McGill University Team

CSME National Design Competiton

adapt3D

Rotary Delta 3D Printer: Technical Report

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1 Introduction

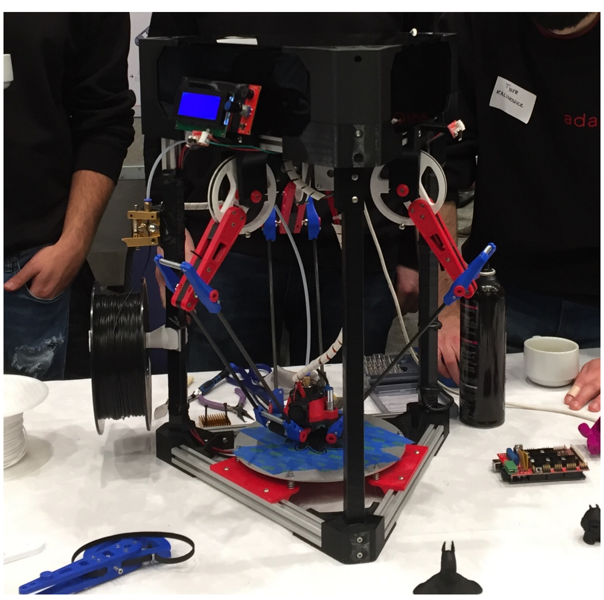
This report summarizes the design process for creating a 3D printer for the annual CSME National Design Competition. The project aims to propose a solution to the problem statement posed by the competition committee.

The chosen printer design is a rotary delta robot 3D printer. This printer features a frame made of a mix of aluminum extrusion beams and 3D printed parts. It is both reliable, produces dimensionally accurate parts, and is easy to use. The defining feature for this printer is its modular tool head. With this design, this printer becomes a machine that is capable of more than 3D printing alone (examples being CNC, lazer engraving, pick and place, scanning, etc...). Our printer is able to adapt to the users needs and do more, and therefore, we have named it the adapt3D.

The following report incorporates a detailed design plan and description, including prototyping and testing of both simulated and physical models. With all of these design considerations and features in place, we are confident that our final product will be rated highly for each evaluation criteria listed in the CSME competition problem statement. This design has successfully meet the competition requirements and remained under budget, making use of 3d printing facilities to keep material costs to a minimum, and using modified open source kinematic software. While linear delta 3D printers are readily available on the market, rotary delta 3D printers are not, making this a unique and competitive product (as described below).

2 Design Embodiment

Typical Delta 3D printers make use of three linearly actuating rails that control the motion of the printing hot-end. These linear rails move along a single axis and act together to create motion in 3D space. For our design, we decided to modify this popular design to make it more useful and innovative. Our design uses non-linear delta kinematics, featuring rotational inputs versus linear motion. Three pulleys, which are actuated by stepper motors via timing belts, attach to bicep arms and span 3D space in a different manner. Each pulley is outfitted with a 'bicep' arm joint, which extends outwards attaching to two carbon fibre rods via specially designed magnet joints. The carbon rods in turn actuate the end effector which moves along the print bed housing to create the desired printer motions.



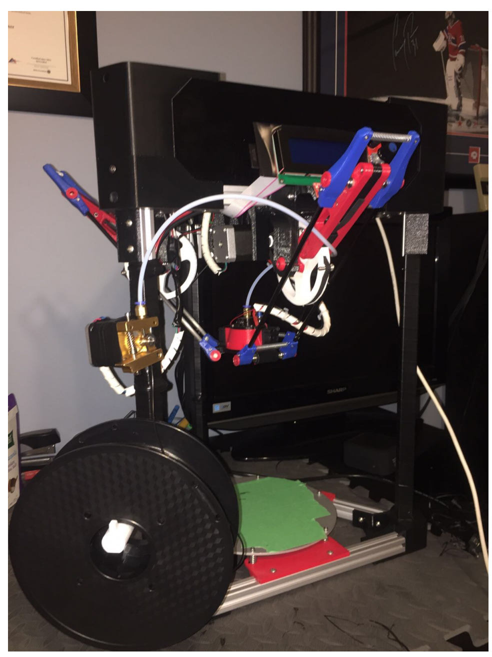


Figure 1: Final Design

The final design incorporates the following features:

