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## Hardware Article

# RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament

Aubrey L. Woern<sup>a</sup>, Joseph R. McCaslin<sup>b</sup>, Adam M. Pringle<sup>c</sup>, Joshua M. Pearce<sup>b,c,d,\*</sup>

<sup>a</sup> Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, USA

<sup>b</sup> Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI, USA

<sup>c</sup> Department of Materials Science & Engineering, Michigan Technological University, Houghton, MI, USA

<sup>d</sup> Department of Electronics and Nanoengineering, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland

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## ABSTRACT

In order to assist researchers explore the full potential of distributed recycling of post-consumer polymer waste, this article describes a recyclebot, which is a waste plastic extruder capable of making commercial quality 3-D printing filament. The device design takes advantage of both the open source hardware methodology and the paradigm developed by the open source self-replicating rapid prototyper (RepRap) 3-D printer community. Specifically, this paper describes the design, fabrication and operation of a RepRapable Recyclebot, which refers to the Recyclebot's ability to provide the filament needed to largely replicate the parts for the Recyclebot on any type of RepRap 3-D printer. The device costs less than \$700 in materials and can be fabricated in about 24 h. Filament is produced at 0.4 kg/h using 0.24 kWh/kg with a diameter  $\pm 4.6\%$ . Thus, filament can be manufactured from commercial pellets for <22% of commercial filament costs. In addition, it can fabricate recycled waste plastic into filament for 2.5 cents/kg, which is <1000X commercial filament costs. The system can fabricate filament from polymers with extrusion temperatures <250 °C and is thus capable of manufacturing custom filament over a wide range of thermopolymers and composites for material science studies of new materials and recyclability studies, as well as research on novel applications of fused filament based 3-D printing.

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\* Corresponding author at: Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI, USA.  
E-mail address: [pearce@mtu.edu](mailto:pearce@mtu.edu) (J.M. Pearce).

## Specifications table

Hardware name	<i>RepRapable Recyclebot</i>
Subject area	<ul style="list-style-type: none"> <li>• Engineering and Material Science</li> <li>• Educational Tools and Open Source Alternatives to Existing Infrastructure</li> <li>• Mechanical engineering and materials science</li> </ul>
Hardware type	GNU General Public License v. 3
Open Source License	\$671
Cost of Hardware	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Source File Repository	

## 1. Hardware in context

In 2015, world-wide plastic production was 322 million tons per year and is growing 3.86%/ year [1]. Both landfilling [2] and incineration [3] of plastic create well-established health and environmental issues [4,5]. Rather than follow a linear model of materials use, a circular economy model can be used to provide sustainability by separating economic growth from resource consumption [6,7]. Thus, recycling, is now established in the circular economy as the optimum treatment of post-consumer plastics [8]. Unfortunately, there can be significant environmental impacts from the collection and transportation of relatively low-density waste plastics to collection centers and reclamation facilities for separation and reconstruction in traditional recycling [9,10]. In addition, in developing regions (and even in some developed economies) the labor for this recycling is provided by waste pickers, which collect post-consumer plastic in landfills, among other places, far below poverty-level wages [11–14]. To reduce the embodied energy of transportation needed for centralized recycling [15], while at the same time potentially improving the financial situation of waste pickers a distributed recycling paradigm has been proposed [14–17].

One method of distributed plastic recycling is to upcycle plastic waste into 3-D printing filament with a recyclebot, which is an open source waste plastic extruder [18]. Previous research on the life cycle analysis (LCA) or the recyclebot process using post-consumer plastics instead of raw materials, showed a 90% decrease in the embodied energy of the filament from the mining, processing of natural resources and synthesizing compared to traditional manufacturing [19,20]. In addition, the recyclebot provides the potential for consumers to recycle plastic in their own homes to save money by offsetting purchased filament [19–21]. Recyclebots are also useful for laboratory and industry prototyping research as failed prototypes can be recycled into filament for future work. Many versions of recyclebots have been developed by both companies (e.g. Filastruder) as well as individuals (e.g. Lyman) [22] including open source versions from the Plastic Bank, Precious Plastic, and Perpetual Plastic. There are also several commercial versions of the recyclebot including the Filastruder, Filafab, Noztek, Filabot, EWE, Extrusionbot, Filamaker (also has shredder) and the Strooder, Felfil (OS), which all could potentially be used for waste plastic. Additionally, there are several examples of commercialized recycled filament (e.g. Filamentive, Fila-cycle and Refil). However, most filament research as well as production is still accomplished with large-scale extruders inappropriate for distributed recycling. These systems range from \$6000 to tens of thousands of dollars for manufacturing level extrusion lines that can produce a few kg/h.

The small extruders on the market as well as the freely posted designs suffer from one or more of the following deficiencies: 1) not open source (thus, do not provide adequate control and customizable features needed for laboratory work [23,24], 2) do not have adequate control (e.g. single speed), which is needed for non-uniform feedstocks of waste plastic, 3) are made from components that are not robust enough to handle contamination as well as composite waste, 4) demand machining experience and access to equipment often unavailable for DIY systems, 5) have high costs, 6) have slow extrusion rates, 7) have limited temperature ranges so cannot do some thermopolymers, 8) do not have a reliable form of process observation (e.g. filament diameter monitoring).

Although some polymers have been successfully recycled as single component thermoplastics such as PLA [25–28], HDPE [18,29,30], ABS [21,30,31], elastomers [32] as well as waste wood composites [33] and carbon fiber reinforced composites [34]. This early work, however, hardly begins to scratch the surface of the potential to use distributed methods to recycle a much longer list of polymers as well as composites made up of multiple distributed waste streams [35]. There is a tremendous potential to further improve the feed stocks as well as recycling 3-D printed parts themselves [36].

To assist researchers meet this potential, a recyclebot designed for fused filament-based 3-D printer filament research is described here that takes advantage of both the open source hardware methodology [37,38] and the paradigm developed by the open source self-replicating rapid prototyper (RepRap) 3-D printer community [39–41]. Specifically, this paper describes the design, fabrication and operation of a RepRapable Recyclebot – an open source 3-D printable waste plastic extruder, which can provide the filament to largely replicate the machine that produces it.

## 2. Hardware description

The RepRapable Recyclebot is an open source [42] compact form of a single screw thermopolymer extrusion system found all over the world in many plastic manufacturing facilities. It is a horizontal built extruder with a 5/8" screw. The design includes an interchangeable hopper, heating zone, channel for cooling, a puller, and a spooler with traversing mechanism. Also included is a light sensor [43], designed by Mulier, for accurately measuring filament diameter. The design is intended to maximize 3-D printable parts that can be fabricated from filament the RepRapable Recyclebot produces. The RepRapable Recyclebot also uses open source electronics. It is controlled by a single LCD screen and knob just like commercial open source RepRap-based 3-D printers (e.g. the Lulzbot Taz). Also, just like many of the types of RepRap 3-D printers, the RepRapable Recyclebot is controlled with a Ramps 1.4 Arduino Shield. The machine can be built for less than \$700 in material costs in roughly 24 h.

The desktop-size low up-front cost RepRapable Recyclebot not only can be largely fabricated from its own output on any form of RepRap-based 3-D printer, but also differs from other open source (or proprietary) 3-D printer polymer extruders on the market because of attributes including: i) all parts are easily sourced from local hardware stores or online, no specialty or machined parts are necessary, ii) adjustable hopper size and shape with emptying feature, iii) aluminum cooling path provides more even cooling than passive or forced-air only methods, which also guides the filament into the puller reducing bad extrusions and providing operators with better control over filament made with sub-optimal feed stocks, iv) adjustable traverse for different spool sizes and v) modular design allows for ease in upgrading (e.g. water bath cooling, pelletizer, or injection molding add-on). These attributes make it ideal as a research system for those investigating novel filaments. This design offers the researcher far more control than most other systems as it is modular and could be turned into many different devices or augmented more easily than others to fit specific needs of the researchers in the lab (e.g. adding higher rated heaters to extrude engineering grade plastics). Such modifications or upgrades are relatively easy on this system, whereas particularly for proprietary system making modifications can be challenging or impossible.

The RepRapable Recyclebot

- enables manufacturing of custom filament in the laboratory for material science studies of new materials and recyclability studies, as well as research on novel applications of fused filament based 3-D printing
- reduces costs of 3-D printing supplies to approximately 2.5 cents per kg if waste plastic is used
- allows for easy and inexpensive repair, reconfiguration and upgrading of the system
- provides a method of distributed recycling (upcycling) in the lab, business, home or by professional waste pickers for profit.

## 3. Design files

### Design Files Summary

Design file name	File type	Open source license	Location of the file
12v DC Motor Mount.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Base Bearing Mount.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Belt for Puller.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Belt for Spooler.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Cart.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Catch Bin.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Control Panel Back.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Control Panel Bottom.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Control Panel Face.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Control Panel Front.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Control Panel Mounting Brackets.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Control Panel Sides.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Coupler V2.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
DC Small Belt Pulley.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Fan Mount.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Feet Bolt Mount for Board.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Filament Roller Half 1.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Filament Roller Half 2.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Filament Sensor Cap.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Filament Sensor.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>

(continued on next page)

Design Files Summary (*continued*)

Design file name	File type	Open source license	Location of the file
Front Bearing Tower.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Guide Blocks.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Guide Wood Mount.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Hopper Cover Screw Cap.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Hopper Empty Hole Cover.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Hopper Insulation Flat.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Hopper Legs.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Hopper Trough.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Large Belt Pulley.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
LCD Knob.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Light Sensor Legs.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Light Sensor Single Leg.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Motor Shaft to Extrusion.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
NinjaflexFeetforBoard.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Power Supply Cap.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Power Supply Cover.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Rod End Brackets.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Slider.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Spooler Hubs.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Switch Mount.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Template for Motor Bracket.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Top Bearing Mount V2.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Trough Holders Bottom.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Trough Holders Top.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Winder Cross Beam.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Winder DC Bearing Tower.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
Wire Loom Mounts.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>
12v DC Motor Mount.ipt	CAD	GNU GPL v3.	<a href="https://osf.io/9hsmb/">https://osf.io/9hsmb/</a>

The use of each of the design files is best determined by the descriptions and rendering shown in Section 5. The STL files generated by the design files are listed in the BOM for 3-D printable parts below. All electronic files are available at <https://osf.io/9hsmb/> and includes a STL model glossary for part identification.

#### 4. Bill of materials

It should be noted that a mixture of metric and Imperial units is used here. Metric units are used whenever possible and all STL files are in mm, however, for all of the standard parts purchased from U.S. hardware stores the original measurement units used are given using inch (") units.

File names for the STL, 3-D printable parts start with the assembly they are a part of and the number of prints needed is at the end of the file name. The costs for Table 2 are derived from filament costs of \$0.025/g for PLA and \$0.086/g for NinjaFlex, these 3-D printing materials can be purchased from most 3-D printer supplies vendors. It should be noted this is the commercial cost of polymer filament. If recycled plastic made from the RepRapable Recyclebot is used the costs drop to \$0.025/kg (or 1000 times less than commercial polymer filaments). Parts were printed with the following settings shown in Table 3.

#### 5. Build instructions

##### 5.1. Breakdown instructions and tips for assembly

1. 3-D print all parts listed in Table 2 with the appropriate material on a fused filament fabrication (FFF) based 3-D printer that can do both hard plastic and elastomers such as a RepRap or Lulzbot Taz 6 with FlexyStruder head. The printer settings that are listed are required to give the parts sufficient strength and durability for extended use on the Recyclebot. Fabricators should be sure that all parts have good layer adhesion after they are done printing. This means that there should be no malformed or missing layers visible to the human eye as summarized in [44] for determining if parts intended for mechanical loading are of acceptable quality. The vast majority of the parts for this system do not undergo significant mechanical stresses. Any parts that appear insufficiently strong should be reprinted before assembly.

**Table 1**

Tools and their uses required for assembly. Note to makers, all of these tools are commonly found in makerspaces or garages and the more expensive tools such as the angle grinder can be eliminated with more simple hand tools such as a hacksaw and pliers.

Tool	Use
1. Soldering Iron and Solder,	for electronics and inserting heat-set nuts
2. Electric Drill,	for drilling holes and screwing into wood
3. Angle grinder or Dremel,	for cutting off bolts and threaded rod
4. Vice or Vice Grips,	for pressing in bearings
4. Knife,	for cutting Kapton tape, insulation
5. Hammer,	for motivating bolts into place
6. Wire Strippers,	for 12 awg to 31 awg wire
7. 8 mm Socket or Wrench	for 5 mm nuts
8. 5/32" Drill Bit,	for drilling out 4 mm holes in plastic
9. 1/8" Drill Bit,	for drilling out 3 mm holes in plastic
10. 5/64" Drill Bit,	for drilling out 1.98 mm Nozzle (for 1.75 mm filament)
11. 13/64" Drill Bit,	for drilling out 5 mm holes in wood, plastic
12. Metric Allen Key Set,	for tightening just about every bolt
13. Tape Measure,	for laying out board position
14. Straight edge, speed square,	for laying out board position
15. Pencil,	for laying out board position
16. Flush Cutter,	for cutting wire, heat shrink and zip ties, part cleanup
17. Lighter or Torch	for heat shrink tubing
18. Safety Glasses	for safety

2. Purchase tools listed in [Table 1](#) and all components in [Tables 4 and 5](#).
3. Place parts into piles associated with the particular assembly following tips for assembly
4. "Machine" the parts that need it, which involves either drilling or angle grinding.
5. Assemble each sub-part assembly
6. Screw onto wood
7. Wire
8. Program
9. Turn on and tune
10. Make filament
11. Share your results with the academic and RepRap communities

Follow these steps for a successful build of a RepRapable Recyclebot. The build instructions are broken into modules where you build each assembly separately and then mount it to the board.

## 5.2. Tips for general assembly

### 5.2.1. Tip #1 Heat set inserts

Using a soldering iron turned to 343 °C (650°F), press heat inserts into the plastic when told to do so in the instructions in the next section. It helps to use the side of the soldering iron. Do not insert the tip inside of the heat insert, it will get too hot, and the heat insert will come out when the iron is removed. Sometimes the inner hole may need to be drilled out with a small drill bit to clean out the plastic that melted into the hole. A properly placed heat insert is shown in [Fig. 1](#) flush mounted in the 3-D printed part.

### 5.2.2. Tip #2 bearing insert

Use a vice or vice grips to press fit bearings into plastic parts as shown in [Fig. 2](#).

### 5.2.3. Tip #3 thumb screw

Use a vice and an 8 mm socket to push a thumb wheel onto a bolt to convert it into a thumbscrew for easy disassembly (see [Fig. 3](#)).

### 5.2.4. Tip #4 layout parts

Find every part needed for each individual assembly and organize them into groups as shown in [Fig. 4](#).

## 5.3. Mechanical assembly

Starting with the extrusion assembly, this is where the pellets are turned into filament. It consists of a hopper, barrel, auger and nozzle. The board will first be laid out to find where the motor brackets will be screwed down, then the rest of

**Table 2**  
3-D printable components.

Component	Number	Cost per unit – USD	Total cost – USD	Material type
Board_Feet (Ninjaflex)_x4.stl	4	\$ 0.26	\$ 1.04	Ninjaflex
Board_Feet Screw Mount_x4.stl	4	\$ 0.08	\$ 0.30	PLA
Control_Panel_Back_x1.stl	1	\$ 1.78	\$ 1.78	PLA
Control_Panel_Bottom_x1.stl	1	\$ 1.58	\$ 1.58	PLA
Control_Panel_Front_x1.stl	1	\$ 2.00	\$ 2.00	PLA
Control_Panel_LCD Knob_x1.stl	1	\$ 0.13	\$ 0.13	PLA
Control_Panel_Mounting Brackets_x2.stl	2	\$ 0.28	\$ 0.55	PLA
Control_Panel_Side_x2.stl	2	\$ 0.98	\$ 1.95	PLA
Control_Panel_Top_x1.stl	1	\$ 1.33	\$ 1.33	PLA
Cooling_Aluminum Trough Fan Mount_x4.stl	4	\$ 0.35	\$ 1.40	PLA
Cooling_Aluminum Trough Holders Bottom_x2.stl	2	\$ 0.08	\$ 0.15	PLA
Cooling_Aluminum Trough Holders Top_x2.stl	2	\$ 0.08	\$ 0.15	PLA
Diameter_Sensor_Body_x1.stl	1	\$ 0.58	\$ 0.58	PLA
Diameter_Sensor_Cap_x1.stl	1	\$ 0.05	\$ 0.05	PLA
Diameter_Sensor_Legs_x1.stl	1	\$ 0.15	\$ 0.15	PLA
Diameter_Sensor_Single Leg_x1.stl	1	\$ 0.13	\$ 0.13	PLA
Extrusion_Auger Coupler_x1.stl	1	\$ 0.43	\$ 0.43	PLA
Extrusion_Hopper Catch Bin_x1.stl	1	\$ 1.18	\$ 1.18	PLA
Extrusion_Hopper Feet_x1.stl	1	\$ 0.63	\$ 0.63	PLA
Extrusion_Hopper Hole Cover_x2.stl	2	\$ 0.05	\$ 0.10	PLA
Extrusion_Hopper Insulation_x1.stl	1	\$ 0.58	\$ 0.58	PLA
Extrusion_Hopper Screw Cap_x1.stl	1	\$ 0.55	\$ 0.55	PLA
Extrusion_Hopper Trough_x1.stl	1	\$ 0.95	\$ 0.95	PLA
Extrusion_Motor Template_x2.stl	2	\$ 0.38	\$ 0.75	PLA
MISC_M3 Thumb Screw Conversion_x12.stl	12	\$ 0.03	\$ 0.30	PLA
Power_Supply_Cover_x1.stl	1	\$ 0.68	\$ 0.68	PLA
Power_Supply_Mount_x1.stl	1	\$ 1.40	\$ 1.40	PLA
Puller&Spooler_Belts_x1	1	\$ 1.21	\$ 1.21	Ninjaflex
Puller&Spooler_Large Belt Pulley_x2.stl	2	\$ 0.48	\$ 0.95	PLA
Puller&Spooler_Small Belt Pulley_x2.stl	2	\$ 0.15	\$ 0.30	PLA
Puller_Base_x1.stl	1	\$ 0.60	\$ 0.60	PLA
Puller_DC Motor Mount_x1.stl	1	\$ 0.18	\$ 0.18	PLA
Puller_Top Bearing Holder_x2.stl	2	\$ 0.15	\$ 0.30	PLA
Roller_Half 1_x2.stl	2	\$ 0.28	\$ 0.55	PLA
Roller_Half 2_x2.stl	2	\$ 0.28	\$ 0.55	PLA
Roller_Wood Mount_x1.stl	1	\$ 0.20	\$ 0.20	PLA
Spooler_Back Bearing Tower_x1.stl	1	\$ 0.95	\$ 0.95	PLA
Spooler_Cross Beam_x2.stl	2	\$ 0.10	\$ 0.20	PLA
Spooler_Front Bearing Tower_x1.stl	1	\$ 0.83	\$ 0.83	PLA
Spooler_Hub_x2.stl	2	\$ 0.65	\$ 1.30	PLA
Traverse_Coupler Half_x2.stl	2	\$ 0.08	\$ 0.15	PLA
Traverse_Motor and Bearing Mount_x2.stl	2	\$ 0.48	\$ 0.95	PLA
Traverse_Slider Guide_x2.stl	2	\$ 0.03	\$ 0.05	PLA
Traverse_Slider_x1.stl	1	\$ 0.23	\$ 0.23	PLA
Traverse_Switch Housing_x1.stl	1	\$ 0.28	\$ 0.28	PLA
Traverse_Threaded Rod Cart_x1.stl	1	\$ 0.35	\$ 0.35	PLA
Wiring_Loom Mounts_x14.stl	14	\$ 0.03	\$ 0.35	PLA

**Table 3**  
3-D printer settings for 3-D printed parts.

Description	Setting
Layer Height	0.2 mm
Infill Density	20%
Wall Thickness	1.0 mm
Support Material	No Support Needed for All Parts

the extruder will be placed on top of those. First, the feet should be screwed to the bottom of the board, and then leveled to provide a nice flat surface that will not slide around while working.

