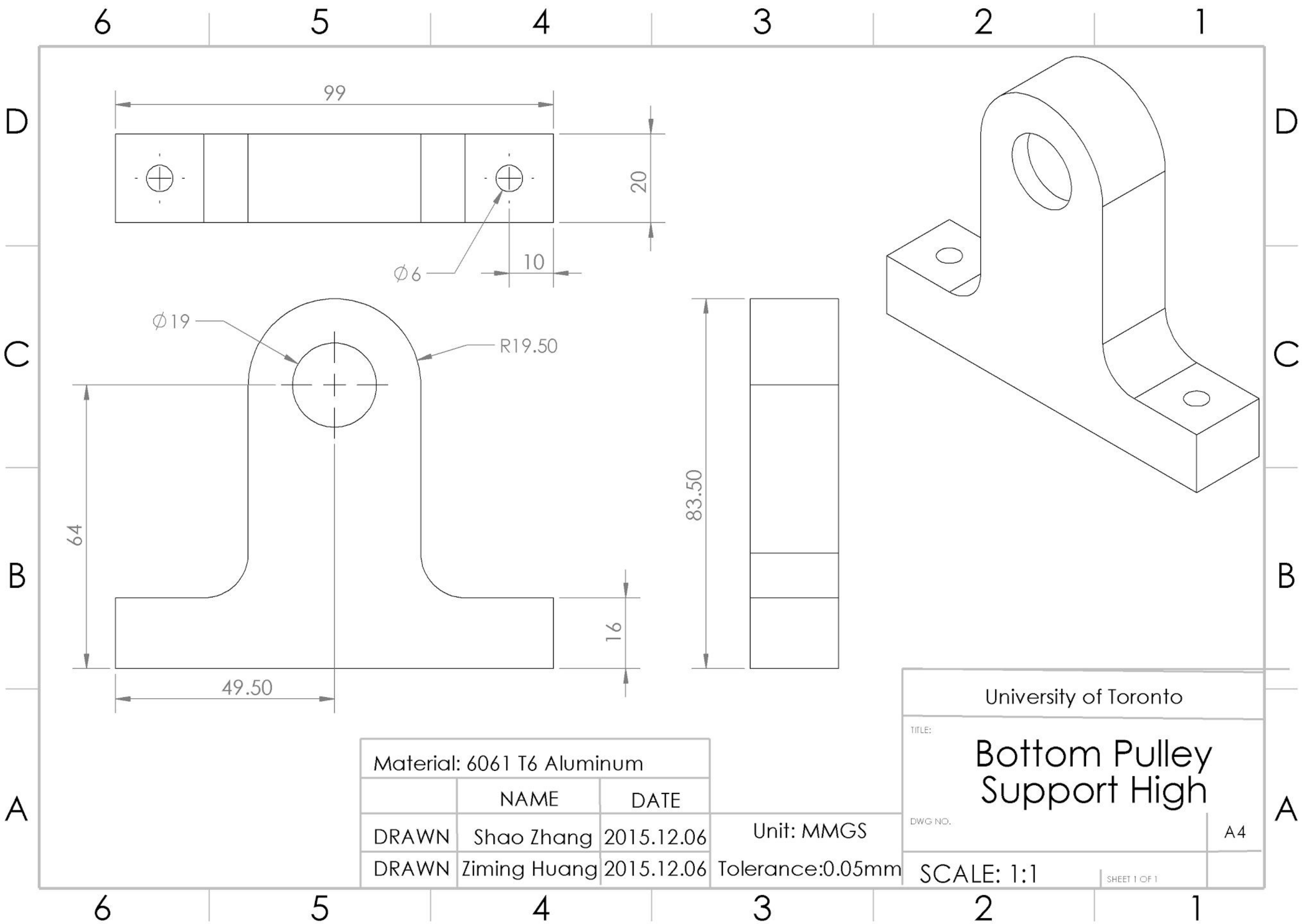
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2015.12.06
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Ziming Huang