- Rotary delta design with pulleys to increase arm movement accuracy via pulley reduction.
- High range of motion and anti-backlash neodymium magnet joints.
- Almost entirely 3D printed frame and components.
- Strong aluminum extrusions for rigidity.
- Heated bed for multi-material printing capabilities.
- Modular tool head design.
- 32-bit LPC 1768 controller board with 1/32 microstepping capabilities.

2.1 Structure

Unwanted vibrations due to timing belts, motors and other moving parts of a 3D printer can lead to negative effects on surface finish and quality of a printed part. The frame of a 3D printer therefore must be sturdy and be able to absorb and dampen these vibrations.

2.1.1 Frame

Drawing inspiration from delta printers on the market, 2020 profile aluminum extrusions serve as the rigid skeletal structure of the entire frame. These profiles offer the strength of aluminum to prevent movement when the printer is running. Using 3D printing to our full advantage, custom designed printed pieces connect the 2020 extrusions at each vertex where they meet. This eliminates the need to purchase metal brackets and allows for more customizable corner brackets (for both utility and style). Aluminum extrusions are also already widely used by the 3D printing community and allow for an open-ended design space where the consumer can modify and customize the printer.

2.1.2 Base

The base of the printer comprises of an equilateral triangle made of the 2020 extrusions and the 3D printed brackets. The bed of the printer rests on top of the extrusions via three printed bed mounts with a spring system to allow for more accurate and on the fly bed levelling during prints, a feature typically only seen on Cartesian printers. A CAD assembly of the base and heated bed is shown in Figure 2 below.

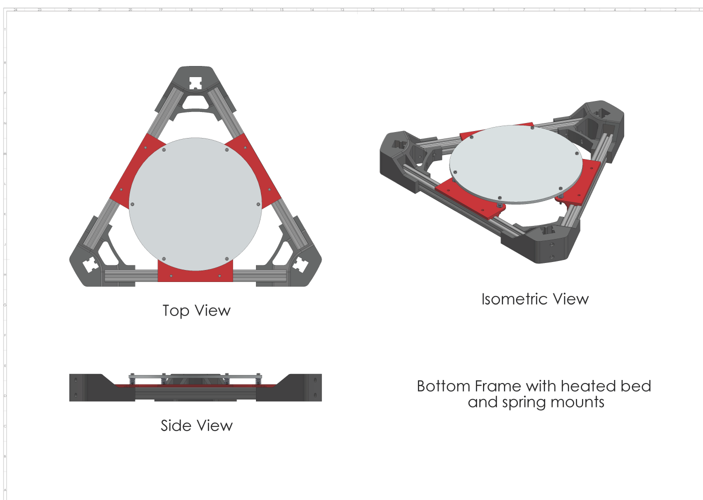


Figure 2: Base Assembly

2.1.3 Electronics Housing

The rotary delta design requires the motors to be housed on top of the printer. To reduce the amount of wires running along the sides of the printers' frame, the control board and power supply are housed in a frame made of 3D printed parts interlocked with laser cut plexiglass. With this configuration, the only wires that run along the frame are those for the heated bed. The top plexiglass piece of the electronics housing is easily removable for ease of access to the control board allowing for any troubleshooting to be done quickly and easily. The electronics housing is also able to support a mount for an optional LCD screen as seen in Figure 3.