### 5.3.1. Extrusion assembly

The extrusion assembly shown in Fig. 5 is broken into the following parts:

- I. Feet
- II. Motor Brackets

**Table 4a**

Mechanical Parts. A detailed list of materials, cost and links are included in the spreadsheet called Final Mechanical BOM [42].

Part	Description	Qty	Unit Cost (US\$)	Total Cost (US\$)
Wood (Frame)	2"X8"X4'	1	\$5.00	\$5.00
Extrusion Screw	5/8" OD X 17" Ship Auger (Dewalt brand)	1	\$18.56	\$18.56
Barrel	1/2 NPT Nipple (6" Length) (Seamless) Threaded both ends	1	\$19.29	\$19.29
Motor Mount/Barrel Mount	3339_0 – Stepper Mounting Bracket (NEMA 23)	2	\$4.00	\$8.00
Nozzle	1/2 NPT Cap High Pressure	1	\$2.55	\$2.55
Heat Sink/Barrel Mount	1/2 in. Galvanized Malleable Iron Floor Flange	1	\$2.74	\$2.74
Barrel Insulation	1" Thick, 7/8" Insulation ID, 3' Length High Temp Insulation	1	\$10.44	\$10.44
Kapton Tape	36 yds Length x 1/2" Width Polyimide Tape	1	\$7.42	\$7.42
Aluminum Cooling Trough	1"X1", 90 deg. .125" thick, 1 ft length	1	\$2.59	\$2.59
Caster Bearings 10 pack	3/8" ID X 7/8" X 9/32" OD Caster Bearings	1	\$17.15	\$17.15
35A Urethane Drive Rollers	35A Abrasion-Resistant Drive Rollers for shaft dia 3/8"	2	\$22.78	\$45.56
Compression Spring	1" Long, fits M5 bolt, Spring Box of 12	1	\$7.26	\$7.26
Threaded Rod	3/8"-16 X 3' OD (Yellow)	1	\$3.15	\$3.15
Smooth Rod	3/8" OD X 36" (Yellow)	1	\$1.38	\$1.38
3/8"-16 Regular Hex Nut	Box of 100	1	\$4.58	\$4.58
M3 Hex Nut	Box of 100	1	\$0.88	\$0.88
M4 Hex Nut	Box of 100	1	\$1.32	\$1.32
M5 Hex Nut Regular	Box of 100	1	\$1.76	\$1.76
M5 Washer	Box of 100	1	\$2.19	\$2.19
M2 Nuts	Box of 100	1	\$1.08	\$1.08
M3 Heat Inserts	Box of 100	1	\$12.30	\$12.30
M2 X 10 Screw	Box of 100	1	\$11.00	\$11.00
M3 X 10 Screw	Box of 100	1	\$5.43	\$5.43
M3 X 16 Screw	Box of 100	1	\$8.44	\$8.44
M4 X 25 Screw	Box of 25	1	\$2.83	\$2.83
M5 X12 Screw	Box of 25	1	\$4.33	\$4.33
M5 X 25 Screw	Box of 25	1	\$5.90	\$5.90
M5 X 65 Screw	Box of 25	1	\$7.96	\$7.96
#6X1" Screw	Box of 100	1	\$5.60	\$5.60
Rubber Bands	Bag of Misc Sizes	1	\$4.24	\$4.24
Recycled 2 Liter Bottle (Hopper)	Bottom Cut off	1	\$0.00	\$0.00
PLA Filament	1 kg Spool PLA	2	\$22.99	\$45.98
<b>Total</b>				<b>\$276.91</b>

**Table 4b**

Electrical parts. A detailed list of materials, cost and links are included in the spreadsheet called Recyclebot Electrical BOM [42].

Part	Description	Qty	Unit Cost (US\$)	Total Cost (US\$)
Power Supply	12VDC 12.5A Power Supply	1	18.96	18.96
Arduino Mega 2560		1	13.99	13.99
Ramps 1.4 – pre-soldered		1	9.58	9.58
LCD Screen	LCD 20x4 + extras – white on blue	1	14.99	14.99
Clickable Rotary Encoder	Flatted shaft push switch Rotary Encoder	1	2.00	2.00
50 mm CPU Fan		4	6.99	27.96
Auger Motor	NEMA 23 stepper motor with 15:1 gearbox	1	55.65	55.65
12 V DC Motor	50 RPM Output at Gearbox	3	14.99	44.97
Speed Controller	PWM Adjustable and Reversible	3	8.87	26.61
20' Heater Coil	Nichrome 60 Wire (5') 8 Ohm/ft <b>NOTE: Specify that you need continuous length</b>	4	3.50	14.00
Heat Controller	Comes with Thermocouple and Relay Needed	1	31.99	31.99
Female-Female Jumper Wires	40 X 6"	1	3.95	3.95
Filament Diameter Sensor	Mulier Light Sensor	1	57.00	57.00
AC Power Cable	6' 3 prong extension cord	1	6.00	6.00
Emergency Stop Switch	Press to cut power	1	10.69	10.69
Switch	SPDT 3P Rocker Switch	2	6.26	12.52
Wire Split-Loom Tubing	20 ft Coil	1	5.95	5.95
Cable Ties	150 Piece Black 8" Cable Tie Pack	1	9.49	9.49
Heat Shrink Tubing	Misc Pack	1	7.99	7.99
Wire	Hookup wire box	1	17.09	17.09
Traverse Switch	DPDT Slider Switch (R13-602B)	1	2.74	2.74
			Total	394.12



**Fig. 1.** Properly placed heat insert.



**Fig. 2.** The use of a vice or vice grips to press fit bearings into 3-D printed plastic parts.

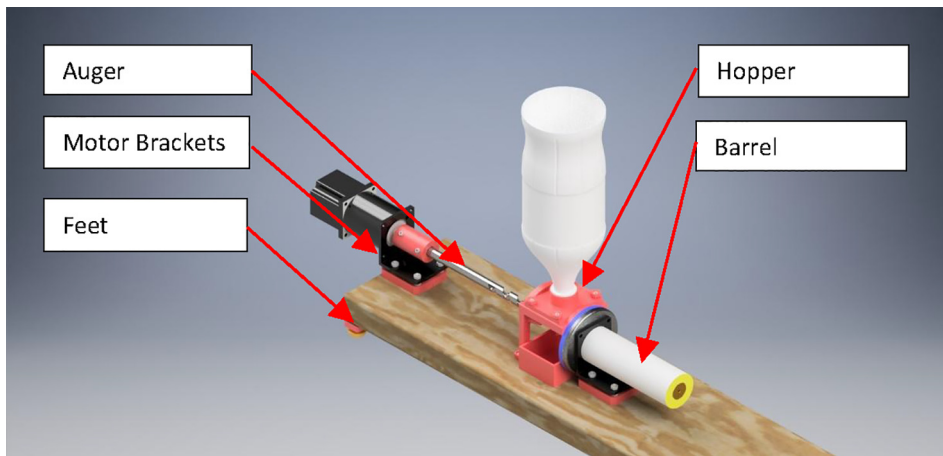
- III. Barrel
- IV. Hopper
- V. Auger
- I. Feet

The feet were designed in order to maintain an elevated height of the wood plank over the surrounding base. Ninjaflex was chosen as the material due to its higher degree of friction resulting in a “rubbery” texture allowing a safe and non-slip contact surface.

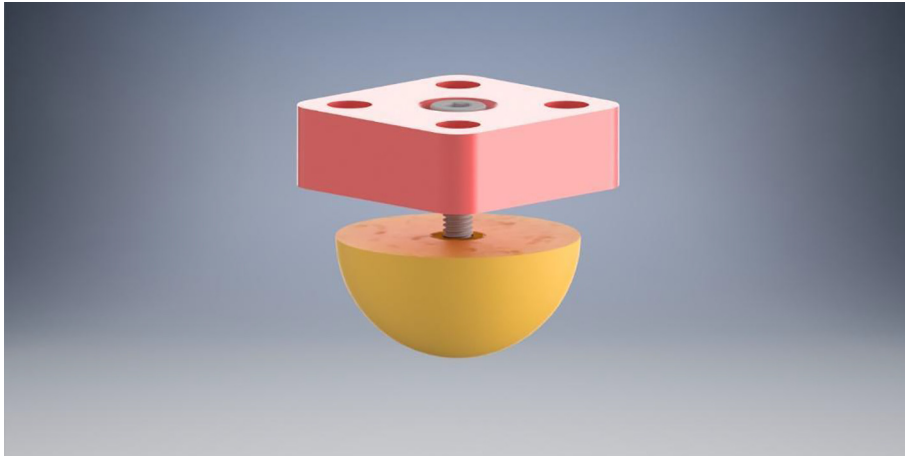
1. Parts required:
  - i. (4) M3X16mm Screw
  - ii. (4) M3 Heat Insert
  - iii. (8) #6 X 1 Wood Screw
  - iv. Board\_Feet (Ninjaflex)\_x4.stl
  - v. Board\_Feet Screw Mount\_x4.stl (see [Fig. 6](#))
2. Insert Heat inserts into Ninjaflex feet following Tip #1 above (see [Fig. 7](#)).







**Fig. 5.** Main components of Extrusion Assembly.



**Fig. 6.** Feet on extrusion assembly.



**Fig. 7.** Heat inserts into NinjaFlex Feet.

### 1. Parts Required

- i. (8) M5X65 Screws
- ii. (16) M5 Nuts
- iii. (8) M5 Washers
- iv. Motor Mount/Barrel Mount
- v. Extrusion\_Motor Template\_x2.stl

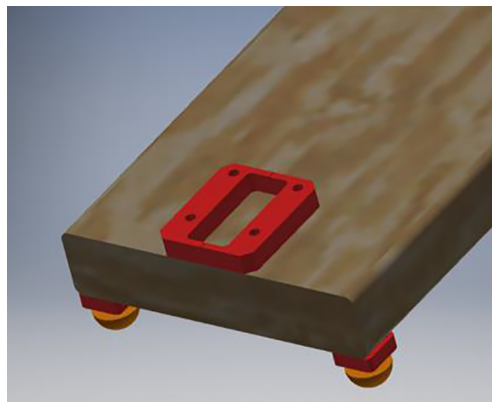
2. Measure width of board and divide by 2 to find midpoint. Align Extrusion Motor Template at midpoint, the longer end of the template goes against the end of the board.
3. Clamp or hold down motor template and drill in the 4 holes with a 13/64" Drill bit (see Fig. 8)
4. Do the same for the second template 13 1/4" from the end of the board (see Fig. 9)
5. Insert the (4) M5X65mm Bolts through the bottom of the wood and printed template with an M5 Washer on it. Then Screw (4) M5 nuts (see Fig. 10).
6. Place motor Bracket on top of Bolt pattern on board. Screw down all (8) M5 nuts to secure the motor brackets (see Figs. 11 and 12)

### III. Barrel

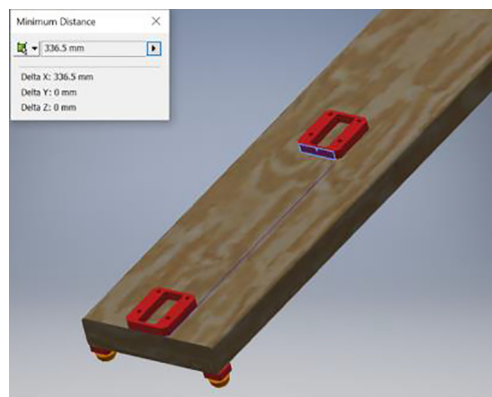
The barrel material was chosen to be steel for its durability and much higher melting point. The use of nichrome wire and uniform spacing is critical for optimal heating and for predicting the internal environment in the barrel as material flows through. Kapton Tape is utilized to protect the wires, prevent them from fusing together, as well as lock them into place. The nozzle size plays a significant role on the material output during filament production, a larger hole will allow more material to flow at a lower pressure. A 2 mm hole was found to be ideal for 1.75 mm diameter filament production.

#### 1. Parts Required:

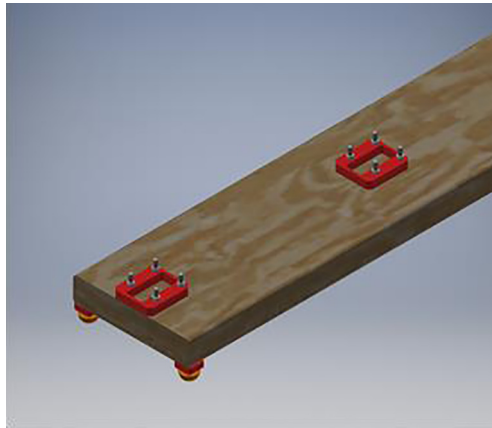
- i. Heat Sink/Barrel Mount
- ii. (2) M5X25mm Screw



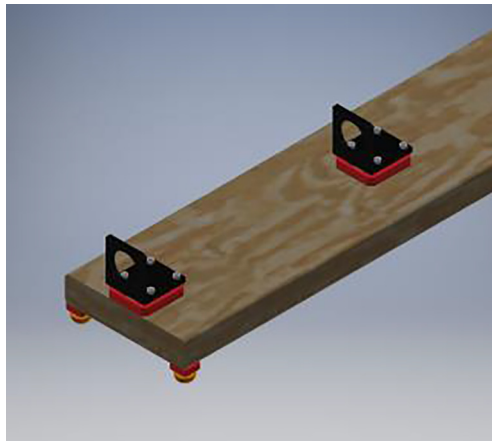
**Fig. 8.** Positioning Extrusion Motor Template.



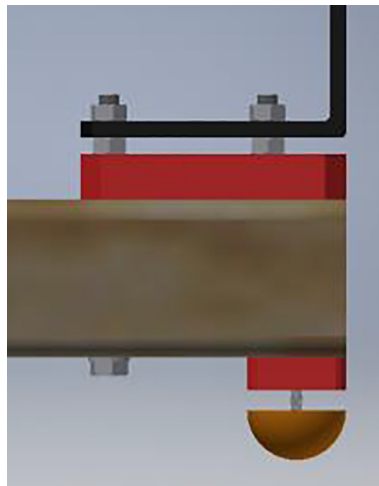
**Fig. 9.** Positioning the second Extrusion Motor Template.



**Fig. 10.** Bolting the Extrusion Motor Templates to the board.



**Fig. 11.** Mounted Brackets.



**Fig. 12.** A side view diagram to help show the layout of the nuts.

- iii. (2) M5 Nut
  - iv. Barrel
  - v. Kapton Tape
  - vi. Nichrome Wire
  - vii. Nozzle
  - viii. Barrel Insulation
  - ix. Thermistor
2. Drill 5/64" or 2 mm hole in brass cap (Nozzle)
  3. Wrap a layer of Kapton Tape around the Barrel, then a layer of equally spaced (~1 mm Spacing) Nichrome wire for the heating element (20 ft), then finally a 2nd layer of Kapton tape to secure the nichrome wire. Make sure to leave wire leads to connect later. **It is important that the wires do not cross.** The layering should be as follows: Barrel – Kapton Tape – Nichrome Wire – Kapton Tape – Insulation (see Figs. 13–15)
  4. Screw on Nozzle and Floor flange (Heatsink) to barrel as shown in Fig. 16.
  5. Attach Heat Sink/Barrel Mount to Second motor bracket with M5X25mm Bolts
  6. Tighten the nozzle onto the barrel until both the barrel and nozzle stop turning.
  7. Tape the thermistor to the nozzle a.
  8. Cut a 5 1/2" length of pipe insulation and wrap the insulation around the barrel.
- IV. Hopper
- The hopper feeds polymer to the system.
1. Parts Required:
    - i. (8) M3X10 Screw
    - ii. (8) M3 Heat Set inserts
    - iii. (2) #6 X 1 Wood Screw
    - iv. 2 Liter Bottle
    - v. Extrusion\_Hopper Catch Bin\_x1.stl



Fig. 13. Assembled barrel.

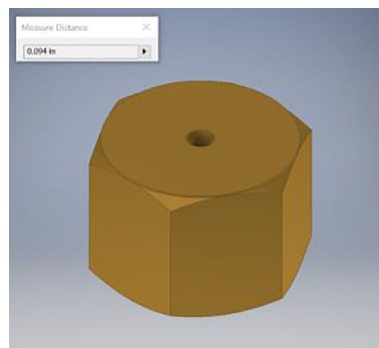
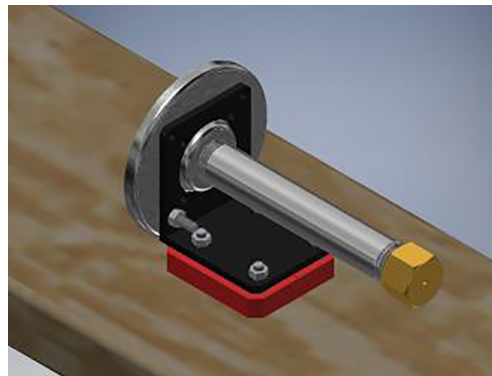


Fig. 14. Nozzle for end attachment on the barrel to control initial filament diameter.