2015.12.06
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University of Toronto
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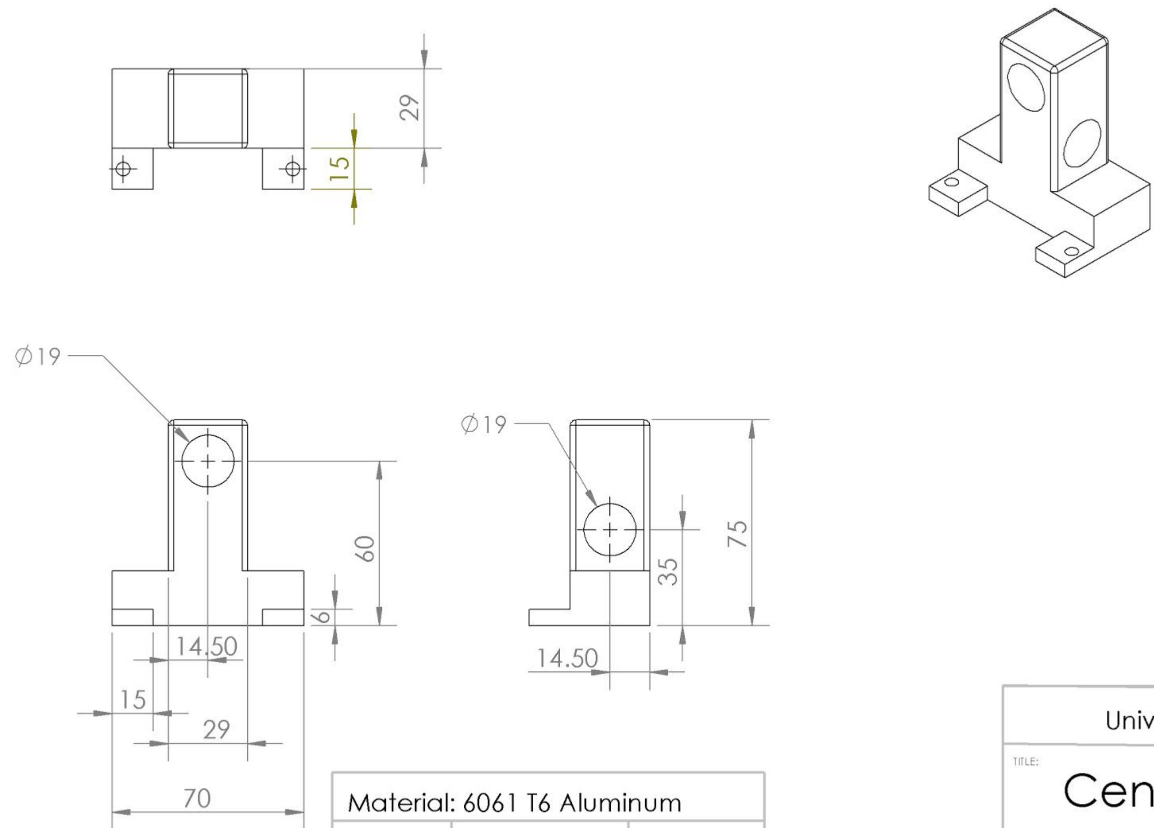