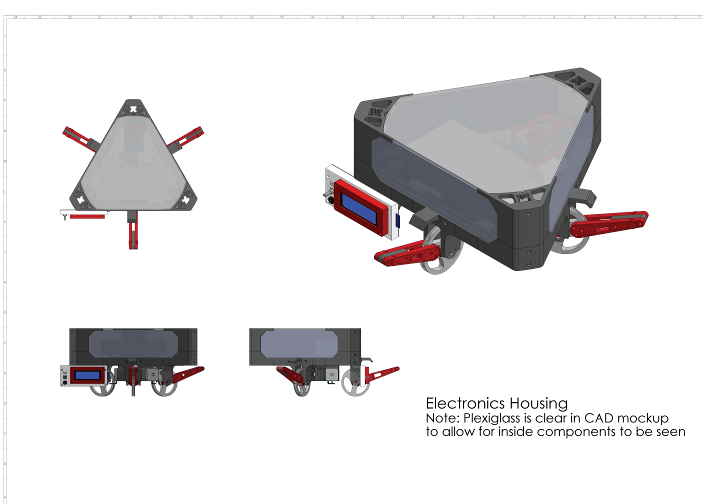


Figure 3: Electronics Housing Assembly With Optional LCD Screen

2.2 Dynamic Components

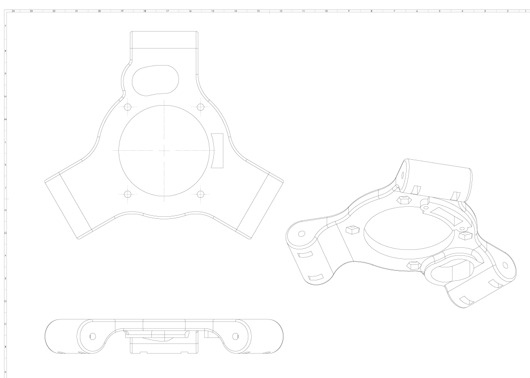
2.2.1 End Effector

The end effector (Figure 4.a) is the component that is actuated by the motors to move in the printing path. It holds the hot end and is designed to have easily replaceable tool heads. The latter is achieved by splitting the end effector into two detachable pieces: the hot end holder and end effector.

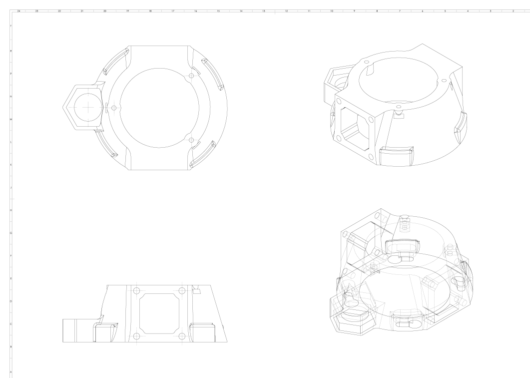
The hot end holder (Figure 4.b) has a twist-and-lock mechanism that uses socket cap screws and guiding holes to fix the two together. This twist-and-lock mechanism is a key feature of the design as it allows for different tool heads with the same mechanism to be swapped in and out with ease. For the 3D printing tool head, two fans are mounted to the hot end holder, one to directly cool the hotend heat sink and the other is for active cooling on the printed part. Active cooling is achieved by having a wall at the outlet of one of the fans, redirecting the air out through a hole at the bottom of the end effector which has a funnel to blow the air onto the printed part. Part cooling results in better surface finish, overhangs and bridging by rapidly cooling the plastic after being printed to minimize drooping.

The end effector is always connected to the actuating arms via magnetic ball joint connections. The magnets provide a strong connection between the effector and arms, allow for quick removal of the end effector.

The end effector parts are all 3D printed in PETG, a high temperature and high strength material. This is useful for heating the hot end above 200C, which would melt any low temperature plastic. By 3D printing the end effector, fabrication is kept in house and third party issues are completely avoided. Furthermore, designing of the parts can be achieved using CAD modeling, allowing for highly customizable designs.