**Fig. 15.** Floor flange.



**Fig. 16.** Assembled nozzle and floor flange.

- vi. Extrusion\_Hopper Feet\_x1.stl
- vii. Extrusion\_Hopper Hole Cover\_x2.stl
- viii. Extrusion\_Hopper Insulation\_x1.stl
- ix. Extrusion\_Hopper Screw Cap\_x1.stl
- x. Extrusion\_Hopper Trough\_x1.stl
- xi. MISC\_M3 Thumb Screw Conversion\_x12.stl

2. Make sure screw can freely turn inside the hopper as shown in [Fig. 17](#).
3. Place Extrusion Insulation for hopper over the bolt heads on the floor flange as shown in [Fig. 18](#).
4. Melt Heat-Set inserts into the hopper as shown in [Fig. 19](#) following Tip #1.
5. Screw on legs with M3X10mm bolts following [Fig. 20](#).
6. Screw on Hole Covers following [Fig. 21](#).
7. (Optional) Place cover on with Thumb Screws following [Fig. 22](#).
8. Place Hopper assemble on board and align with barrel as shown in [Fig. 23](#).
9. Attach with (2) M5X25 Bolts and M5 Nuts using the top holes on the hopper and floor flange.

#### V. Auger

The auger moves the feedstock to the hot zone for extrusion.

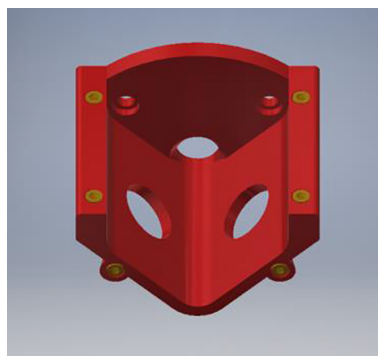
1. Parts Required:
  - i. Auger
  - ii. Geared Nema 23 Stepper Motor
  - iii. (4) M3 Heat set inserts
  - iv. (4) M3X10 Bolts
  - v. (4) M4 X 20 Bolts (Came with Motor)
  - vi. Extrusion\_Auger Coupler\_x1.stl



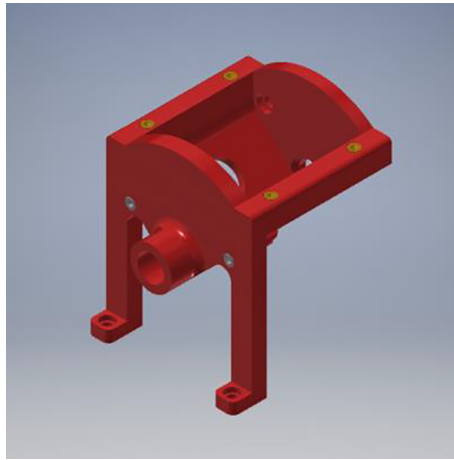
**Fig. 17.** Screw inside of hopper.



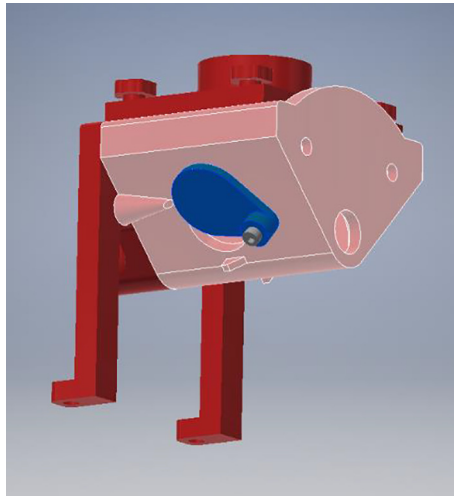
**Fig. 18.** Insulation for hopper.



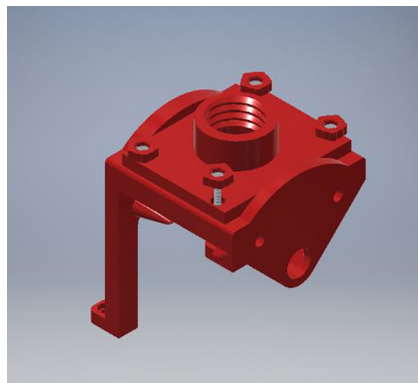
**Fig. 19.** Heat set inserts inside hopper.



**Fig. 20.** Hopper with legs.

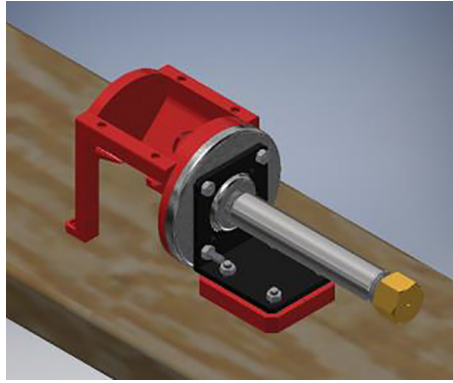


**Fig. 21.** Placement of hole covers.



**Fig. 22.** Optional hopper cover.





**Fig. 23.** Hopper assembly on board.

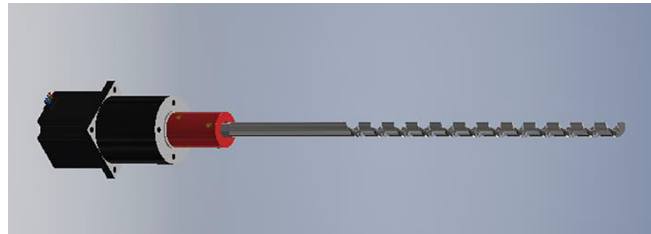
2. Cut tip of auger off. Use the barrel to gauge where the tip of the auger gets too big to fit. Then cut it off with a Dremel or angle grinder. Make sure to put an angle in it as shown in [Fig. 24](#), this helps move the plastic into the nozzle area.
3. Melt heat inserts into the coupler and mount Auger as shown in [Fig. 25](#).



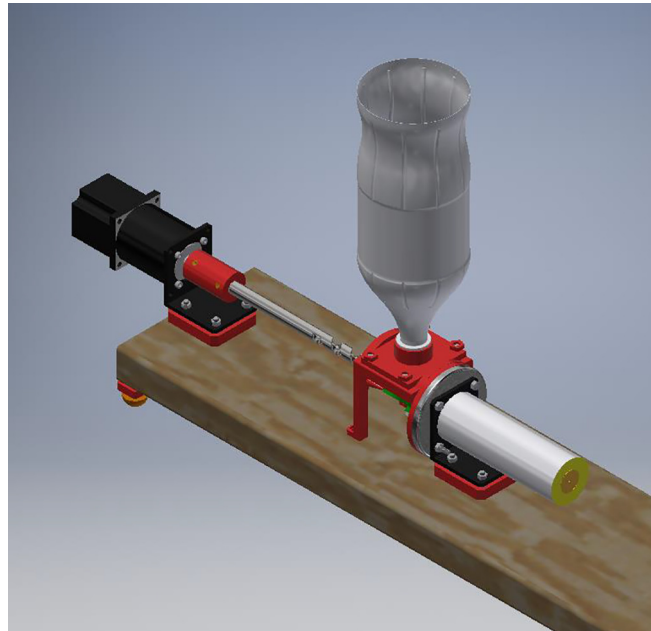
**Fig. 24.** Angle cut in Auger.



**Fig. 25.** Mounted Auger in coupler.



**Fig. 26.** Auger coupler and motor secured into single unit.



**Fig. 27.** Assembly completed of the mechanical parts after assembly 5.

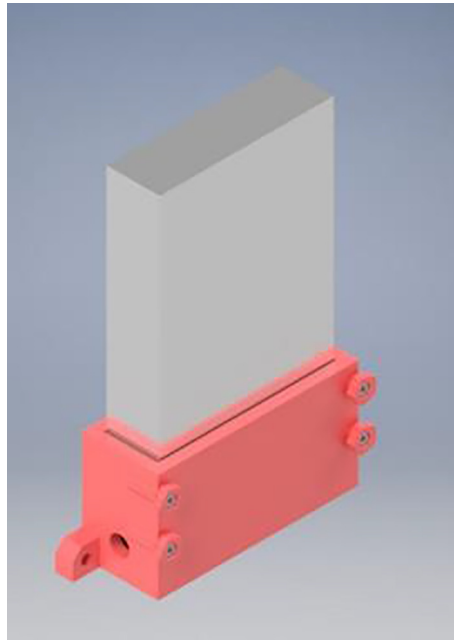
4. Couple the auger and the motor and secure with the M3X10 Bolts as shown in [Fig. 26](#).
5. Align the screw through the hopper and barrel.
6. Attach the Nema 23 geared stepper motor to the first motor bracket with the provided screws from the motor as shown in [Fig. 27](#).

### 5.3.2. Power supply

The power supply is where the mains voltage from the wall is converted to 12 V to power the control panel. It has an entrance on the left side and exit on the right side for wires. The cover should be installed before operating the Recyclebot. The Power Supply Assembly shown in [Fig. 28](#) is broken into the following parts:

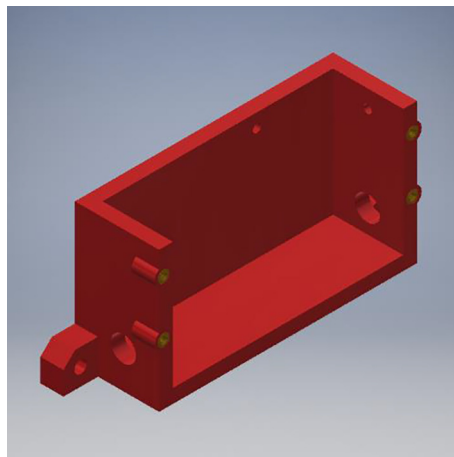
#### I. Power Supply

1. Parts Required:
  - a. 12 V power Supply
  - b. (7) M3 X 10 mm Bolt
  - c. Power Supply\_Cover\_x1.stl
  - d. Power Supply\_Mount\_x1.stl



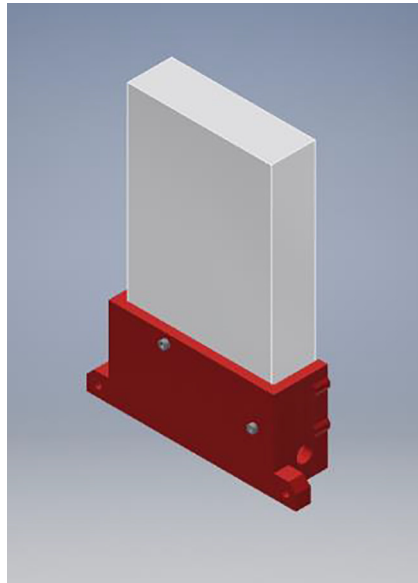
**Fig. 28.** Power Supply Assembly.

1. Melt heat inserts into Power Supply cover as shown in [Fig. 29](#)

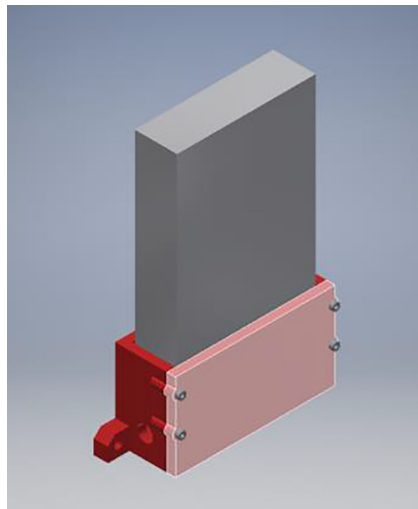


**Fig. 29.** Heat inserts into power supply cover.

2. Mount Power Supply to the cover with (3) M3X10mm bolts in each of the holes around the box as shown in [Fig. 30](#).
3. Mount the Power Supply Cap on the front with (4) M3X10mm Bolts as shown in [Fig. 31](#).
4. Screw to board with wood screws following [Fig. 32](#)



**Fig. 30.** Mounting power supply.



**Fig. 31.** Power Supply Cap mounting.

### 5.3.3. Cooling

The cooling assembly consists of an angled aluminum piece with fans blowing down to cool both the filament and the aluminum. The fans are adjustable to different locations and also the speed is adjustable through the software. As hot filament material is extruded out of the nozzle, if the temperature control is correct, it has a slightly viscous rheology. As that material touches the thermally conductive aluminum through the outside of the filament solidifies completely and becomes hardened. However, since polymers in general are poor thermal conductors the interior of the filament maintains a much lower viscosity and a higher temperature. This combination allows aluminum, as long as it is properly cooled, to be a non-stick surface for near molten filament material. Additionally, the filament is capable of being pressed by the rollers, elongated without cracking and spooled with a severe curve and tensioning force while maintaining its continuity.

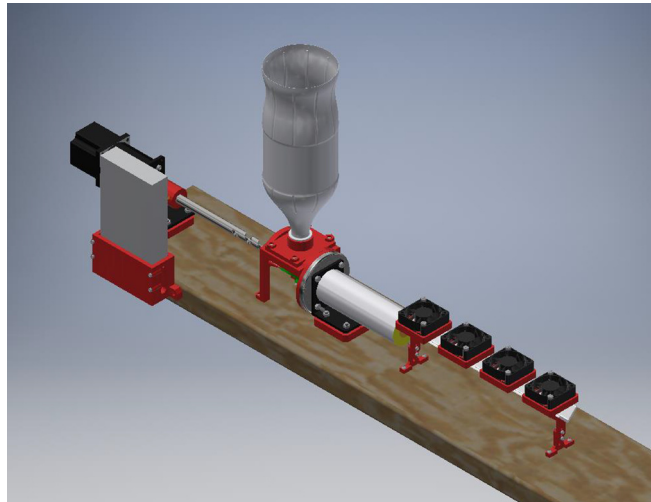


Fig. 32. Power supply on main assembly.

The Cooling Assembly is broken into the following parts shown in Fig. 33:

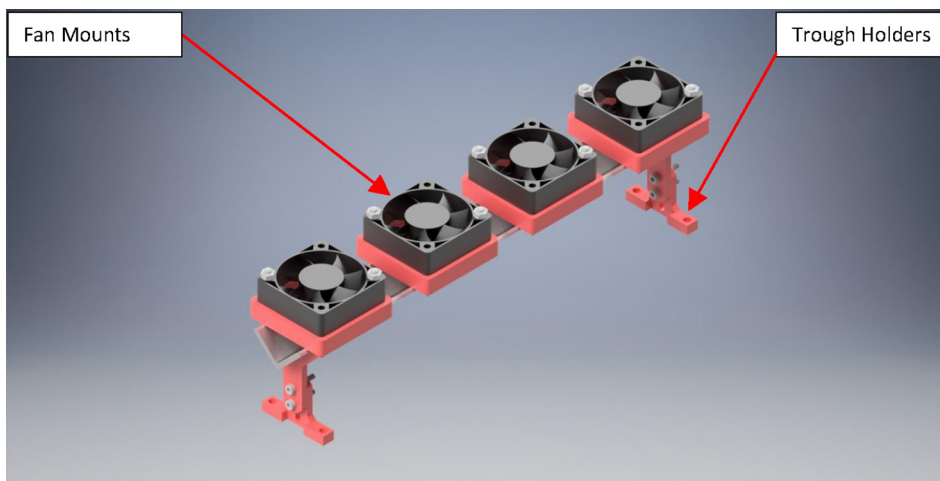
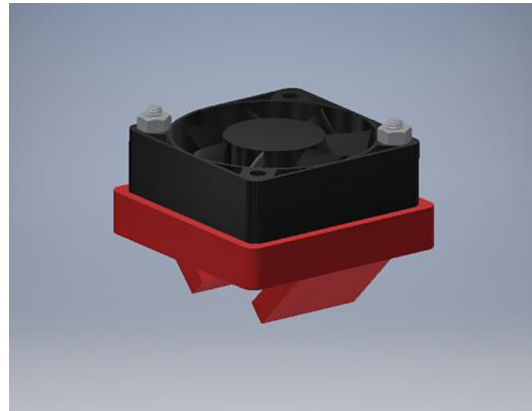


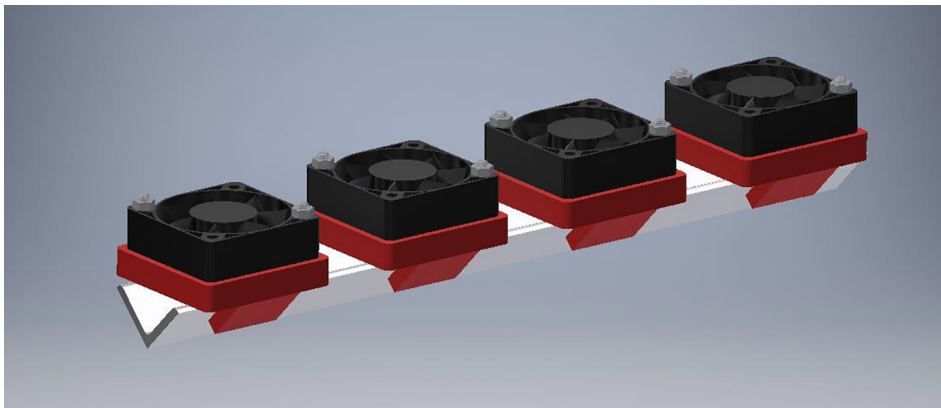
Fig. 33. The Cooling Assembly.

- I. Fan Mounts
- II. Trough Holders (see Fig. 34)
- I. Fan Mounts
  - 1. Parts Required:
    - i. Fans X4
    - ii. M4X25 Bolt X8
    - iii. M4 Nut X8
    - iv. 1" 90-degree aluminum angle
    - v. Cooling\_Aluminum Trough Fan Mount\_x4.stl
    - vi. Cooling\_Aluminum Trough Holders Bottom\_x2.stl
    - vii. Cooling\_Aluminum Trough Holders Top\_x2.stl



**Fig. 34.** Fan mount.

2. Secure fan to fan mounts with (2) M4X25mm bolt
3. Repeat step 2 three more times to get a total of four fan assemblies as shown in [Fig. 35](#).