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University of Toronto

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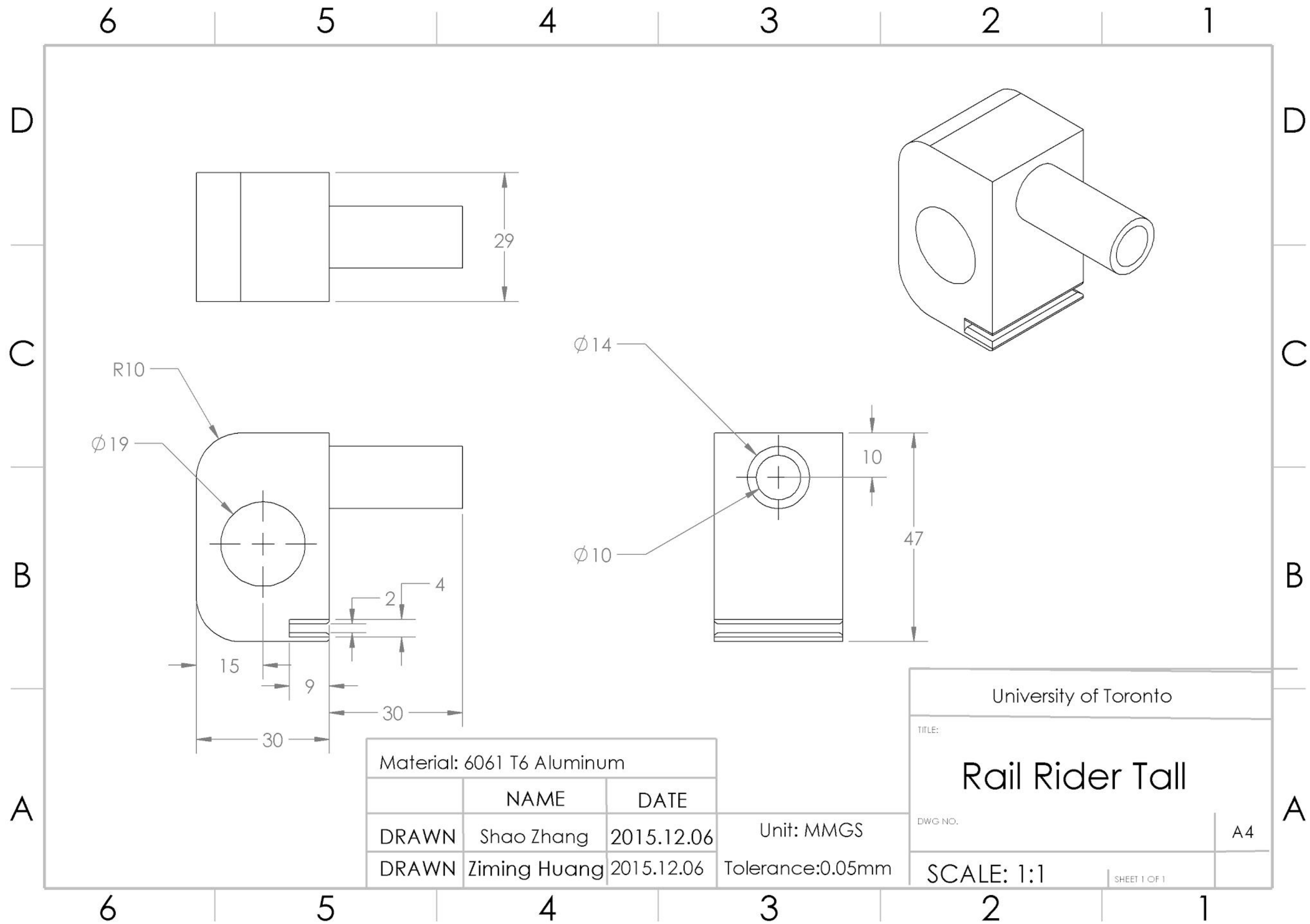
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2015.12.06
DRAWN