(a) End Effector



(b) Hot End Holder

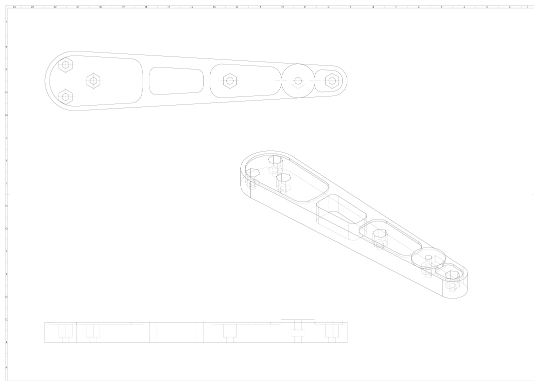
Figure 4: End Effector Components

2.2.2 Bicep Arms

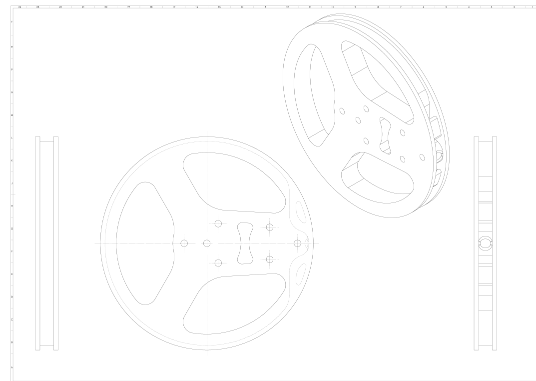
The kinematics of our rotary delta printer rely on the arm geometry. There are two arms that are used to actuate the end effector, the bicep and the forearm. For each bicep arm, there are two forearms connected via magnetic ball joints. Consider the connection of the two forearms to the bicep at the top and the end effector at the bottom; a parallelogram is formed with the top and bottom connections always parallel. As long as the top connection remains horizontal, so will the bottom. The use of the two forearms assures that the end effector remains horizontal.

The bicep is actuated by the motor with a GT2 timing belt. A 7.2:1 gear ratio between the motor and the arm pulley works in conjunction with a 4:1 gear reduction between the pulley and the bicep arm to increase the resolution of the printer. To maintain belt tension, the timing belts are threaded through the pulley wheel and are tightened at the other end locking mechanism. Two 608ZZ bearings are press-fitted to the sides of the pulley (one on each side) which allow for smooth rotation about the biceps pivot point. The bicep arm is made of two arm pieces that are fitted to either side of the pulley wheel. At its far end, a gap-filling piece is fitted between the two sides of the arm to ensure rigidity.

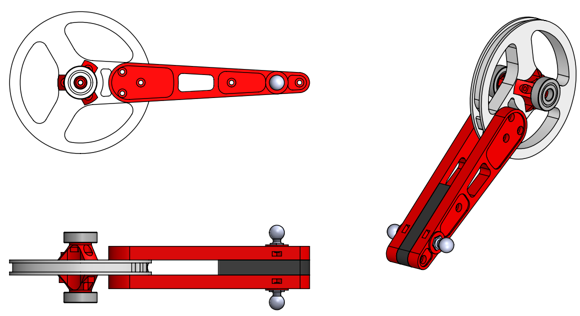
All of the bicep parts are 3D printed in PETG at a high infill percentage so that there is no deflection at the far end of the bicep. The main components of the bicep arm are shown in Figure 5 below.



(a) Arm Details



(b) Pulley Details



(c) Bicep Arm Assembly

Figure 5: Bicep Arm Features

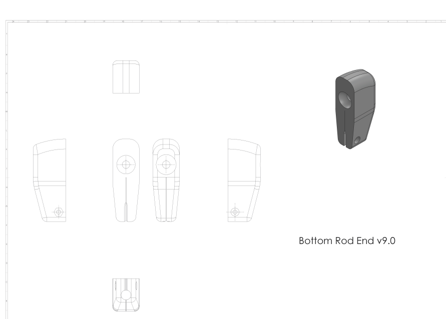
2.2.3 Forearm Joints

The forearms of the printer are roughly twice the length of the bicep actuators, and are required to be extremely rigid. 5mm diameter carbon fibre hollow rods are used in our design for increased rigidity in the forearms to reduce jerk in the end effector when accelerating and decelerating.