**Fig. 35.** Fan assembly.

4. Slide them onto the aluminum trough

### III. Trough Holders

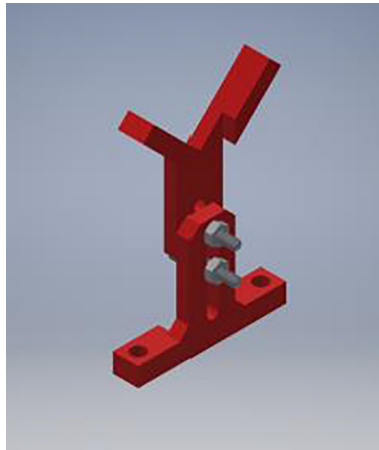
#### 1. Parts Needed:

- i. (2) Aluminum Trough Holders Top (STL)
- ii. (2) Aluminum Trough Holders Bottom (STL)
- iii. (4) M3X10 Bolt
- iv. (4) M3 Nut
- v. Wood Screws

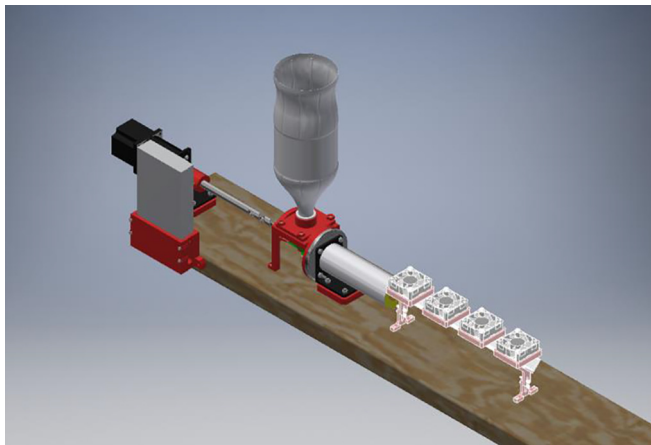
2. Put together 2 sets of trough holders with (4) M3X10mm bolts and (4) M3 nuts as shown in [Fig. 36](#)
3. Screw to board and align with nozzle hole on extrusion assembly
4. The trough holders are adjustable by loosening and tightening the 2 M3 bolts and sliding the top up or down
5. The assembly should resemble [Fig. 37](#).

#### 5.3.4. Control Box

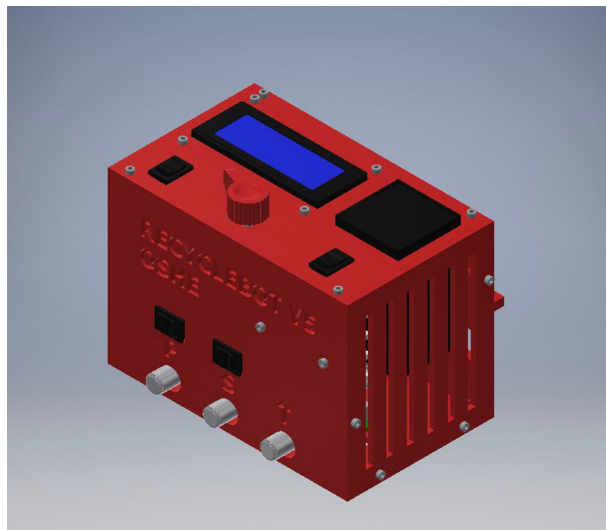
The control panel houses all the electronic controls for the entire Recyclebot. It fits everything perfectly, but is heavy with wires once everything is installed. It is recommended to use hot glue on all the terminals to keep the connections sturdy over the life of the machine. Some filing on the switch holes may be required to fit in the rocker switches, they were designed to fit snugly (see [Fig. 38](#)).



**Fig. 36.** Trough holder.



**Fig. 37.** Assembly with fan mounts.



**Fig. 38.** Control box assembly.

The Control Box Assembly is broken into the following parts:

### I. Control Box

1. Parts Required:
  - i. (20) M3X16mm Bolt
  - ii. (20) M3 Nuts
  - iii. LCD Screen
  - iv. Clickable rotary Encoder
  - v. RAMPS 1.4
  - vi. Solid State Relay
  - vii. Cooling Fan
  - viii. Control Panel\_Back\_x1.stl
  - ix. Control Panel\_Bottom\_x1.stl
  - x. Control Panel\_Front\_x1.stl
  - xi. Control Panel\_LCD Knob\_x1.stl
  - xii. Control Panel\_Mounting Brackets\_x2.stl
  - xiii. Control Panel\_Side\_x2.stl
  - xiv. Control Panel\_Top\_x1.stl

Notice: The printed parts may need to be sanded to fit together.

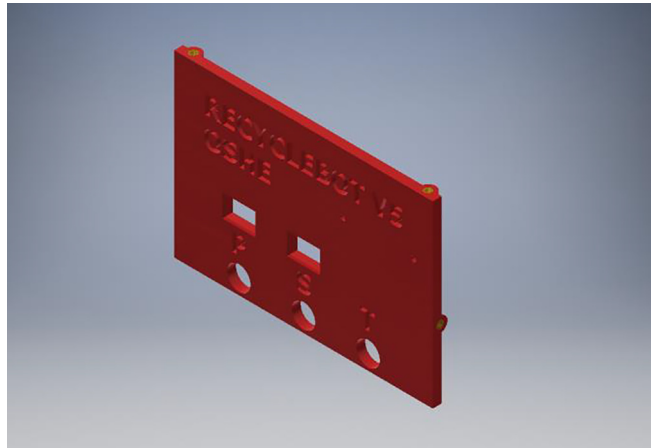
2. Attach the LCD screen with (4) M3X 16 mm bolts as shown in [Fig. 39](#)



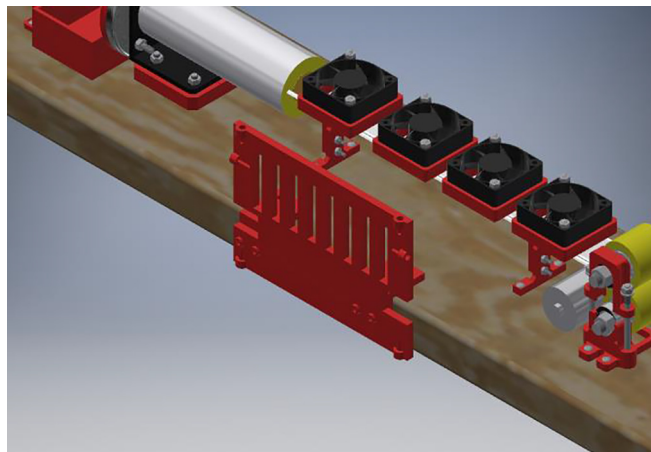
**Fig. 39.** Mounting LCD, Heater Control, Switches and Rotary Encoder with knob to front cover.

3. Next Attach the Rotary Encoder through the hole next to the LCD screen, tighten to the top plate with provided nut
4. Place Knob on rotary encoder shaft
5. Attach Heater controller with provided surface hold (white piece)
6. Attach x2 Rocker Switches onto the Control panel top (see [Fig. 40](#))
7. Mount the back panel to the board with the mounting brackets and 4 M3X16mm bolts and nuts (see [Fig. 41](#)).
8. Mount the solid-state relay (under the heat controller in the Figure), and both reversing switches to the front plate. Then mount the motor controllers to the bottom plate and mount the RAMPS to the 2 mounting holes sticking out of the bottom plate. Everything is mounted with M3X10 or M3X16mm bolts (see [Fig. 42](#))
9. Attach Top Plate with LCD Screen, to the rest of the control box with M3X10mm bolts threading into the heat inserts as placed before (see [Fig. 43](#)).
10. Attach the separate control panel assembly to the back plate already mounted on the board. Keep the sides off until the wires are organized (see [Fig. 44](#)).
11. Finally, once the wires have been organized, mount the sides on with M3X10mm bolts threading into the heat inserts as set before (see [Fig. 45](#)).

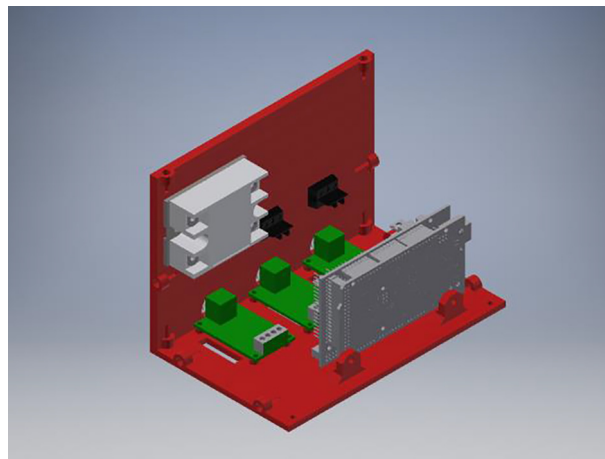




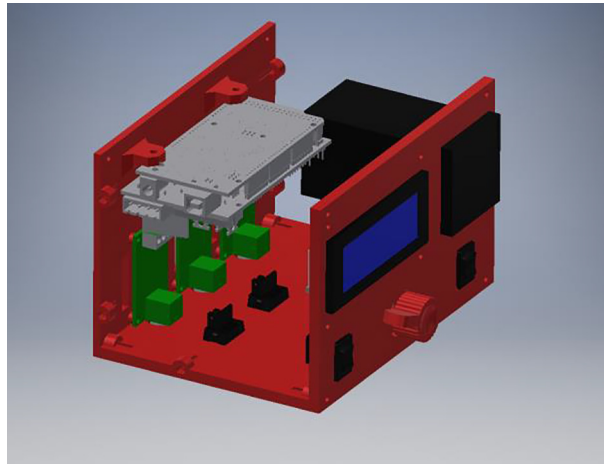
**Fig. 40.** Add Heat inserts to all panels with the round protrusions.



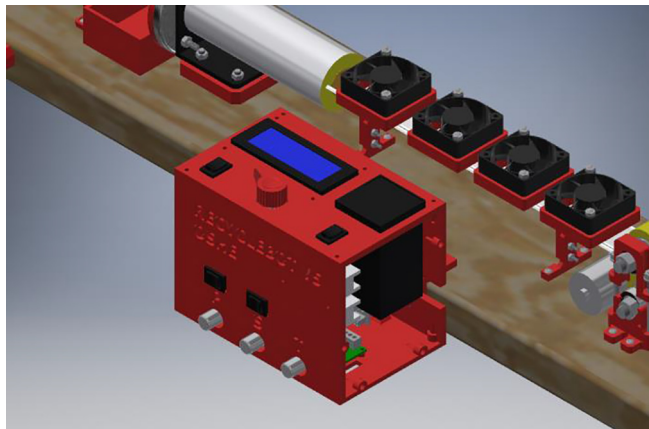
**Fig. 41.** Mounting back panel to the board first, place directly in front of cooling fans.



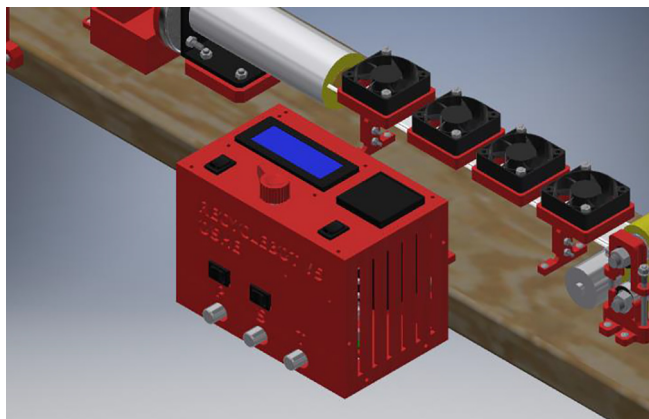
**Fig. 42.** Placement of all electronic components.



**Fig. 43.** Attaching top panel to front panel.



**Fig. 44.** Attaching the rest of the control box minus the sides.



**Fig. 45.** Assembly with controller.

### 5.3.5. Puller

The puller is a crucial part of the RepRapable Recyclebot, it determines the diameter of the filament. The faster it is pulling, the smaller the diameter will be, the slower it is pulling, the larger. When making filament, users must manually tune this motor speed to get the correct diameter. This should only need to be done once per material, but the diameter might change due to external variances like temperature swings or the hopper misfeeding, so users may want to monitor the diameter while manufacturing the filament. This becomes more important when working with non-uniform feedstocks and composites (see Fig. 46).

The Puller Assembly is broken into the following parts:

- I. Puller Rollers
- II. Motor Mount
- I. Puller Rollers
  1. Parts Required:
    - i. (4) Springs
    - ii. (7) Wood Screws
    - iii. (4) Zip ties
    - iv. (2) Urethane Rollers
    - v. (2) 5/8" Threaded Rod 2X (3.75" and 5.5" Lengths)
    - vi. (9) 5/8" Nut
    - vii. (4) M5 X 65 Bolt
    - viii. (4) M5 nut
    - ix. Puller&Spooler\_Belts\_x1
    - x. Puller&Spooler\_Large Belt Pulley\_x2.stl
    - xi. Puller\_Base\_x1.stl
    - xii. Puller\_Top Bearing Holder\_x2.stl

2. Press in bearings into the base, and the two top bearing holders following Tip #2 as shown in Fig. 47.

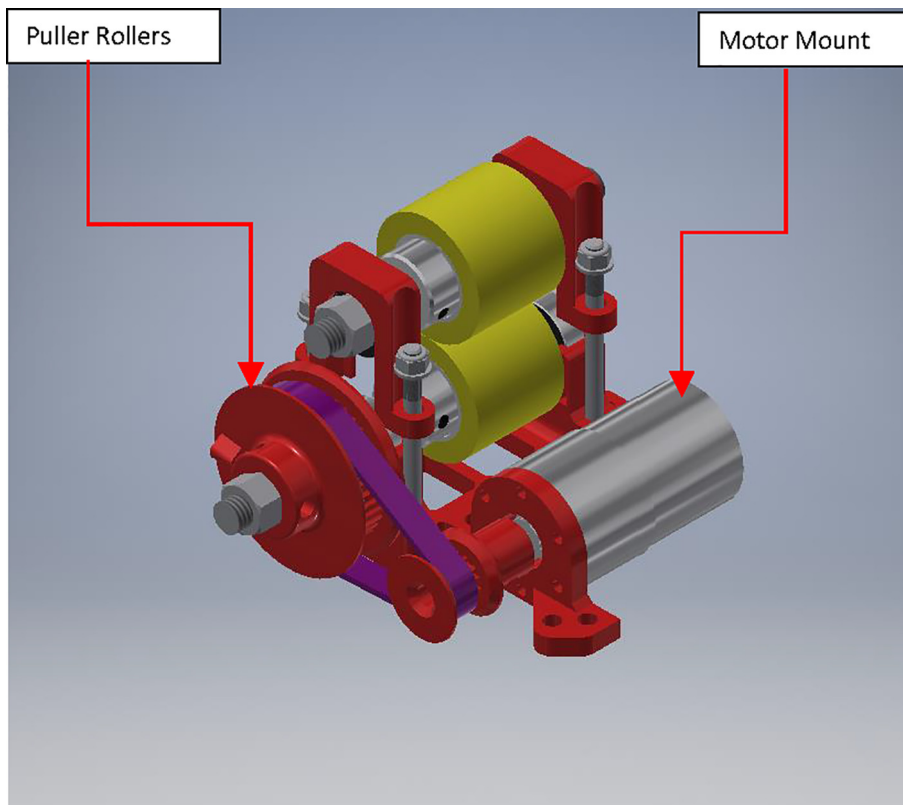
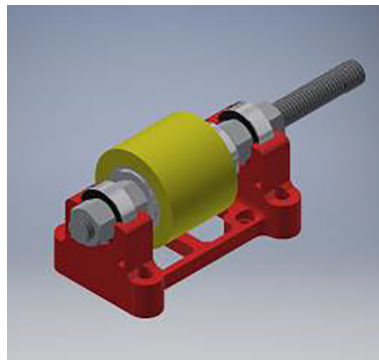


Fig. 46. Puller assembly with labeled main parts.

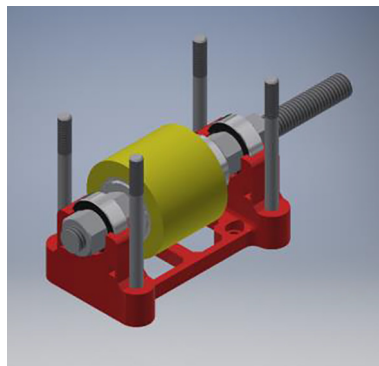


**Fig. 47.** Bearings in the base.

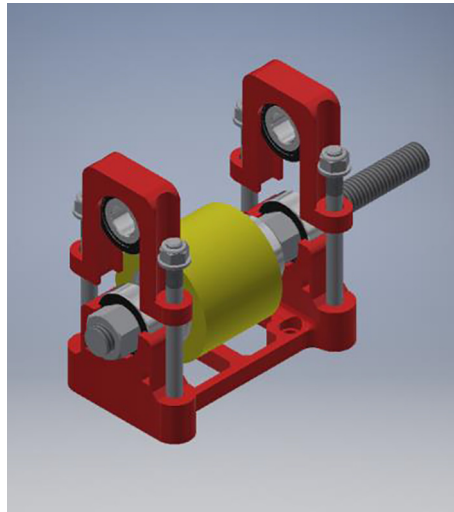
3. Layout the 5.5" rod with (4) nuts and a urethane roller. Make sure roller is tightened down on threaded rod using set screw and that the entire rod and roller spin freely as shown in [Fig. 48](#).
4. Run (4) M5 X 65 mm bolts through the bottom of the base as shown in [Fig. 49](#)
5. Place the top bearing mounts with bearings in them on the M5 X65mm bolts as shown in [Fig. 50](#). WARNING: DO NOT PUT NUTS ON YET.
6. Place springs on the M5X65mm bolts over the top bearing mounts, then secure with an M5 nut as shown in [Fig. 51](#).
7. Layout the top threaded rod (3.5") the same way as the bottom rod. It is easier to then screw in the rod from one of the sides through all the nuts and urethane roller as shown in [Fig. 52](#).



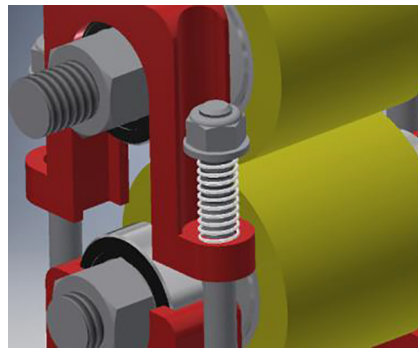
**Fig. 48.** Roller assembly.