Ziming Huang
2015.12.06
Unit: MMGS
Tolerance:0.05mm
University of Toronto
TITLE:
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DWG NO.
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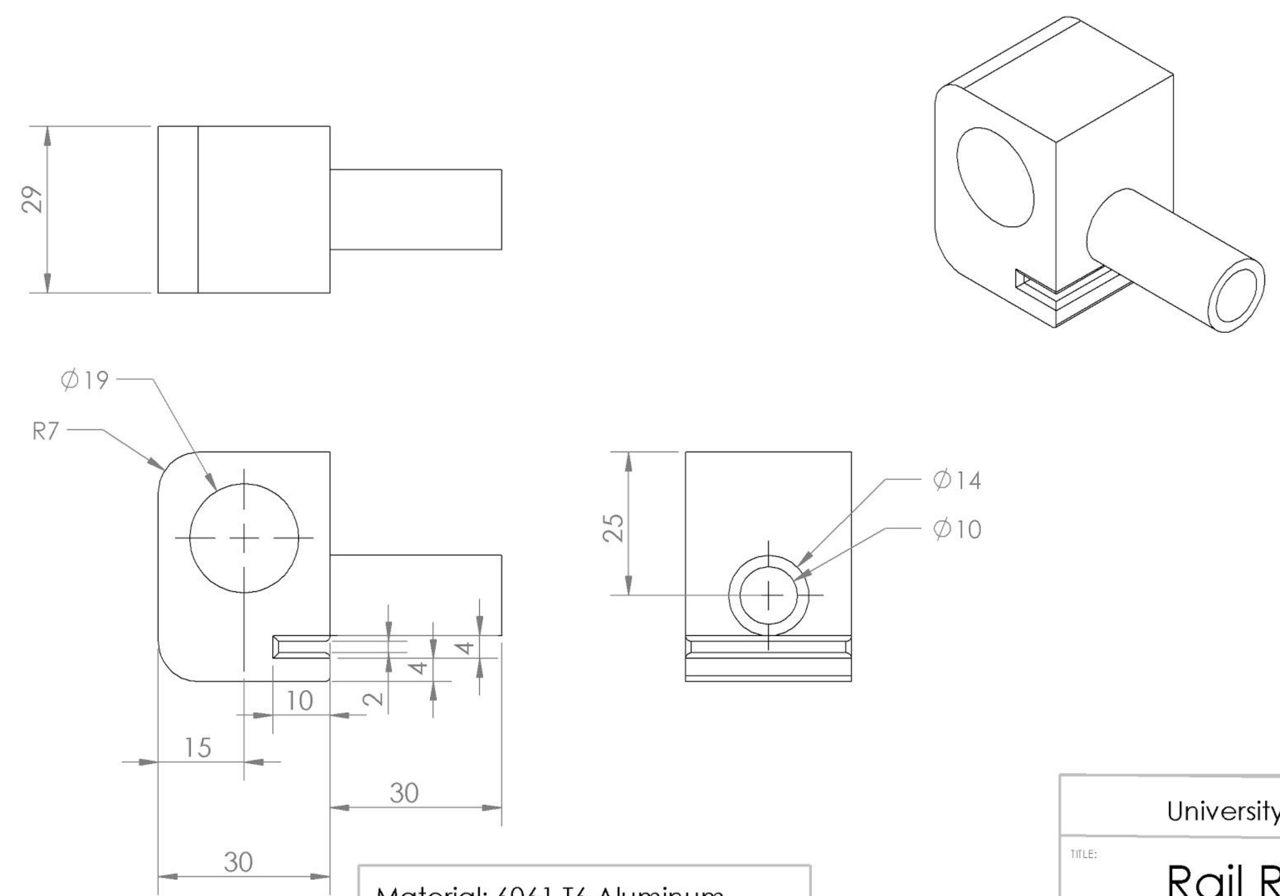
SHEET 1 OF 1