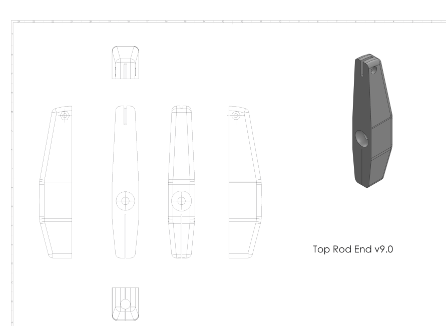
The forearms must be joined to the bicep arms and the end effector using high mobility joints. The two options for delta robot joints are the traditional and more common ball and socket joints, and the less common neodymium magnet ball joints.

Ball and socket rod ends are the typical go to for delta printers and offer a fairly large range of motion as well as a tight press-fit connection between the ball and socket. However, ball and socket joints are notorious for inducing backlash when printing at higher speeds, where the printer is most likely to undergo faster accelerations and decelerations. Magnetic ball joints help alleviate a lot of that backlash, while having a slightly bigger range of motion. That being said, magnetic ball joints are much harder to design around since a custom casing is required depending on the size of each magnet. The end effector must also be designed carefully as to not allow the magnets to get close enough to interfere with one another.

The final design (Figure 6) utilizes 10mm diameter by 15mm tall cylindrical neodymium magnets. The magnets sit inside of a 3D printed rod end which in turn connects to 5mm diameter carbon fibre rods. Each of the three delta arms has a pair of carbon rods connected by a spring to further reduce the chances of backlash and other vibrations in the rods.



(a) Bottom Rod End



(b) Top Rod End

Figure 6: Neodymium Magnet Rod Ends

2.3 Electronics and Circuitry

2.3.1 Power Supply

The power source has the task of supplying all electrical components with the current and voltage they require. The design features a 30 amp 12 volt DC power supply, more than enough to power all of the electronics.

2.3.2 Motors

To achieve three-dimensional movement, three stepper motors are required in different planes of motion each connected to a bicep arm. For high accuracy, our design incorporates 400 steps per revolution DC stepper motors, meaning for every step of the motor the shaft moves 0.9 degrees. These motors are rated for up to 2.4 amps.

A fourth motor is used to drive plastic filament through the extruder. For this purpose, a 200 steps per revolution DC stepper motor does the job just fine. This motor is rates for up to 1.7 amps.

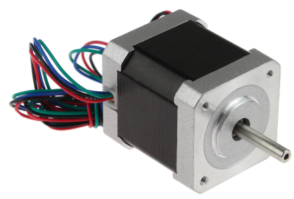


Figure 7: Stepper Motor

2.3.3 Hot End

An all metal E3D v6 hotend (Figure 8) is used to melt the incoming solid filament of plastic provided by the extruder into a viscous fluid, which is then pushed through the nozzle and re-solidified into the desired shape.

The hot end consists of 3 main components: the heat sink, the heating block and the nozzle. Since a phase change occurs in the hot end it is crucial that it's temperature be regulated, consistent and predictable. For this reason, a thermistor is placed inside the heating block and controlled with a PID control system built into the software of the printer. The heat sink is designed to dissipate heat from the not yet melted plastic filament, however a fan blowing on the is always needed to increase this cooling to a sufficient amount. The latter avoids clogging the nozzle from premature melting and re-solidifying filament.

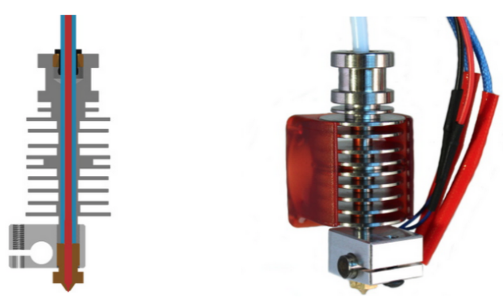


Figure 8: E3D v6 Hot End

2.3.4 Fans

Two 25mm brushless DC fans will are attached to the end effector. One of these fans provides cooling to the heat sink of the hot end and the other provides cooling for the nozzle. It is imperative that we keep our non-heating components cool in order to provide the most precise print possible.