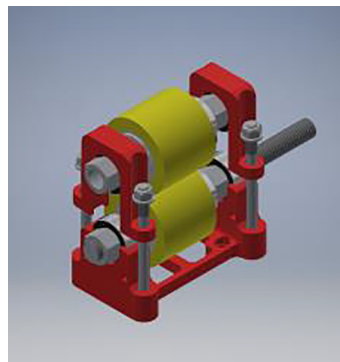
**Fig. 49.** Roller assembly with bolts.



**Fig. 50.** Top bearings mounted on roller assembly.

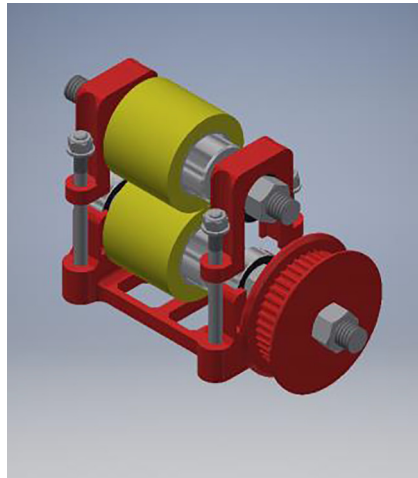


**Fig. 51.** Placement of springs in roller assembly.

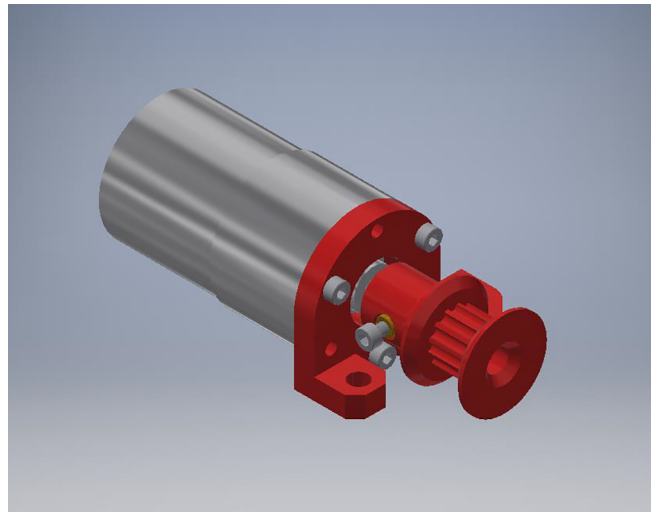


**Fig. 52.** Top roller assembly.

8. Place the Puller&Spooler\_Large Belt Pulley\_x2.stl on the bottom threaded rod and secure in place with another nut as shown in [Fig. 53](#) (see [Fig. 54](#)).



**Fig. 53.** Placement of large belt pulley on roller assembly.



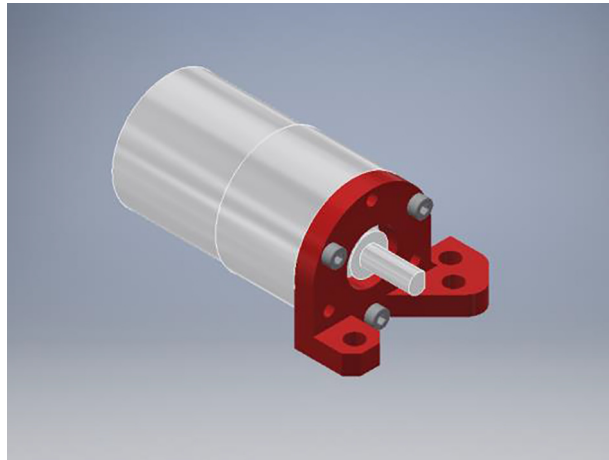
**Fig. 54.** Motor mount.

## II. Motor Mount

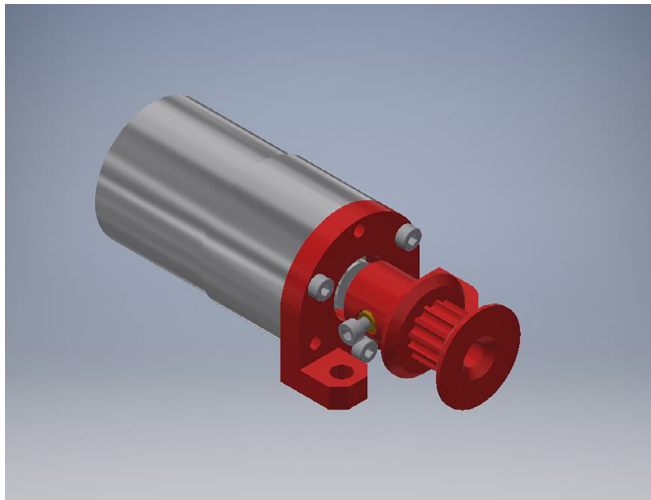
### 1. Parts Required

- i. 12 V DC Motor
- ii. (4) M3X10 Bolts
- iii. (1) M3 Heat set insert
- iv. Belt (Ninjaflex) or Rubber bands
- v. Puller\_Base\_x1.stl
- vi. Puller\_DC Motor Mount\_x1.stl

2. Melt an M3 heat insert into the Small Belt pulley, Secure on 12 V DC motor with M3x10mm bolt as shown in [Fig. 55](#).
3. Mount 12 V DC motor with (3) M3x10 mm bolts as shown in [Fig. 56](#)



**Fig. 55.** Small belt pulley assembly on motor.



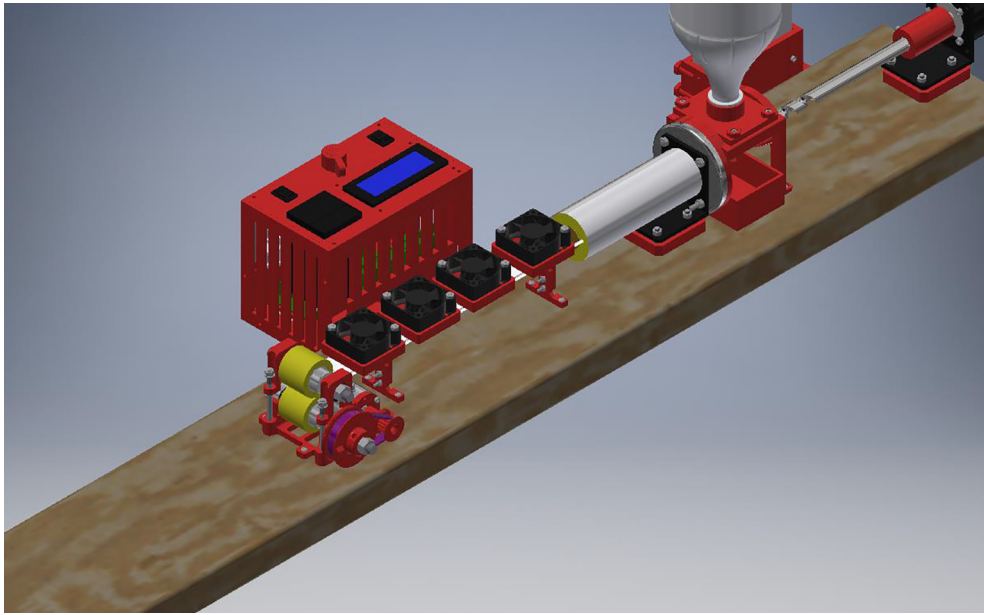
**Fig. 56.** Motor mount fully assembled.

4. Slide on pulley, tighten down M3X10 Bolt
5. Attach belt and then screw entire assembly into board. Making sure to keep belt tensioned and rollers completely in the center of the aluminum cooling trough as shown in [Fig. 57](#).

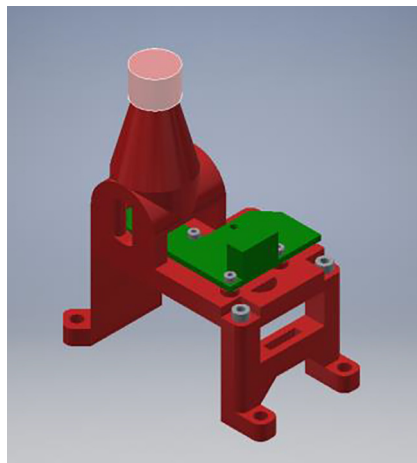
#### 5.3.6. Diameter sensor

The diameter sensor automatically reads the filament diameter at every location as it is extruded. The sensor consists of a PCB that was designed by Filip Mulier, an LED, and a printed enclosure for it. In the future, an upgrade for the RepRapable Recyclebot would be to have a feedback loop to determine how large the diameter is and then change the puller speed to maintain a uniform diameter.

The Diameter Sensor Assembly shown in [Fig. 58](#) is broken into the following parts:



**Fig. 57.** Puller on main assembly.



**Fig. 58.** Diameter sensor assembly.

## I. Diameter Sensor

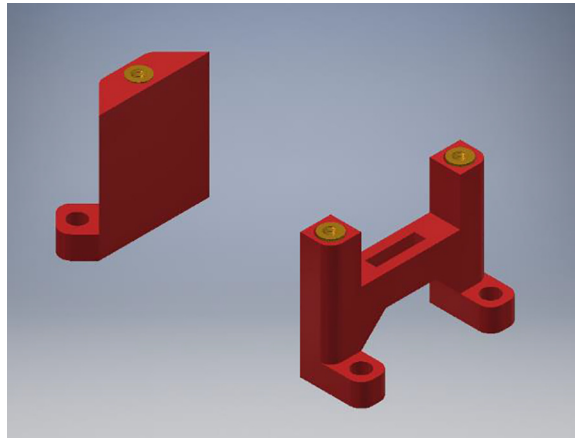
### 1. Parts Required:

- i. Mulier Filament Sensor PCB Kit
- ii. (3) M3 Heat Inserts
- iii. (3) M3 X 10 mm bolts
- iv. (3) M2X10 mm bolts
- v. (3) M2 Nuts
- vi. Diameter Sensor\_Body\_x1.stl
- vii. Diameter Sensor\_Cap\_x1.stl
- viii. Diameter Sensor\_Legs\_x1.stl
- ix. Diameter Sensor\_Single Leg\_x1.stl

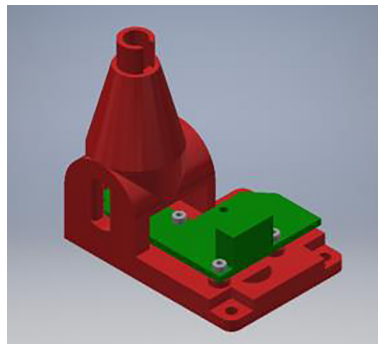
1. Melt (3) M3 Heat inserts into the Legs and single leg as shown in [Fig. 59](#).

2. Screw the PCB to the Frame with M2X10mm bolts and M2 nuts as shown in [Fig. 60](#)



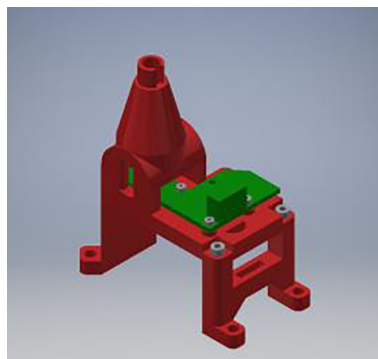


**Fig. 59.** Heat inserts in legs.

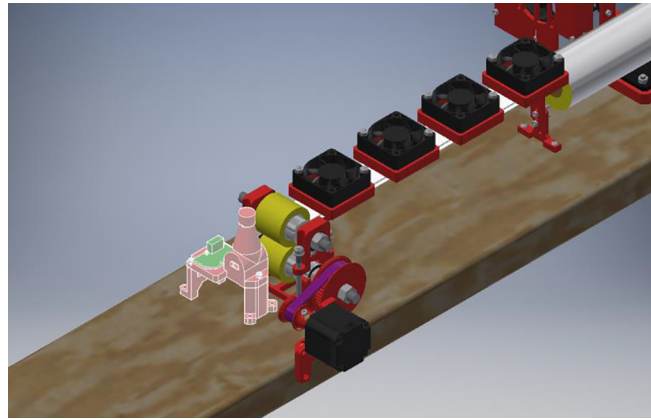


**Fig. 60.** PCB placed on Frame of diameter sensor.

3. Screw the legs to the main frame with M3X10mm screws as shown in [Fig. 61](#)
4. Place LED and cap onto the top of the frame and screw into the board, aligning the opening to the middle of the puller roller as shown in [Fig. 62](#).



**Fig. 61.** Legs placed on frame of diameter sensor.



**Fig. 62.** Placement of diameter sensor on main assembly.

### 5.3.7. Roller guide

The roller is essential for keeping tension in the filament for spooling and to guide it straight through the diameter sensor. The filament guide is adjustable to increase or decrease tension. The filament should be run through the diameter sensor and underneath the roller guide.

The Roller Guide Assembly (Fig. 63) is broken into the following parts:

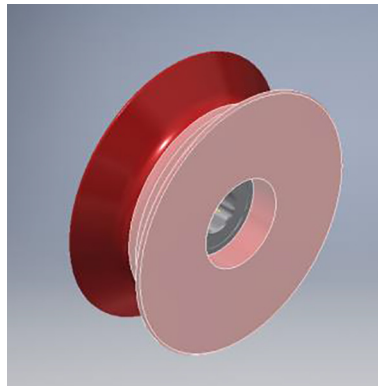


**Fig. 63.** Roller guide.

- i. Roller
- ii. Wood Mount
- I. Roller
1. Parts Required:
  - i. (1) Ball Bearing
  - ii. (1) Threaded Rod (3")
  - iii. (3) 5/8" Nuts
  - iv. Roller\_Half 1\_x2.stl
  - v. Roller\_Half 2\_x2.stl
2. Press Bearing into Roller half 1 as shown in Fig. 64.
3. Press Roller half 2 on other side until assembly is tight as in Fig. 65.

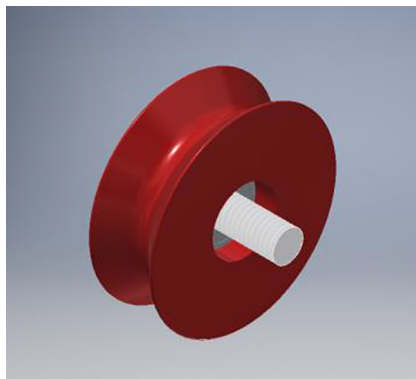


**Fig. 64.** Bearing in Roller Half 1.

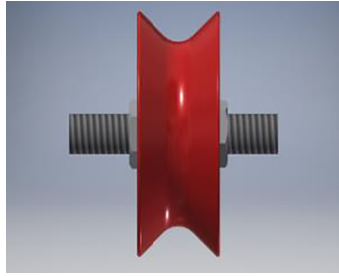


**Fig. 65.** Both halves of Roller on bearing.

4. Place Rod through the bearing as seen in [Fig. 66](#).
  5. Tighten 5/8" Nuts on both sides of bearing as shown in [Fig. 67](#)
- II. Roller Wood Mount
1. Parts Required:
    - i. 5/8" Nut
    - ii. Roller\_Wood Mount\_x1.stl



**Fig. 66.** Both halves of Roller on bearing with rod.



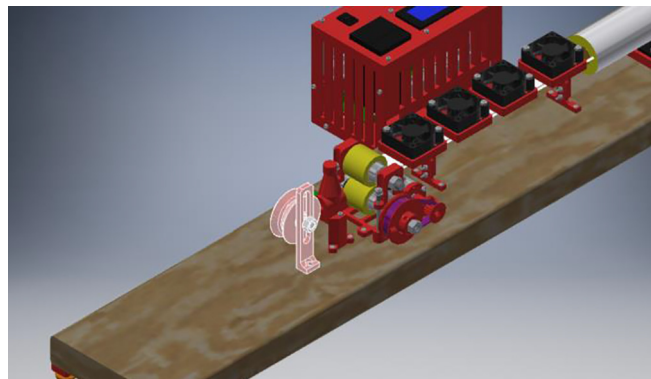
**Fig. 67.** Both halves of Roller on bearing with rod and nuts.

2. Place previously built assembly onto the guide wood mount and tighten another 5/8" nut as shown in [Fig. 68](#).
3. The guide is adjustable up and down by loosening and tightening this nut.



**Fig. 68.** Roller on mount.

4. Place on full assembly as shown in [Fig. 69](#).



**Fig. 69.** Full assembly with roller.

### 5.3.8. Traverse assembly

This assembly winds filament onto an empty spool evenly and prevents the filament from overlapping. If the filament is not spooled tightly, it will not be able to fit an entire kilogram of plastic. The system works by using a speed-controlled DC motor to turn a threaded rod that has a nut running along it. The nut is attached to the cart with a guide roller on it. A slider switch is attached to the wood and the cart moves back and forth to throw the switch. The switch will change the direction of the DC motor and therefore change the direction of the cart. The limits of this system are that it uses rubber bands to overcome the force to throw the switch. This could be upgraded in the future to use a more robust system of flipping the switch to change the motor speed. Currently, the speed needs to be manually tuned to find the correct travel distance for the speed that the system is currently extruding at. Future work could automate this process.

The Traverse Assembly shown in Fig. 70 is broken into the following parts:

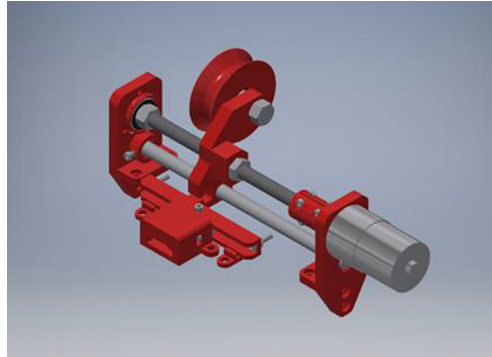
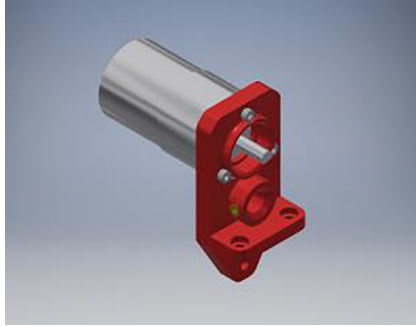


Fig. 70. Traverse Assembly.