Material: 6061 T6 Aluminum		
	NAME	DATE
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DRAWN	Ziming Huang	2015.12.06

Unit: MMGS

Tolerance:0.05mm

University of Toronto

TITLE:

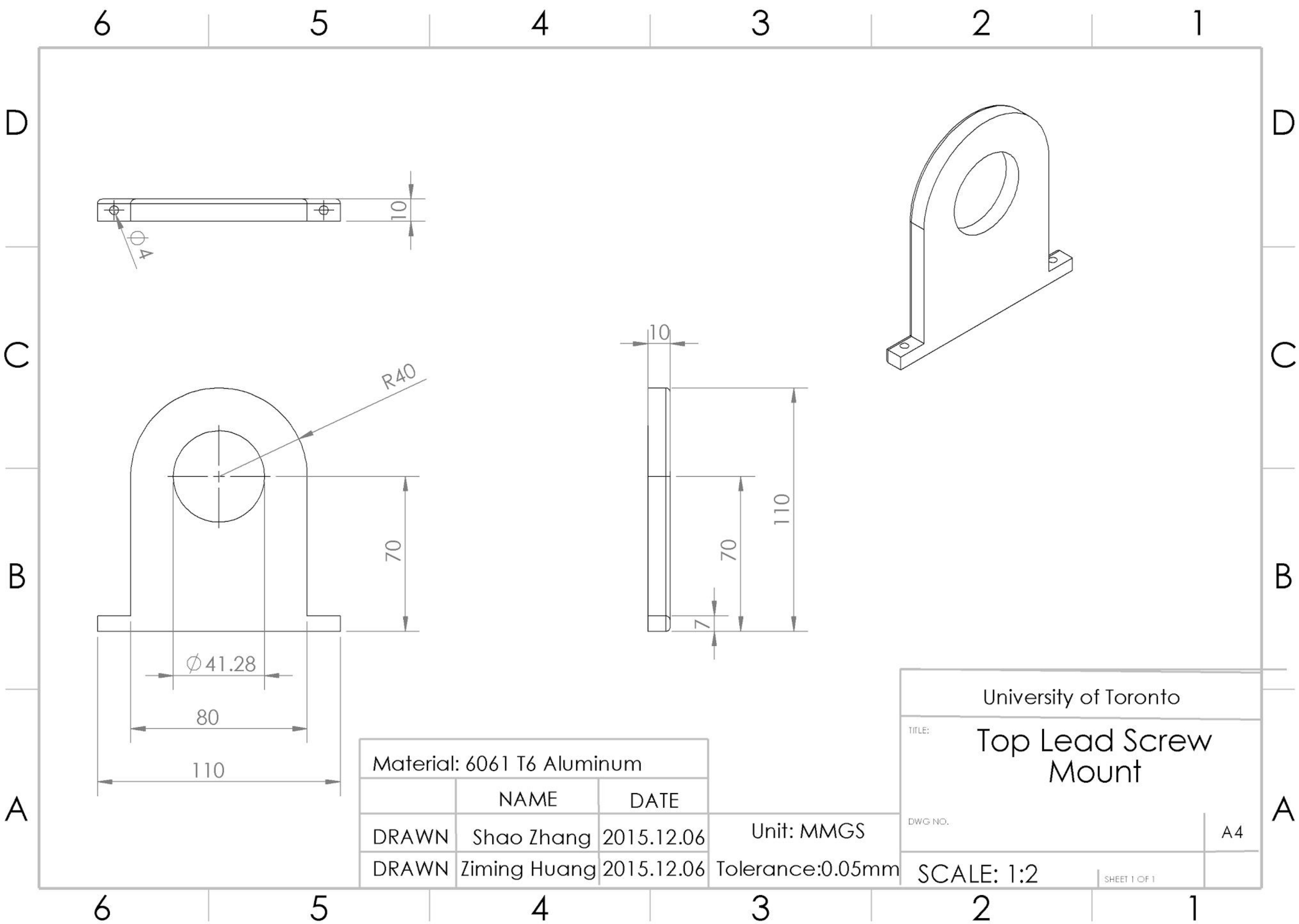
Rail Rider

DWG NO.