2.3.5 Sensors

3D printers do not technically know exactly where the nozzle is in three dimensional space, they only know where they are in relation to the home position. The home position is where all three bicep arms are at their maximum angle of 40 degrees above the horizontal, it is at this angle that the nozzle is at it's maximum height from the print bed.

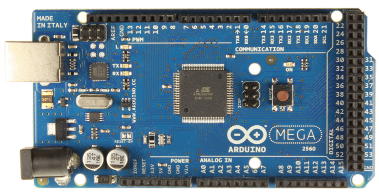
This calibration is realised by using a set of sensors called endstops. Endstops are simple switches which output either a 0 or 1, for untriggered and triggered. These sensors can be activated either by physical pushing a button or lever, or via a proximity sensor. Our design incorporates three mechanical endstops at the homing position angle and an induction proximity sensor in the end effector, allowing for automatic bed probing and leveling with the heated bed platform.

2.3.6 Heated Bed

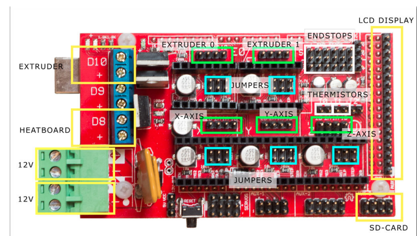
The inclusion of a heated aluminum bed to our 3D printer drastically improves the quality of the finished product. Heated beds allow for a more gradual cooling and setting of the plastics used in the printing process. This prevents warping of the initial layers. The heated bed also allows for printing with high temperature materials such as ABS or PETG. The heated bed has a thermistor which monitors and regulates temperature via a PID controller just like the hot end.

2.3.7 Control Board:

Most 3D printers on the market run on 8-bit processors such as the Arduino Mega 2560 (Figure 9a). These processors run alongside the Ramps 1.4 board (Figure 9b) which acts as an interface between the Arduino and each electrical component of the printer.



(a) Arduino Mega 2560



(b) Ramps 1.4 Board

Figure 9: Typical 3D Printer Controller Board Setup

After rigorous testing with the Arduino Mega and Ramps board. For a typical Cartesian 3D printer an Arduino and Ramps board would be more than enough to efficiently calculate movements and control each electronic component. However, since the movement algorithms for rotary deltas are constantly converting from polar coordinates to Cartesian, the processor needs to work much faster and harder. This strain on the processor caused stepper drivers to overheat, resulting in jagged print surfaces, lag when printing and limited us to 1/8 microstepping. Therefore we concluded to step away from the Arduino and Ramps boards and move to a 32-bit system with the MKS SBASE v1.3 control board.

This new control board (Figure 10) offers the same DRV8825 drivers with up to 1/32 microstepping, two extruder motor ports, multiple tool head ports, six endstop ports, an LCD screen port (supports full colour and touch screen modules), as well as Ethernet capabilities.

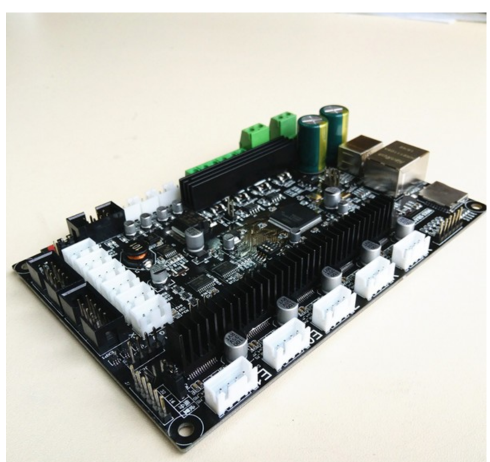


Figure 10: MKS SBASE v1.3 Control Board

2.4 Software

The MKS SBASE board runs on a software called Smoothieware. It is specifically built with 32-bit architecture systems in mind with a focus on multiple tool head machines. This falls perfectly into the design space of this project since it has the ability to have multiple tool heads with our quick-lock hot end system.