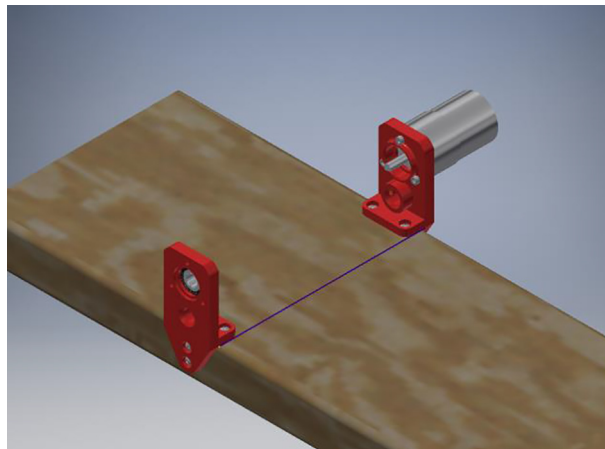
1. Parts Required:
  - i. (2) Ball Bearing
  - ii. 6 7/8" Long Threaded Rod
  - iii. 7 5/8" Long Smooth Rod
  - iv. 12 V DC Motor
  - v. (12) M3X10mm Bolts
  - vi. (2) M3 Heat Inserts
  - vii. (7) 3/8" Nuts
  - viii. (1) Threaded Rod (3")
  - ix. Roller\_Half 1\_x2.stl
  - x. Roller\_Half 2\_x2.stl
  - xi. Traverse\_Coupler Half\_x2.stl
  - xii. Traverse\_Motor and Bearing Mount\_x2.stl
  - xiii. Traverse\_Slider Guide\_x2.stl
  - xiv. Traverse\_Slider\_x1.stl
  - xv. Traverse\_Switch Housing\_x1.stl
  - xvi. Traverse\_Threated Rod Cart\_x1.stl
2. Press Bearings into Traverse\_Motor and Bearing Mount\_x2.stl (1) as shown in Fig. 71
3. Mount 12 V DC motor onto the other bracket as shown in Fig. 72
4. Mount both brackets to the board and align with a speed square. Screw in with (8) wood screws (Fig. 73).
5. Slide on smooth rod through bottom holes. Secure with (2) m3x10 bolts (Fig. 74).
6. Start assembly of the traversing cart. Place 3/8" Nuts into each side of the cart, one of them will stick out about 1/4". Screw in rod to make sure smooth rotation, if it is not smooth, push in or pull out the nut and try again. The two nuts are to avoid backlash (see Figs. 75–77).
7. Place 3.5" Rod through the top hole of the cart (Fig. 78).
8. Follow the directions above for creating the roller guide shown above (see Fig. 79).
9. Remove rod, slide through bearing and then re-thread the rod onto the car assembly, thread the rod until it reaches the motor.
10. Install the coupler with (4) M3X10mm Bolts and Nuts (see Figs. 80 and 81).
11. Drill a 3 mm hole into the DPDT switch (Fig. 82).
12. Mount the switch in Traverse\_Switch Housing\_x1.stl (Fig. 83).
13. Screw on slider to the switch as shown in Fig. 84.



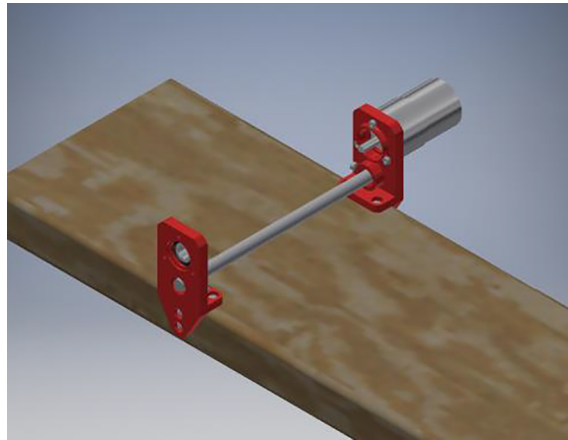
**Fig. 71.** Bearings in Traverse Threaded Rod End Bracket.



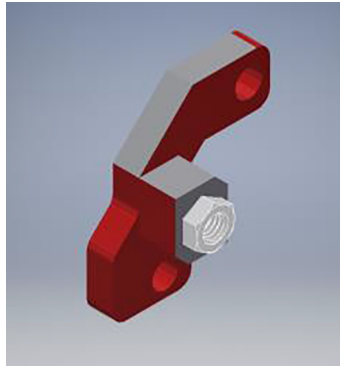
**Fig. 72.** 12 V DC motor mounted on bracket.



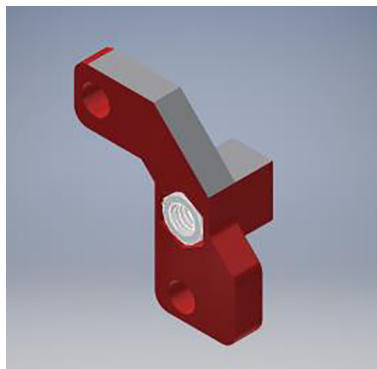
**Fig. 73.** Mounting brackets with wood screws.



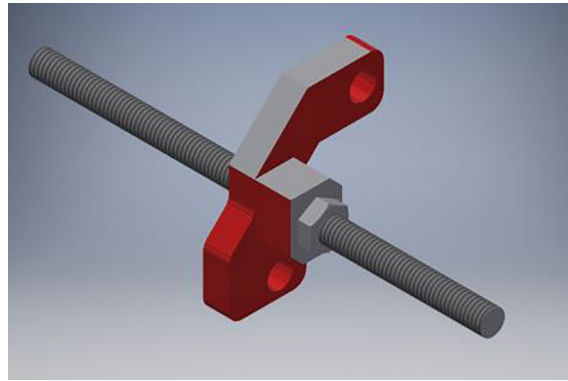
**Fig. 74.** Slide in smooth rod and secure.



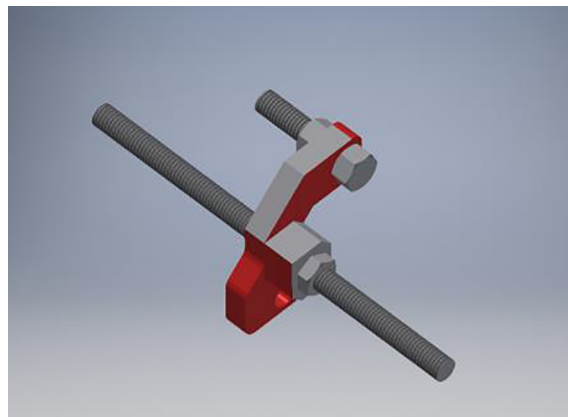
**Fig. 75.** Nuts on side of the cart right.



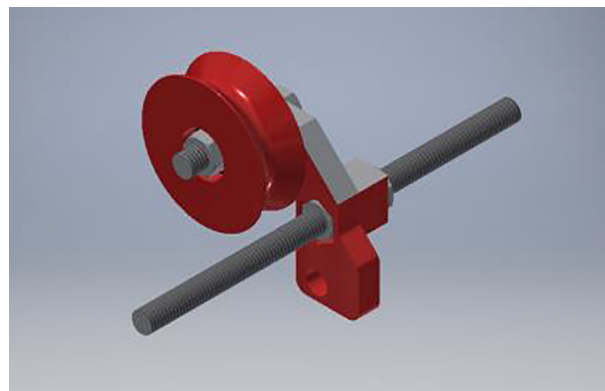
**Fig. 76.** Nuts on side of the cart left.



**Fig. 77.** Threaded rod inserted into cart.

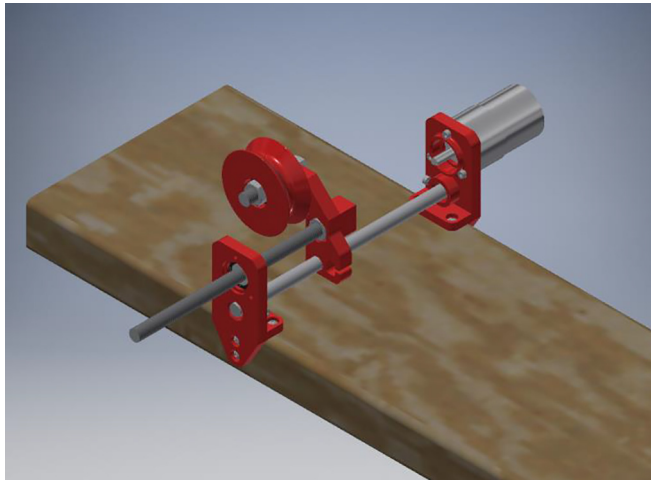


**Fig. 78.** Rod (bolt) placed through the top hole of cart.

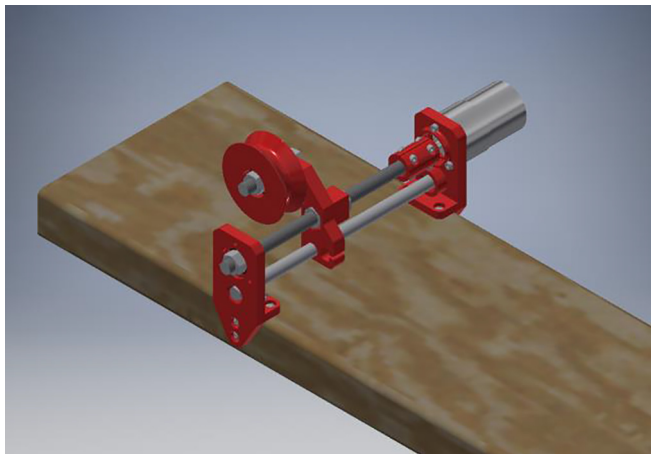


**Fig. 79.** Roller guide installed on cart.

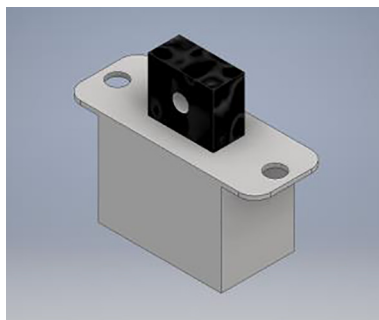




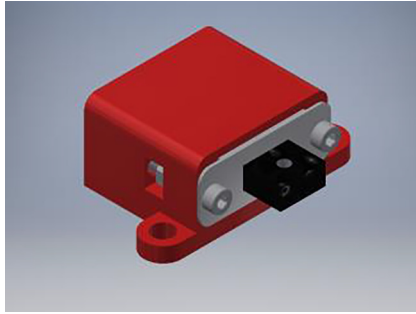
**Fig. 80.** Rods installed on motor bracket.



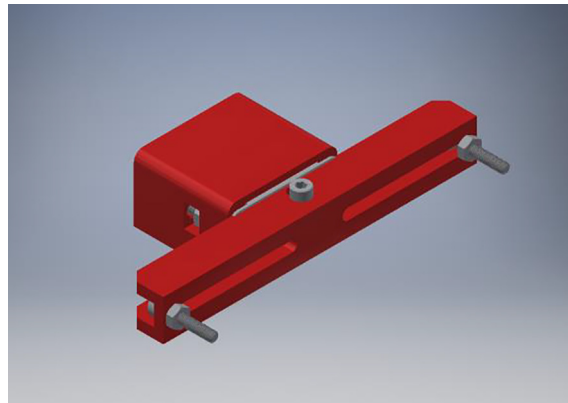
**Fig. 81.** Threaded Rod coupled with Motor.



**Fig. 82.** M3-sized hole in switch.

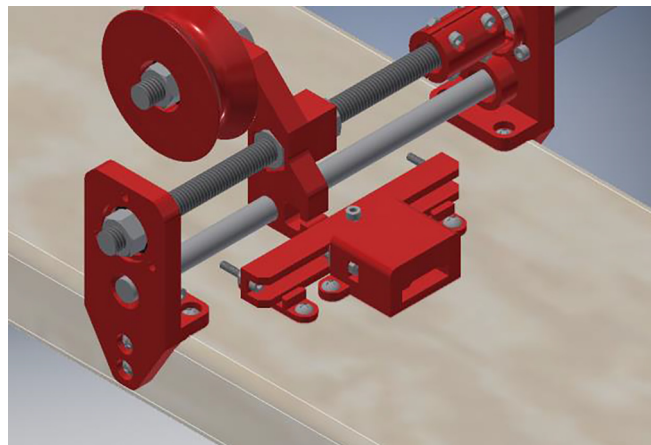


**Fig. 83.** Switch in housing.

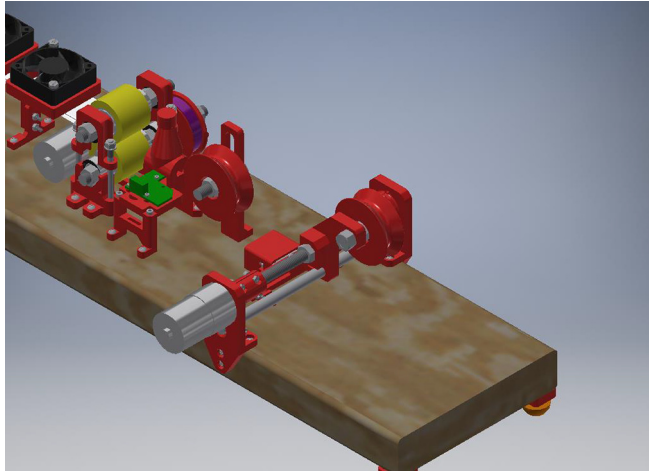


**Fig. 84.** Slider mounted on the switch.

14. Add M3X16mm bolts to each side. These are where the rubber bands will wrap around to provide more force to throw the switch
15. Mount the switch and slider guides to the board (Fig. 85).
16. Wrap rubber bands through the cart and back to each of the M3X16mm bolts. Experiment with whichever ones work the best at throwing the switch. The final assembly is shown in Fig. 86.



**Fig. 85.** Mounted switch and slider guides.

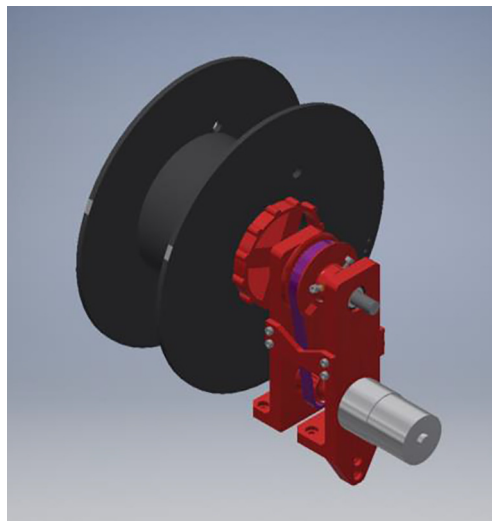


**Fig. 86.** Final Traverse assembly on main board.

### 5.3.9. Spooler

The spooler is the system that winds the filament onto the spool. Once wired correctly, the speed and direction can be varied to accompany different filament sizes and extrusion speeds. It has a built in “clutch” system from using a smooth belt. This is to prevent the spooler from pulling the filament through the entire system and making the diameter inconsistent. The empty spool can be loaded by unscrewing one of the hubs and placing the new spool onto the threaded rod and tightening the hub back on.

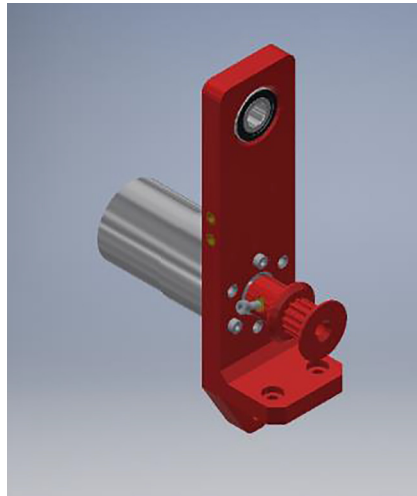
The Spooler Assembly (Fig. 87) is broken into the following parts:



**Fig. 87.** Spooler Assembly.

- i. Spool (Recycled)
- ii. (4) 5/8" Nut
- iii. (2) Bearings
- iv. (12) M3X10 Bolts
- v. (10) M3 Heat set Inserts
- vi. 12 V DC Motor
- vii. Wood Screws
- viii. Puller&Spooler\_Belts\_x1
- ix. Spooler\_Back Bearing Tower\_x1.stl

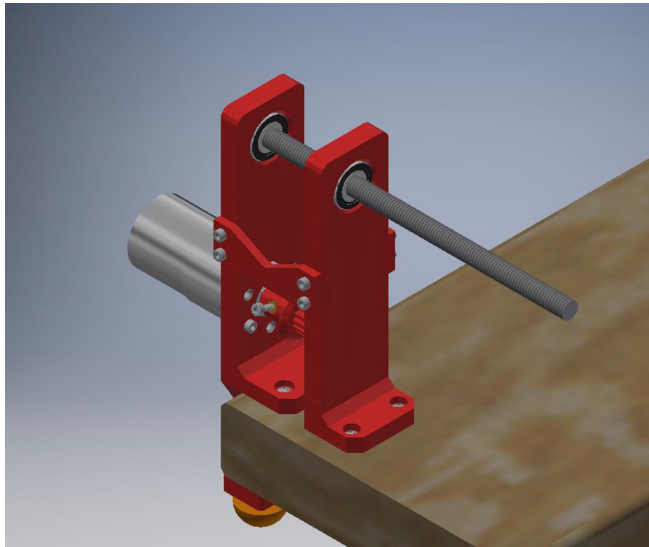
- x. Spooler\_Cross Beam\_x2.stl
  - xi. Spooler\_Front Bearing Tower\_x1.stl
  - xii. Spooler\_Hub\_x2.stl
  - xiii. Puller&Spooler\_Large Belt Pulley\_x2.stl
  - xiv. Puller&Spooler\_Small Belt Pulley\_x2.stl
1. Press a bearing into the bearing tower
  2. Install the motor to the winder motor mount with (4) M3 X 10 bolts
  3. Melt in 4X m3 heat inserts on each side of the bearing towers where the tower cross beam will go.
  4. Place small pulley on 12 V DC motor, secure it with an M3X10mm bolt (steps 1–4 shown in [Fig. 88](#)).
  5. Screw back bearing tower to board
  6. Press another bearing into the opposite bearing tower as shown in [Fig. 89](#).
  7. Align both bearing towers with the threaded rod and attach the Spooler\_Cross Beam\_x2.stl
  8. Screw front bearing tower onto board
  9. Remove threaded rod.
  10. Screw in printed tower cross beam with 4 M3 X10 bolts on each side of the 2 upright bearing towers as shown in [Fig. 90](#).
  11. Melt M3 heat inserts into the large pulley



**Fig. 88.** Bearing in bearing tower with motor and pulley.

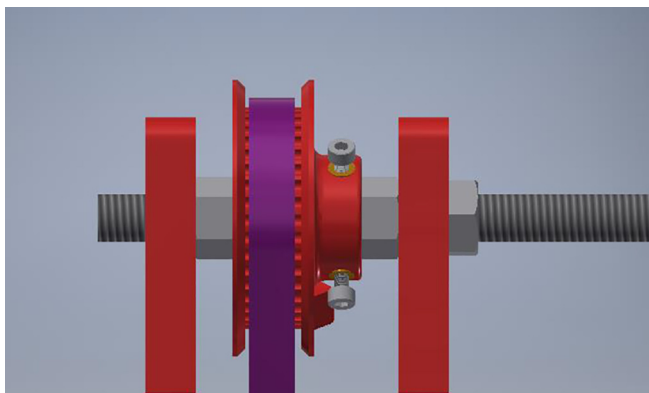


**Fig. 89.** Bearing in opposite bearing tower.

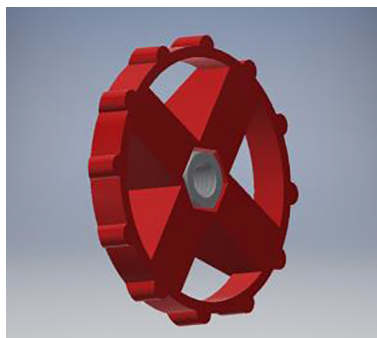


**Fig. 90.** Inserting printed tower crossbeam.

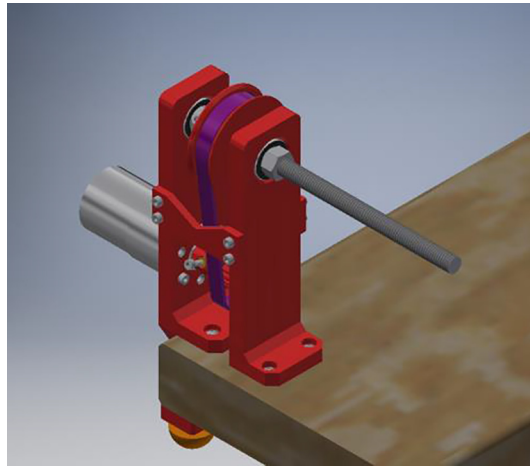
12. Add the top threaded rod, it is easiest if you slowly rotate each of the components on. Do not forget to add the belt now, because cannot be added if the rod is all the way on. Secure the large pulley with M3X10mm bolts as shown in [Fig. 91](#).
13. Press a nut into both of the spooler hubs ([Fig. 92](#)).
14. Add the spooler hub to the threaded rod shown in place and bare in [Fig. 93](#) and assembled in [Fig. 94](#).