A4

SCALE: 1:1

SHEET 1 OF 1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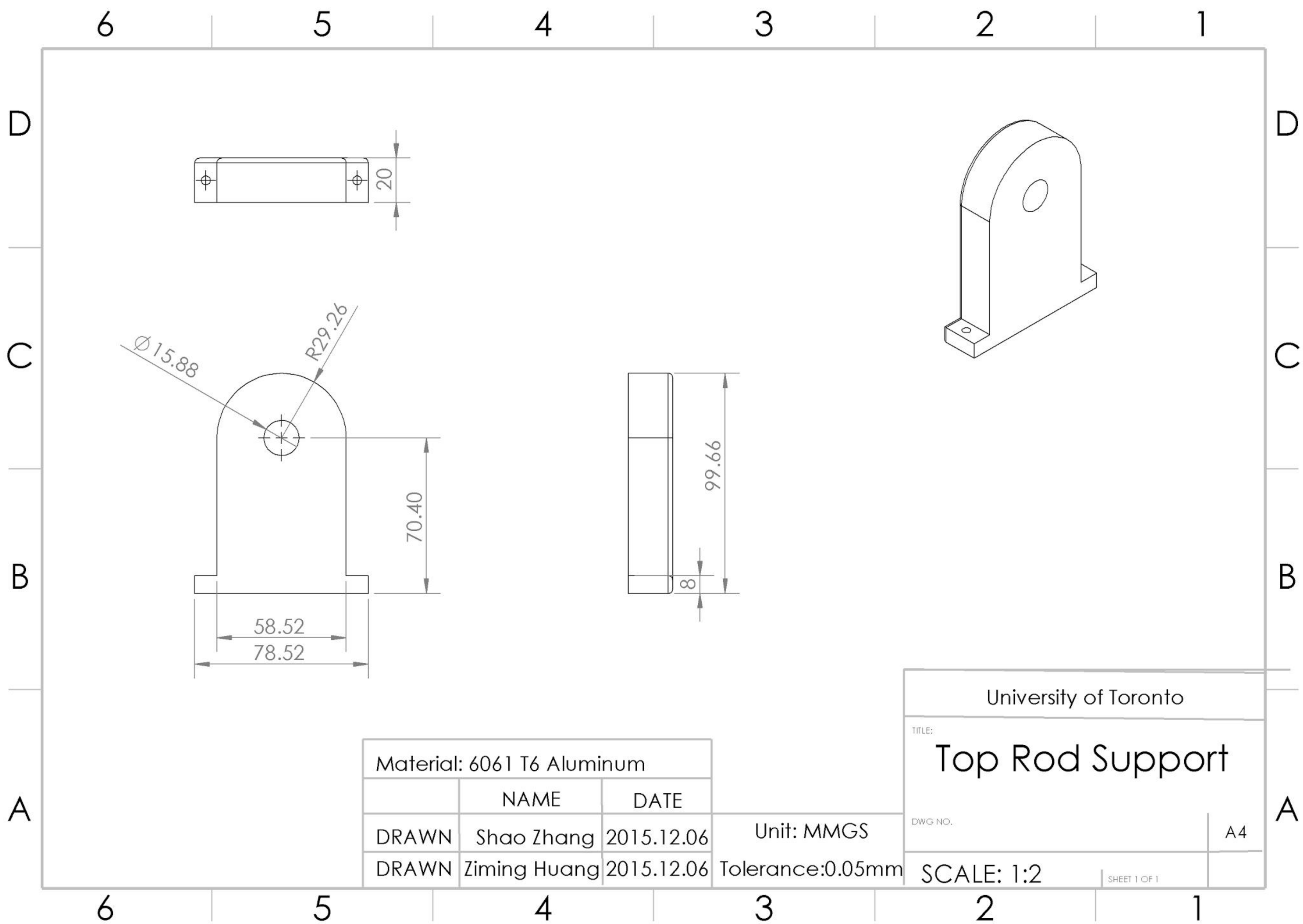
2015.12.06
DRAWN
Ziming Huang
2015.12.06
Unit: MMGS
Tolerance:0.05mm
University of Toronto
TITLE:
Top Lead Screw Mount
DWG NO.
A4
SCALE: 1:2
SHEET 1 OF 1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DRAWN Ziming Huang 2015.12.06
Unit: MMGS
Tolerance:0.05mm
University of Toronto
TITLE:
Top Rod Support
DWG NO.
A4
SCALE: 1:2
SHEET 1 OF 1

8.0 Appendices

Appendix A: different types of step motors

Table 5 Different types of step motors[59]

Types	Rotor	step angles(°)	Steps per revolution	Advantage	Disadvantage
Permanent Magnet (PM)	magnetic rotor	7.5-15	48-24	One of the most common type. Low cost	low resolution
Variable Reluctance (VR)	Non-magnetic, geared rotor				
Hybrid	Magnetic, geared rotor	3.6-0.9	100-400	Better speed, resolution than PM. One of the most common type	Higher cost than PM

Mechanism[59]:

<u>Variable Reluctance (VR):</u> This type of motor consists of a soft iron multi-toothed rotor and a wound stator. When the stator windings are energized with DC current the poles become magnetized. Rotation occurs when the rotor teeth are attracted to the energized stator poles.