The Smoothiware software is extremely easy to configure and comes preloaded with sample configurations of different types of machines, including rotary deltas. However, rotary deltas are still very niche in the 3D printing market and support for this type of motion is very limited. This meant that although the smoothiware can handle the complex motion, lots of thought had to go into configuring the software correctly. For example, if some of the geometric values in the code that are used for workspace analysis are slightly off of their actual real world values, the motion of the robot will not be precise.

3 Fabrication

In order to demonstrate the versatility, convenience, and adaptability of 3D printing technology, our printer has been meticulously designed to be mostly 3D printed parts. For the few parts that could not be made using 3D printed parts, such as the aluminum profile frames, are all off the shelf and readily available. Therefore the printer requires no traditional machining whatsoever.

3.1 3D Printed Components

3D printing the majority of the printer components has allowed us to keep costs low while maintaining the functionality of a conventional 3D printer. The final parts have been printed out of PETG, a plastic material that has both strong thermal resistance and high strength properties.

To ensure the dimensional accuracy of the final prototype, all of the 3D printed components have toleranced according to the specific shrinkage factor of PETG. The added tolerance ensures a precise fit between component connections.

3D printing parts allows for design and testing without the need of conventional manufacturing tools, reducing the overall cost of production. This process allows for greater flexibility in the design process, allowing many iterations to be tested before selecting the final component design.

The main drawback to 3D printing is the time it takes to manufacture the components, the largest of which took upwards of 8 hours each to complete. Issues with part warping and print failure - due to malfunctions - also cause unwanted setbacks and waste valuable time. There is also one more inherent issue when using mostly 3D printed parts: tolerances differ from printer to printer. Errors such as this were minimized by tolerancing parts for the specific printer they were made on.

3.2 Off the Shelf Components

All fasteners, framing and bearing components were purchased off the shelf to ensure correct tolerances and stability, as well as make the manufacturing process much simpler. Metric fasteners and bearings are used throughout the design, ranging from M2 to M4 sizing. About 4.3 meters worth of 2020 profile aluminum extrusions are required for the printer, 3 pieces cut to 150mm, 6 to 300mm, and the remaining amount split evenly in 3 for the vertical frame.

Standardized components allow for the costs to be kept low without sacrificing dimensional accuracy. This is crucial for our design due to the precision needed in the structure (to obtain quality prints). The T-slot beams also allow for the wires to be safely and discretely run across the frame of the printer.

3.3 Electronic Components

The electronic components used in this build are standardized 3D printer components which can be sourced at local hobby shops or online via sites like Amazon or Aliexpress.

3.4 Laser Cut Components

Rounding out the design, laser cut plexiglass is used for the electronics housing. This gives the printer a sleek look as well as keeps all wiring localized in the top of the frame.

3.5 Assembly

Once the components are printed, the assembly of the design is straightforward. The aluminum beams slot into the frame joints and are secured with square locking nuts and M4 screws to create the outer frame. The motors are mounted into one circular piece in the center of the frame. Each bicep arm is mounted in plane with a motor on the edge of the top of the frame. A GT2 timing belt is then run from the gear on the motor to the pulley. The forearms are fit into their printed joints and magnets for the magnetic ball joints are glued with epoxy inside of their casings. After the end effector is outfitted with two 25mm fans as well as an induction sensor, it can be attached to the forearm ball joints.

On the base of the frame, the heated bed is secured via 6 screws with springs to allow for on the fly z leveling. An MK8 extruder assembly is mounted to the side of one of the aluminum extrusions along with a 3D printed spool mount.

4 Final Design Description and Performance

4.1 Final Components

The following is a list of each subsystem and it's components. A breakdown of individual costs can be seen in Figure 12 in the appensix.