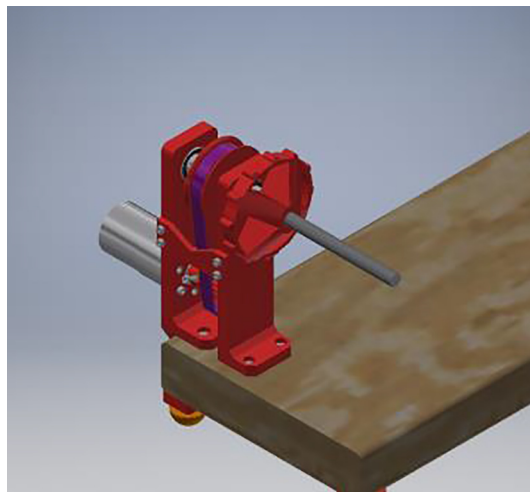
**Fig. 91.** Large pulley assembly on spooler.



**Fig. 92.** Nut in spooler hub.

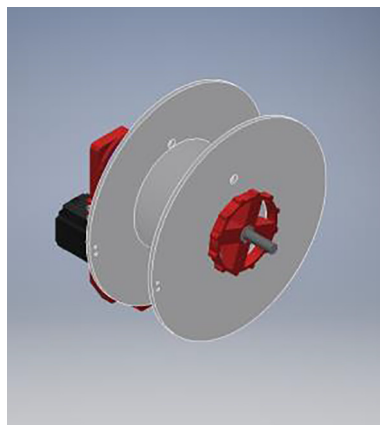


**Fig. 93.** Spooler Assembly ready for hubs.



**Fig. 94.** Add hub and tighten.

15. Finally add an empty spool and secure it with the final spooler hub (Fig. 95) and mount on main assembly (Fig. 96).



**Fig. 95.** Added spool to spooler.

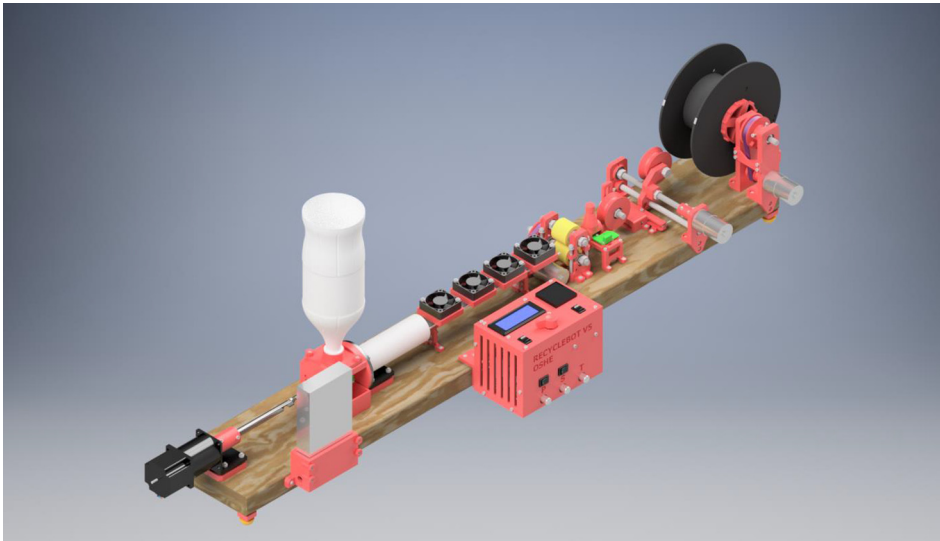


Fig. 96. Spooler mounted on main assembly. Completed mechanical build.

5.4. Electric wiring

The wiring is setup in two separate systems. The 110 V system that runs the heating element, and the 12 V system that runs the auger motor, RAMPS/Arduino board, DC motors, motor controllers, diameter sensor and LCD.

The 12 Volt power runs from the power supply to the RAMPS board, which is then distributed to the LCD, diameter sensor and auger motor. Separate wires are run from the power supply to each of the motor controllers.

The 110 V system has wires connected to the 110 V ports on the power supply. The 110 V runs directly to the heater controller and relay for the heater. The frame is grounded to the power supply ground. The ground is connected to one of the bolts holding on the floor flange of the barrel. The entire system is switched from the wall outlet with an emergency stop switch to cut power in case of malfunction.

The electrical wiring involves the following steps:

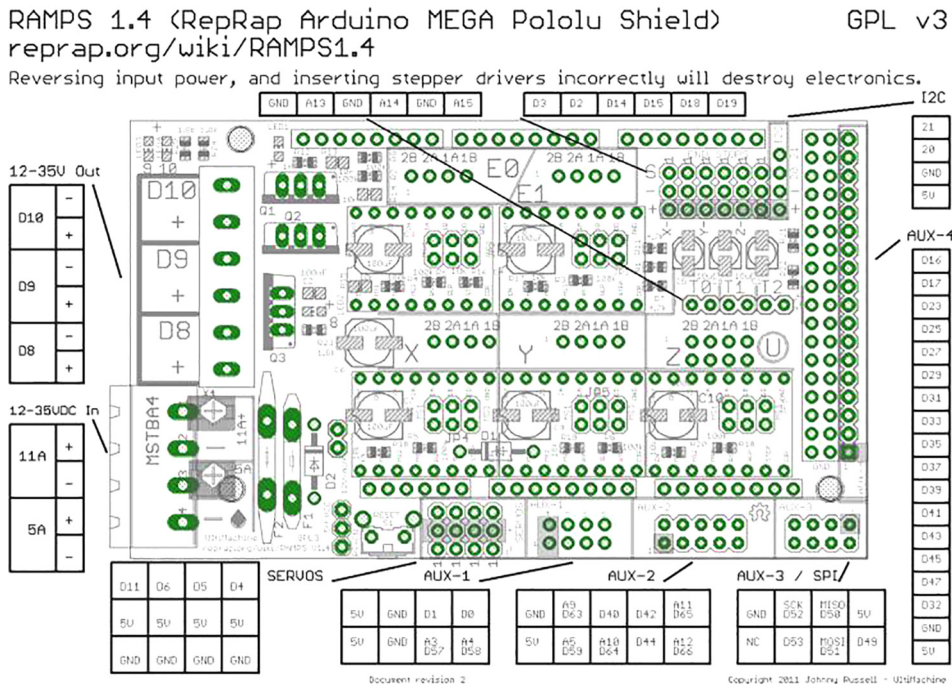


Fig. 97. RAMPS board layout.

1. Remove the cover from the controller box and the RAMPS board.
2. Place DDRV 8825 motor drivers on x, y, z, and Eo output pins on the RAMPS board as shown in Fig. 97.
3. Wire the heater controller following Fig. 98.
4. Wire the temperature sensor following Fig. 99. It should be noted that for the thermistor, longer wires need to be soldered to it so that it will reach to the control box. Finally, care should be taken to make sure the thermistor leads do not cross, which results in a bad reading.

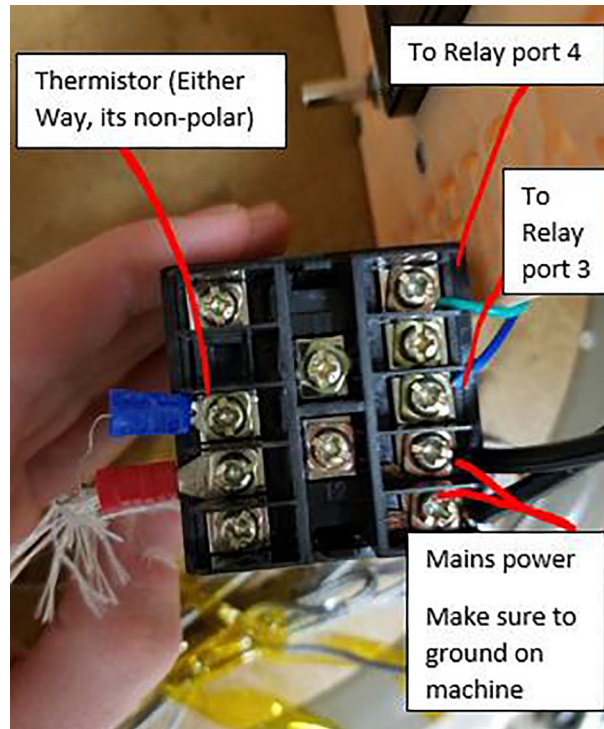


Fig. 98. Heater controller wiring.

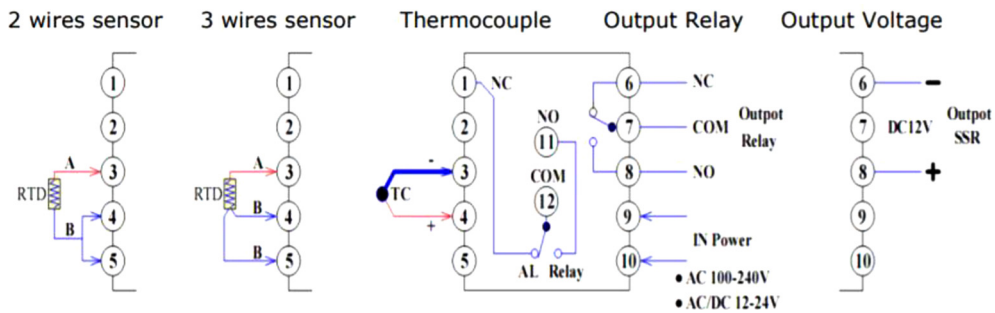


Fig. 99. Wire diagram for temperature sensor.



A wiring diagram for the entire system is shown in Fig. 100.

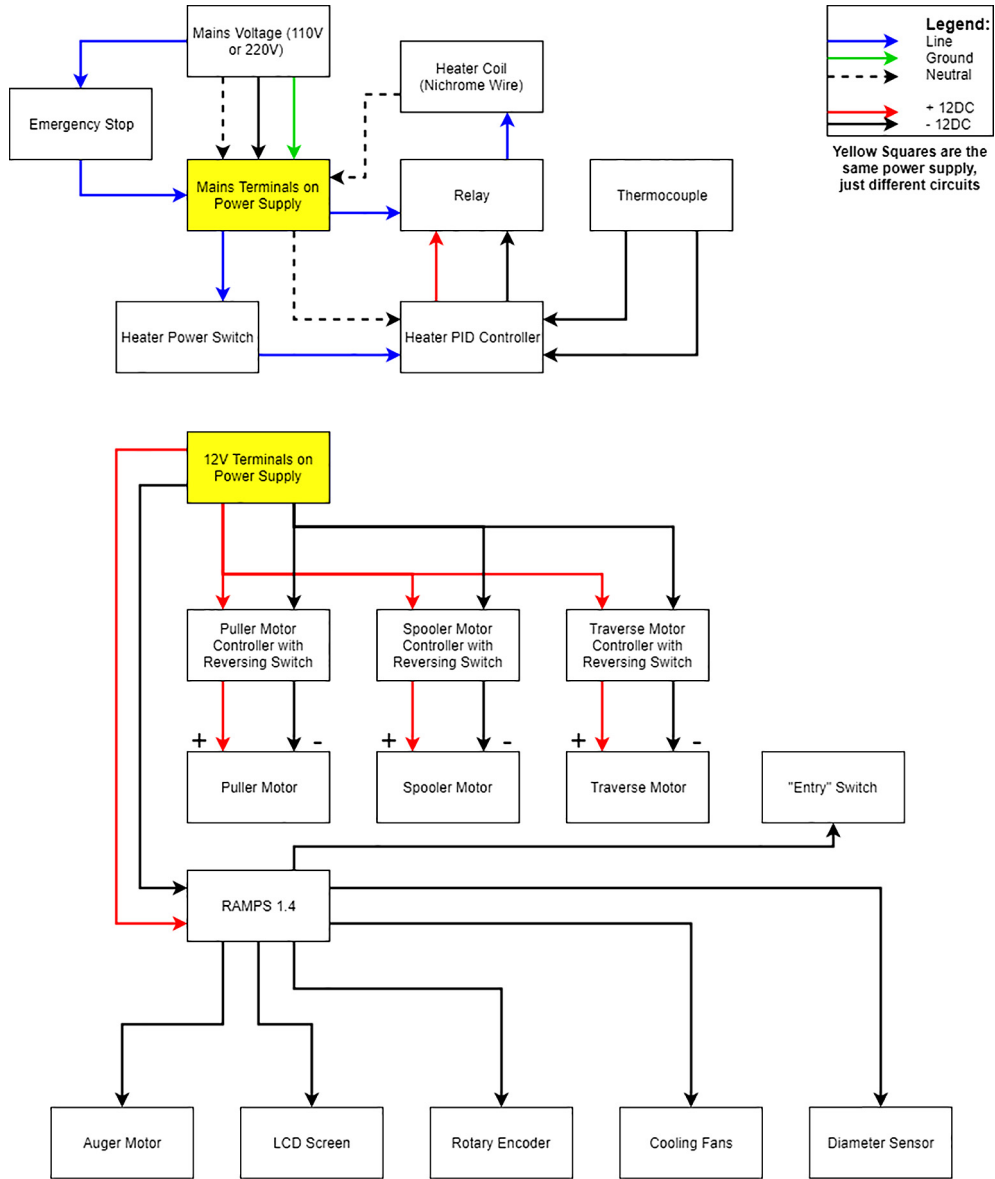


Fig. 100. Wiring diagram for the entire system.

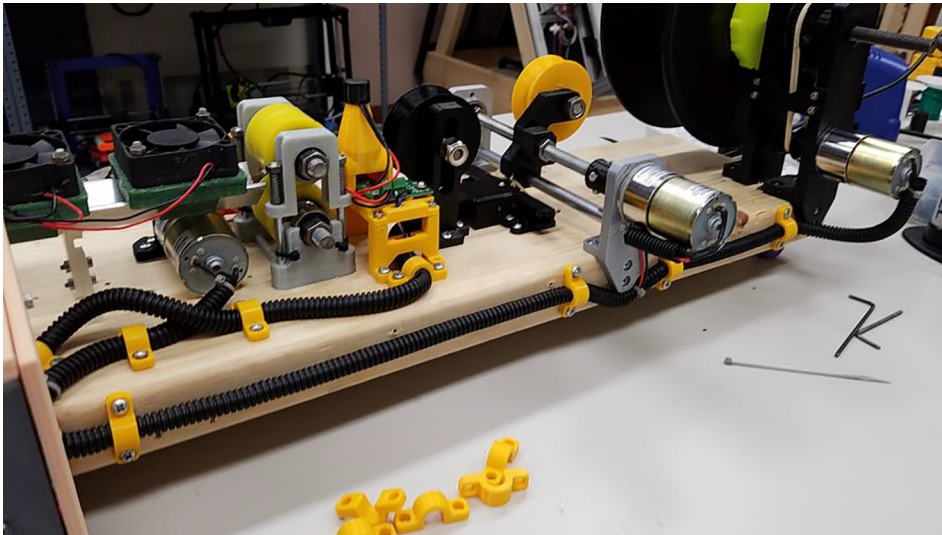
5. Wire the remaining electronic components following Table 5 and Fig. 100.

**Table 5**  
RAMPs 1.4 Pinout.

Component	Component Port	RAMPs 1.4 Port
Mulier Sensor	Positive Output Negative	RAMPs 5 V RAMPs A3 RAMPs Ground
LCD Screen	1 2 3 4 5 6 11 12 13 14 15 16	RAMPs AUX-4 53 RAMPs AUX-4 Ground RAMPs AUX-2 Ground (Top left) RAMPs AUX-4 51 RAMPs AUX-4 49 RAMPs AUX-4 47 RAMPs AUX-4 45 RAMPs AUX-4 43 RAMPs AUX-4 41 RAMPs AUX-4 39 RAMPs End-stop 5 V (closest to AUX-4) + I2C RAMPs End-stop ground (closest to AUX-4) – I2C
Rotary Encoder (Looking at the pins)	Left (3 pin side) Middle (3 pin side) Right (3 pin side)	RAMPs 2 RAMPs Ground (end stops closest to Aux 4) RAMPs 3
	Left (2 pin side) Right (2 pin side)	RAMPs Ground RAMPs 14
Auger	4 Pin Stepper Wire	X motor Slot
Cooling fans	“+” “-”	d10 + d10 –
“Entry” Switch	“+” “-”	D11 Ground

Note if menu function is reversed, switch rotary encoder pins Left and Right.