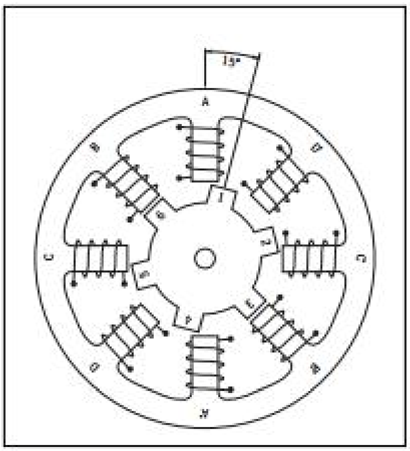

Figure 1. Cross-section of a variable-reluctance (VR) motor.

Permanent Magnet (PM):
Often referred to as a “tin can” or “canstock. Its name implies have permanent magnets added to the motor structure. The rotor no longer has teeth as with the VR motor. Instead the rotor is magnetized with alternating north and south poles situated in a straight line parallel to the rotor shaft. These magnetized rotor poles provide an increased magnetic flux intensity and because of this the PM motor exhibits improved torque characteristics when compared with the VR type.

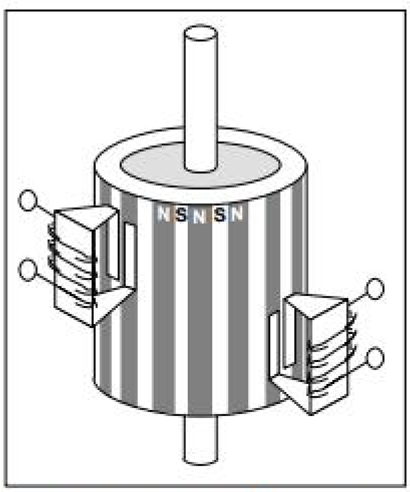

Figure 2. Principle of a PM or tin-can stepper motor.

Hybrid:
The hybrid stepper motor combines the best features of both the PM and VR type stepper motors. The rotor is multi-toothed like the VR motor and contains an axially magnetized concentric magnet around its shaft. The teeth on the rotor provide an even better path which helps guide the magnetic flux to preferred locations in the air gap. This further increases the detent, holding and dynamic torque characteristics of the motor when

compared with both the VR and PM types

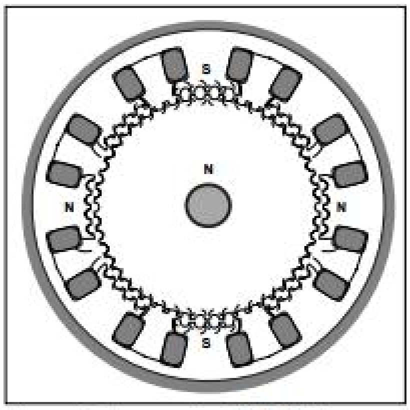

Figure 3. Cross-section of a hybrid stepper motor.

Table 6 2 and 5 phases motor[60]

	steps per rotation	increment per step	torque
2 phases	200	1.8	lose torque up to 40%
5 phases	500	0.72	increase torque by up to 10%

Table 7 Motor types[38]

Motor model	length(mm)	width(mm)	surface area (mm^2)	continuous operating torque	full step increment
NEMA 14	38-51	38	1444-1938	1.8-2	1.8
NEMA 17	51-70	44	2244-3080	7.5-8.8	1.8
NEMA 23	76-127	57	4332-7239	17-35	1.8
NEMA 34	102-165	89	9078-14685	22-70	1.8

Table 8 Subtypes with different rpm in NEMA 23[62]:

subtype of NEMA 23	Max rpm	length(mm)	width(mm)	continuous operating torque
	600	76	57	17
	900	127	57	35
	2250	102	57	23