4.1.1 Frame

- 2020 Profile Aluminum Extrusion Framing
- PETG Printed Joints and bed mounts
- Plexiglass Electronics Housing

4.1.2 Delta Components

- PETG Delta Arms, End Effector and Pulleys
- Carbon fibre Diagonal Rods
- Magnetic Ball Joints with 10x15mm Neodymium Magnets
- 608ZZ Bearings
- GT2 Timing Belts
- 1.25" Zinc Plated Wire Springs (0.25" OD)

4.1.3 Electronics

- MKS SBASE v1.3 Control Board
- 12V/30A (360W) Power Supply
- (3x) 400 steps/revolution NEMA 17 Motors
- (1x) 200 steps/revolution NEMA 17 Motors
- (2x) 25mm Cooling Fans (for the hot end)
- (1x) 35mm Cooling Fan (for cooling the circuit board)
- E3D V6 Hotend
- 200mm Diameter Circular Heated Bed
- (3x) Mechanical Endstop Sensors
- (1x) LJ12A3-4-Z/BX Inductive Proximity Sensor

4.2 Performance

In practice, the printer has a cylindrical print volume with a 100mm diameter and a maximum height of 130mm. This print volume is approximately 3 times the 70mm x 70mm x 70mm minimum volume outlined by the competition, exceeding our goal of doubling the necessary print volume. Testing shows that the dimensional accuracy of the prints is within 2 percent error of the reference .STL file. The printer can reach speeds of up to 60mm/s with ease as well as achieve layer heights as small as 100 microns.

The most noticeable improvement made from the original prototype to final product was the 32-bit circuit board. The amount of delta movement calculations being computed per second has been increased three fold, resulting in extremely smooth surface quality, smooth printing motion and very tight dimensional accuracy.

Figure 11: CSME Design Competition Test Piece with MKS SBASE Board

5 Conclusions and Recommendations

This report summarizes our progress to reach a final design for the CSME National Design Competition. We will be constructing a Delta 3D printer with the intention of bringing innovative features and a quality machine to the competition in May 2017. With the help of the McGill 3D Printing Team, it is our goal to compete as a top contender in the final competition.

Our final design is the accumulation of extensive research, industry experience, and innovative ideas which have produced an exciting and and unique 3D printer. Magnetic joints, carbon fibre rods, 3D 3D printed parts, high quality electronics, a heated base, and a simplified design will yield a printer that is capable of printing with very high quality, and at low cost.

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7 Appendix

Subsystem / Part	No. of Parts	Quoted Unit Price	Total Quoted Price
Frame/Structural Components			
2020 Aluminum Framing	4300	0.00$	15.91$
PETG for all 3D printed components	2.5	24.99$	62.48$
Plexiglass	1	15$	15$
Electronics			
Nema 17 Stepper Motor 1.8 degrees	1	7.96$	7.96$
Nema 17 Stepper Motor 0.9 degrees	3	12.46$	37.38$
Mechanical Enstop Sensors	3	0.40$	1.20$
Proximity Sensor (induction)	1	3.24$	3.24$
25mm Brushless DC Fan	2	1.64$	3.28$
35mm Burshless DC Fan	1	3.99$	3.99$
30A Power Supply	1	14.92$	14.92$
Heated Bed (200mm diameter)	1	12$	12$
E3D V6 Hotend	1	9.71$	9.71$
MKS SBASE v1.3 Control Board	1	61.42$	61.42$
MK8 Extruder Kit (without motor)	1	4.28$	4.28$
Mechanical Components			
608-ZZ Bearings	6	0.11$	0.66$
Zinc-Plated springs	12	0.17$	2.02$
Metallic Ball Joints	12	1$	12$
10mmx15mm Neodineum Magnets	12	2.00$	24.00$
5mm Diameter Carbon Rods	1500	0.003053333333	4.58
Various Screws and Nuts (M2, M3 and M4)		10$	10$
TOTAL			296.48$

Figure 12: Bill of Materials - Quoted Prices from Aliexpress