6. Organize wires with the wire loom and the 3-D printed wire loom mounts shown in use in [Fig. 101](#).



**Fig. 101.** Wire loom mounts.

## 5.5. Software

Download and open the Arduino Software (<https://www.arduino.cc/>). Download the software for the RepRapable Recyclebot from ref [42]. Open the program folder and make sure each of the program files open as tabs in the Arduino IDE environment. Plug in the Arduino using a USB cord to your computer. Next go to Tools > Board > Mega 2560. Make sure the proper port is selected for the Arduino. Finally hit the Upload button and make sure there are no errors. You should now see the main menu of the Recyclebot on the LCD screen. Unplug from your computer before powering up the machine using its own power.

## 6. Operation instructions

Tools needed to operate the system are shown in Table 6.

**Table 6**  
Tools and their uses required for operation.

Tool	Use
<ul style="list-style-type: none"> <li>• Tweezers,</li> <li>• Heat Resistant Gloves,</li> <li>• Flush Cutters,</li> <li>• Tape,</li> <li>• Scale,</li> <li>• Cup,</li> <li>• Calipers,</li> <li>• Safety Glasses,</li> <li>• Fan,</li> </ul>	<ul style="list-style-type: none"> <li>for guiding hot plastic to puller</li> <li>for protection against hot plastic</li> <li>for cutting excess filament</li> <li>for attaching filament to spool</li> <li>for weighing spool, and pellets</li> <li>for transferring pellets to hopper</li> <li>for assuring correct diameter</li> <li>for safety</li> <li>for ventilation</li> </ul>

### 6.1. Basic overview of recycling plastic waste

After classifying and separating the plastic to ensure that roughly equivalent melting points are used simultaneously (unless making some form of composite), it is cleaned, shredded into small pieces, and dried to control moisture content. The amount of cleaning will depend on the waste stream. However, in general the plastic should be cleaned to remove all visible contaminants (e.g. using mild soap and water to remove food particles from food containers). After cleaning if necessary the feedstock is dried and then shredded. To improve the filament quality, it is also possible to sieve the pieces into uniform size batches to help maintain the consistency of the feed rate and the resultant uniformity of the extruding filament. This can be accomplished with 3-D printed sieves. Shredding can occur using an office shredder [18], as well as commercial granulator, shredder (e.g. Shredbuddy or Filamaker shredder used in project Seafood to recycle ocean waste) or with the use of an open source shredder [45]. Waste plastic shards, powder or pellets are fed into the recyclebot through the hopper, and transported to the heating pipe by the cut-off auger, which is driven by a motor. The plastic is compressed and melted in this heating pipe and can be extruded through the nozzle to form filament for fused filament fabrication-based 3-D printing. More complex processes can be followed to make composites following ref [33]. However, most thermoplastics partially degrade during the recycling processes, as the heating-extruding cycle weakens the polymer [25,26]. This leads to a fixed number of iterations (e.g. 5x) before they must be chemically processed or additional virgin polymer, or less-recycled polymers must be added to enable the mechanical strength needed for some applications. To provide the foundation of a circular economy [21], considerably more work is needed in this area and the RepRapable RecycleBot enables this research to take place for low capital costs.

### 6.2. Safety

For safe operation of the RepRapable Recyclebot, please be aware of the following warnings:

- Burn Warning – The barrel, heat sink and nozzle of the extruder is hot during operation avoid touching these areas to prevent burns.
- Pinch Warning – Do not stick fingers or tools into the extruder hopper while screw is turning, the screw can pull tools or fingers towards the extruder inlet. Also, avoid sticking fingers between the Puller Rollers, or any belts and pulleys on the machine.
- Electrical Shock Warning – The Recyclebot uses both 12 V DC and mains voltage, ensure proper hookup and grounding procedures to avoid electrical shock.
- Static Shock Warning – The filament extruder and winding mechanism can create a static charge, although not inherently dangerous to operators, care must be taken to avoid accidental discharge on sensitive electrical equipment.

- Proper Ventilation Warning – Only use the Recyclebot in a well-ventilated area and on known polymers. Using some polymers (e.g. fluorinated ethylene propylene or FEP) could result in the release of toxic gasses. Only operate at temperatures recommended for extrusion of a particular polymer to avoid decomposition or burning.

If at any point, an emergency occurs, immediately hit the emergency stop button and unplug the machine. Never leave the machine unattended.

### 6.3. Operation

1. Plug in the machine and release the emergency stop to turn it on. The power supply should turn on, and the LCD screen should light up (Fig. 102).
2. Make sure all the knobs are off, and the heater is currently off, then flip the “Entry Switch below the LCD screen, this will progress you through the initial menus, these menus are not functional yet, so click the rotary encoder into skip until you get to the fan cooling section. Set this to 0% to allow for warm up. Fig. 103 shows the cooling settings.
3. Navigate to the “Manual” menu (Fig. 104).
4. Warm up extruder by turning on the PID Heater Controller with the switch below it (Fig. 105).
5. Once the heater reaches the desired temperature, wait an additional 12–15 min to allow for entire barrel and plastic to warm up. Then turn on the auger by going to Manual > Auger > Power > On (Fig. 106).
6. Feed in polymer into the hopper as shown in Fig. 107.
7. Once the auger is on, slowly start to turn the puller (P) knobs until the puller rollers start to turn.
8. Once the plastic starts to extrude, grab the plastic with a pair of tweezers or pliers, navigate the filament through the cooling section and place into the already powered puller. The filament should be pushed automatically through the diameter sensor, then guide the filament under the first tensioner, over the traverse tensioner and wind it onto the spool (Fig. 108).
9. Turn the traverse (T) motor on by turning the knob until it begins to spin, this also needs to be finely tuned to find the best speed for even winding.
10. Adjust speeds of both the puller and winder to find the perfect spot for making the desired diameter of filament.

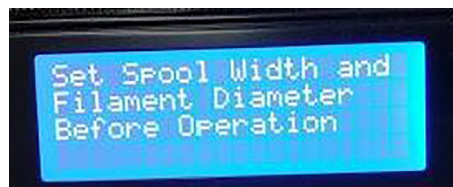


Fig. 102. Initial power up screen.



Fig. 103. Cooling power intensity settings.



Fig. 104. Manual menu.



Fig. 105. RepRapable Recyclebot switches.



Fig. 106. Auger Power Selection.



Fig. 107. Plastic in hopper.

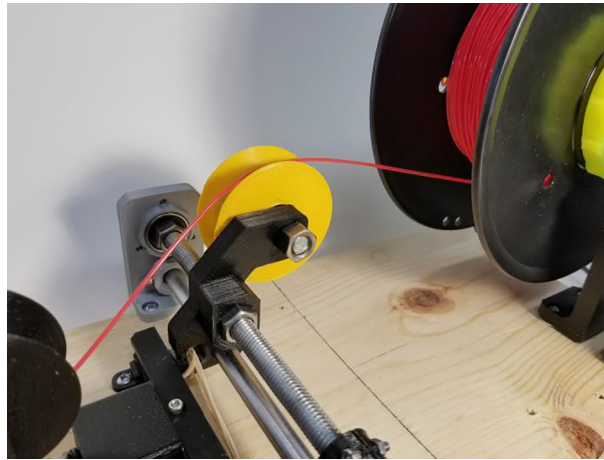


Fig. 108. Filament over traverse and winding on spool.

## 7. Validation and characterization

The RepRapable Recyclebot (Recyclebot V5) shown operating in Fig. 109 was tested with various polymers and can handle any thermopolymer up to a maximum temperature of 250 °C. It should be noted that the highest temperature achievable is 287 °C, which is the maximum operating temperature for the Nichrome wire. However, 250 °C is the maximum tested to provide a safety factor.

The RepRapable Recyclebot was validated with PLA the most common desktop FFF 3-D printing filament. The system can create a full kilogram spool of virgin PLA measured with a digital balance ( $\pm 0.01$  g) in 2.5 h ( $\pm 10$  min). The PLA extrusion rate is 0.4 kg/h after the initial heating of 30 min. is complete so in a 24-h period running continually the system can produce more than 9 spools (9.4 kg). The diameter was monitored in real time over the entire spool with the Mulier system and verified with a digital caliper ( $\pm 0.001$  mm). The diameter has a variation of  $\pm 4.6\%$ . The energy used to manufacture the filament was recorded with a digital multimeter ( $\pm 0.01$  kWh). The machine used a total of 0.24 kWh for the whole process of making 1 kg of filament. This is notably more efficient than past Recyclebot designs [17,18,21]. Thus, filament can be manufactured for very low costs as well as with a reduced environmental footprint [19–21].

The cost per kilogram of Natureworks Ingeo Biopolymer PLA pellets is \$5.50. Thus, for the cost of electricity of 10 cents per kWh, filament costs can be reduced to \$5.52/kg or less than 22% of current commercial filaments. It should be noted there is a wide range in the costs of commercial filaments, with many suppliers well over \$25/kg. Examples of both virgin filament (made from PLA pellets at 210 °C) as well as recycled filament (from waste PLA at 200 °C) are shown in Fig. 110. The RepRapable Recyclebot can also use ground up PLA from old or failed 3-D prints as well as PLA waste (e.g. cleaned and ground up food containers) as shown in Fig. 111 with comparable results to that of colored virgin PLA that was also made in the extruder and PLA that was purchased. Using waste plastic and only the costs of electricity (e.g. excluding labor costs and capital

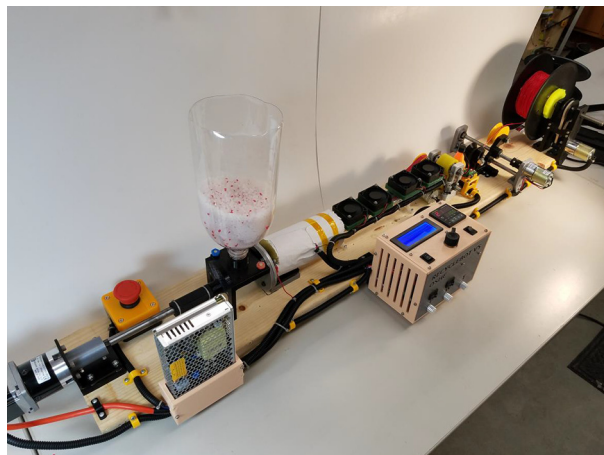
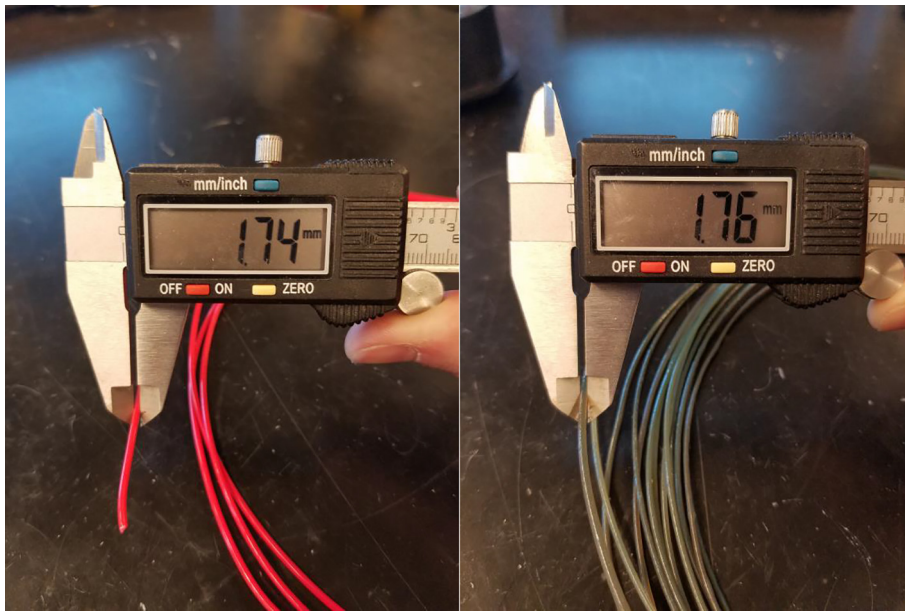


Fig. 109. Fully Operational RepRapable Recyclebot in production.



**Fig. 110.** Digital caliper verification of  $\pm 0.01$  mm for 1.75 mm a) filament from virgin PLA pellets (red) and b) filament from recycled PLA (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 111.** Comparison between printed products from recycled PLA (Made, left), virgin PLA (Made, middle) and virgin PLA (Purchased, right).

equipment costs) the RepRapable Recyclebot can produce filament at less than 2.5 cents per kg, which is 1000X less than the currently available commercial filament. This makes the remarkable reduced costs of 3-D printing scientific equipment [24,46–51] even more clear. In addition, as the RepRapable Recyclebot is largely printed this can decrease the cost of it by about \$40 for the plastic to make itself.

Overall the system has been shown to be functional to be used in laboratories for fabricating filament for 3-D printing experiments. It is meant primarily as a materials preparation tool for the rapidly expanding FFF materials science and engineering community. However, the RepRapable Recyclebot can still be improved. The current limits of the design of the Recyclebot are that it only has manual operation where motor speeds must be adjusted until the desired diameter is reached. The design also has a limiting factor of how much filament can be made in a certain amount of time due to the small barrel, single heating zone and screw size. If the barrel was increased in diameter and length, the overall length of the recyclebot would need to increase because of the extra length of aluminum that would be needed to cool off the larger amount of filament running through at one time. Finally, the recyclebot requires that the inlet particles be approximately uniform to ensure consistent material feed into the auger, which will result in uniform material extrusion through the nozzle and thus a reliable

filament diameter. This can be accomplished by making and chipping filament, but each pass through the recycling process reduces the mechanical properties (yield and elongation for example) of the polymer through a reduction in molecular weight [25,26]. Reduction in mechanical properties of polymers also has the consequence of broadening the liquidus region for the given polymer, resulting in a less defined temperature where the polymer is completely liquid or solid resulting in less predictable rheology control during the filament production process.

## 8. Future work

The RepRapable Recyclebot is an open source hardware platform intended to be improved by the community. It can be further improved with i) software enabled feedback loops and quality control, ii) real time changes in extrusion settings based on monitoring (e.g. PID control of filament diameter to change pull speed), iii) alternative cooling mechanisms such as a liquid bath to extend the range of polymers that can be used, and iv) a library of presets for known recyclable thermopolymers [35]. In addition, further work could improve the design to minimize the amount of polymer (and thus cost and print time) by optimizing the percent infill based on the mechanical loading for each component. Additional work is needed to compare vertical as used in ref [21] and a design for a RepRapable version (Fig. 112) or angled systems to the horizontal recyclebot system described here.

Far more work is needed to use recyclebots to explore all of the potential recycling possibilities from the most common to the least common and to gauge the impacts of additives on filament. Recently, for example, Zander et al. [52] demonstrated how to make fused filament feedstock from the most readily available and largest quantity recycled plastic, polyethylene terephthalate (PET), on a commercial system that would be exceptionally valuable to replicate on a low-cost recyclebot system. On the other hand, Hart et al. [53] showed how products as highly specialized as MRE pouches could be processed into 3-D printing filament. Making filament from known feed stocks and additives could help the current lack of information about material ingredients in most plastic products until consumer rights laws are modernized [54].

In addition, the optimal parameters for the RepRapable Recyclebot need to be found and reported for each waste feedstock and the interactions between the various parameters internal to the Recyclebot (e.g. extruder temperature, speed and nozzle diameter) and external to it (e.g. room temperature and humidity) need to be quantified and shared. In addition, work is needed to quantify the impact of size uniformity of waste polymer feedstock to filament quality as recycled waste and particularly composites can be made up a large size distribution of particles. For example, small particles can aggregate and stick to the auger as it warms by thermal conduction during extrusion potentially limiting feedstock from being moved to the hot zone at an even rate. Methods to solve this problem are needed. Far more work is needed on the impact of additives on filament properties. For example, here a 5% mixture by weight of pellets was used to die the filament red (shown in Figs. 109–111) using a master batch colorant. Further work could optimize the colorant needed for different colors and shades and gauge the impact of any type of additives to filament quality and materials characteristics.

Lastly, an open source pelletizer addition is needed for the RepRapable Recyclebot design. By fabricating pellets rather than filament from some feed stocks (e.g. wood waste polymer composites that need two passes to make uniform high-quality filament [33] can be reduced to one for pellets) both the polymer mechanical properties can be preserved through multiple cycles as well as reducing the embodied energy, costs, and time needed for each processing recycle loop. Significant progress has been made by the maker/RepRap communities [55,56], the academic community [57,58] and open source hard-

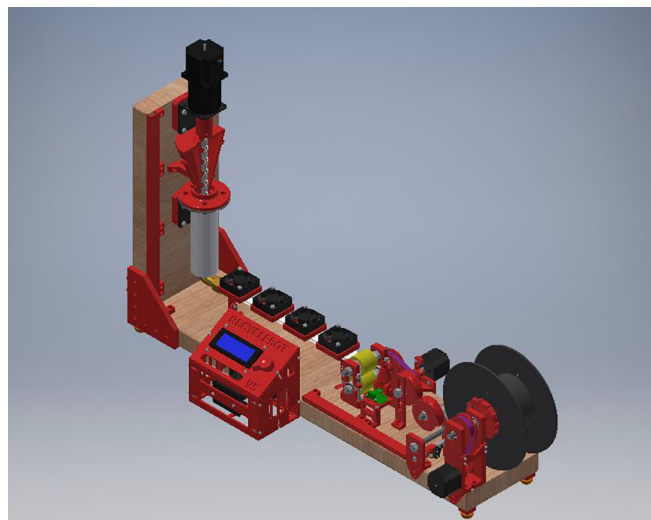


Fig. 112. Vertical RepRapable Recyclebot design.



ware companies like re:3D [59] in making viable pellet-based 3-D printing systems. With the addition of an open source pelletizer the RepRapable Recyclebot will be able to recycle waste into high-quality filament for applications demanding tight tolerances and control as well produce pellets for large volume recycling and direct fabrication with large-format 3-D printers. This will thus help democratize not only filament manufacturing but also aid in the expansion of viable forms of distributed recycling at the small scale.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.ohx.2018.e00026>.

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