Appendix B

Table 9 Comparison of metal alloys

Alloy Properties	Titanium Alloy[63]	Aluminium Alloy[64]				Magnesium[65]	Stainless Steel[66]
	Ti-6Al-4V	Per. Mold 356-F	Per. Mold 356-T6	Die Cast 380	6061-T6	AM60	304
Tensile Strength (MPA)	880	180	228	324	310	130	510
Density (KG/M^3)	4430	2766	2766	2713	2766	1800	7850
Young's Modulus (MPA*10^3)	113.8	NA	72.4	71	71	45	190

Why do we choose aluminium alloy[67]:

- Aluminium has one third density of steel or copper - lightest commercially available metals
- Aluminium has advantage over steel in cold environments - its tensile strength is inversely proportional to the trend of temperature change.
- Excellent resistance to corrosion - form a layer of aluminum oxide surface over aluminium when exposed to air.
- Thermal conductivity is three times greater than of steel - significant material for both cooling & heating environments.
- High electrical conductivity - one third weight of aluminium conduct twice as much electricity of same weight of copper does.
- Excellent light reflector - ideal insulating material

Table 10 Properties of selected aluminium alloys[68]

	Formability	Machining	Corrosion	Strength	Typical

	or Workability		Resistance		Applications
Alloy 1100	Excellent	Good	Excellent	Low	Metal Spinning
Alloy 2011	Good	Excellent	Poor	High	General Machining
Alloy 2024	Good	Fair	Poor	High	Aerospace Application
Alloy 3003	Excellent	Good	Good	Medium	Chemical Equipment
Alloy 5052	Good	Fair	Excellent	Medium	Marine Applications
Alloy 6061	Good	Good	Excellent	Medium	Structural Applications
Alloy 6063	Good	Fair	Good	Medium	Architectural Applications
Alloy 7075	Poor	Fair	Average	High	Aerospace Applications

Appendix C

Extruder:

- Classification of extruders
    - Single screw extruder

- Twin screw extruder
- Subtype 1 - Single screw extruder
    - Mechanism
        - The screw mixer melts the entering plastic materials and push melting plastic into extruder which forms their expected shape
        - Rely on friction between the material and barrel for flow
        - Material properties matters (Use different screw with respect to different fed materials)
    - Equipment
        - Hopper
            - feed material to the extruder
        - Screw
            - runs across the machine
        - Optional static mixers at the end
    - Advantages
        - Cheaper than twin screw extruder
        - Less shear
        - High thru put
        - Widely used, suitable for various materials
    - Disadvantages
        - Poor mix than twin screw extruder
        - Rely on physical properties
        - Temperature regulation needed
- Subtype 2 - Twin screw extruder
    - Mechanism
        - Same mechanism as single screw extruder but with two intermeshing screws
        - Rely on friction minimally
        - Rely on properties of extruders and screws instead of material properties
    - Equipment
        - Meshing characteristics
        - Type of rotation
    - Advantage
        - Good mix
        - Properties of screw matters not properties of material
        - No temperature regulation needed
    - Disadvantage
        - More expensive than single screw extruder

Table 11 Extruders Features

Classification of Extruders	Mechanism	Equipment	Advantages	Disadvantages

Single Screw Extruder	- Rely on friction between the material and the barrel for flow - Driven by the properties of the material. Use different screw to deal with different material being fed. - A screw mixer melts the entering plastic materials,push the melting plastic material through the extruder and form their expected shape.	- Hopper : feed material to the extruder - Screw : runs across the machine - Optional static mixers at the end	- Cheaper than twin screw extruder - Less shear than twin screw extruder - High thru put - Generally be used to various materials	- Poor mixing capability than twin screw extruders - Relies on physical properties to run the extruder - Need temperature regulation
Twin Screw Extruder	- Rely on friction minimally - Rely on properties of extruders and screws instead - Same mechanism but with two intermeshing screws	- Meshing characteristics - Type of rotation	- Good mixing capability - Properties of screw matters, not properties of material - No needed of temperature regulation [67]	- More expensive than single screw extruder[67]

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