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Understanding the LulzBot TAZ 5 3-D Printer and Dual Extruder V3 Print Head

prepared by Dwight D Hofstetter Jr
Bennett Aerospace, Inc.
Raleigh, NC

under contract SURV SUB REL 3 CLIN 5 L 11600.03.0005.0000

NOTICES

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14. ABSTRACT
This report documents the processes and procedures that the US Army Combat Capabilities Development Command Army Research Laboratory's Explosive Effects Branch follows to produce plastic and rubber components with the LulzBot TAZ 5 3-D printer. The printer operates using the fused deposition modeling method to produce parts like explosive containers, surrogate mines, electronics cases, instrumentation mounts, and demonstration pieces for illustration purposes in a fast, cost-effective, and repeatable manner. SolidWorks computer-aided design (CAD) part files are converted to stereolithography files and imported into the Cura printer host slicing-application software, which cuts the model into horizontal layers, creates a printing path for the print head to follow on each layer of the model, and controls the movement of the TAZ 5. A basic understanding of the hardware, the filament material, the slicing application, and the CAD model is required to set proper parameters to produce a satisfactory part. A print job can fail at times but the outlined troubleshooting methods can reduce downtime.

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Contents

List of Figures

1. Introduction/Background

Since its inception in the 1980s, additive manufacturing, also referred to as 3-D printing, has become an invaluable tool in prototyping and small-scale production.[1,2] For over five years, the Explosive Effects Branch (EEB) of the US Army Combat Capabilities Development Command Army Research Laboratory has used a LulzBot TAZ 5 3-D printer to produce cost-efficient and accurate parts with quick build times through a process called fused deposition modeling (FDM). These created parts are used as experimental components as well as prototype demonstration pieces.

The FDM process takes raw material, typically a plastic in the form of cylindrical spooled filament, and extrudes it through a heated print head. The TAZ 5 uses a cylindrical filament with a 3-mm diameter that is wound on a plastic spool. Feeder cogs grip the filament and drive it down to the print nozzle. The print-head assembly leaves a printed layer made from the melted and extruded filament as it moves parallel to the print bed. After each layer is complete, the print head is elevated to the height of the next layer to begin printing a new layer. FDM printers use inexpensive components and consumables making them some of the most cost-efficient and widely used printers on the market. More advanced printers such as stereolithography (SLA) printers can use lasers to cure resin, which produces more accurate prints but components and consumables are more expensive.

Examples of EEB's manufactured components include explosive containers, surrogate mines, electronics cases, instrumentation mounts, and prototype-scale vehicles. The most intricate shape locally produced with the TAZ 5 has been in the form of a bolt with ¼ in.-20 thread. With the addition of the LulzBot Dual Extruder v3, the EEB's TAZ 5 has the ability to build a part with two different structural materials, or one structural material and one support material. Figure 1 shows the EEB LulzBot TAZ 5 with the Dual Extruder v3.

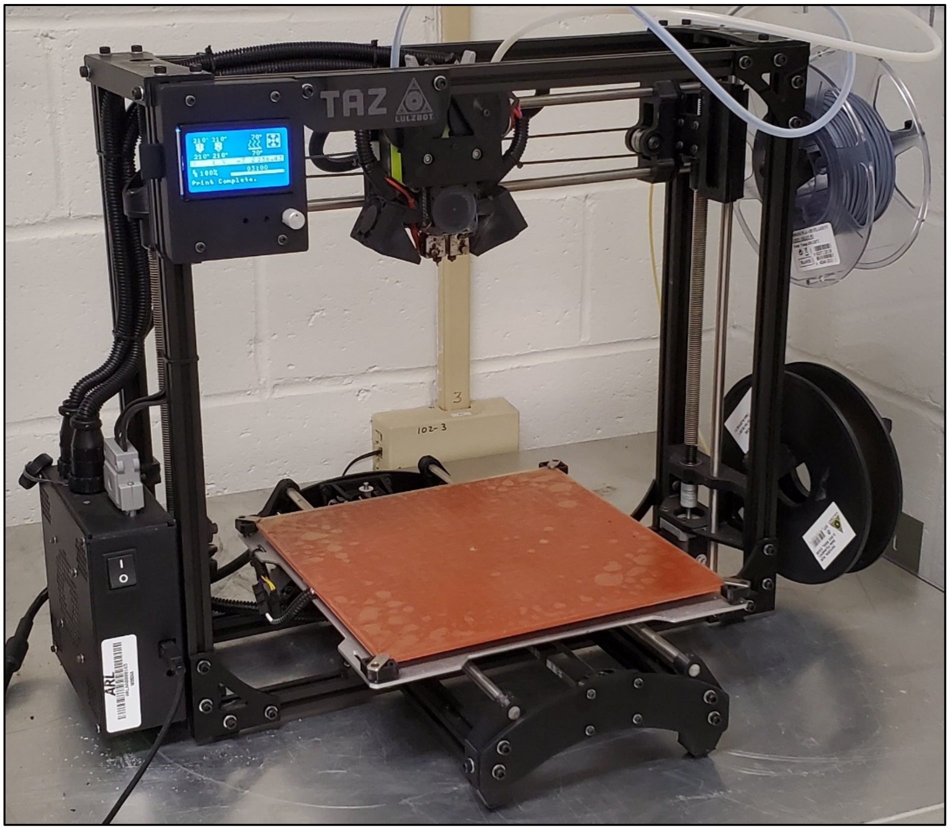

Fig. 1 LulzBot TAZ 5

This report provides details of the TAZ 5 system used by EEB. First, the specific TAZ 5 printer hardware is described to familiarize the reader with capabilities and limitations of the physical machine. Then, the filament that is used is discussed. Next, the software program that EEB uses to digitally control the TAZ 5 is reviewed and EEB-recommended optimal settings for size, strength, table adhesion, detail, overhang support, and speed are outlined. Considerations for computer-aided design (CAD) of parts to be made with the LulzBot are introduced. Finally, preprint machine preparation, the initiation of a 3-D print, and how to troubleshoot failed prints are explained. This report is intended to be a valuable companion to the user's manual and not as a replacement for the manual.

2. 3-D Printing Process

Although the TAZ 5 has proven a very capable machine, the operator must understand its limits to take full advantage of its efficiency. The LulzBot TAZ 5 User Manual,[3] TAZ Bed Leveling,[4] and Tips and Tricks: Dual More with the Dual Extruder v3[5] documents provide a detailed explanation of the operation of the TAZ 5. The four major components required to print with the EEB system include the printing hardware, filament, a slicing application, and a CAD program.

2.1 Hardware

The LulzBot TAZ 5 is an unenclosed desktop 3-D printer with a heated print bed. Some FDM printers are built with an enclosure around the build area but the TAZ 5 does not have this feature. The frame of the printer is made up of both extruded aluminum and 3-D printed components. The primary components of the printer include the nozzle, print head, and bed/table. The heated print bed promotes adhesion between the part and the print surface and the printable area is 290 × 275 mm (11.4 × 10.8 inches). The print head can be elevated to a height of 250 mm (9.8 inches). Figure 2 shows the printable volume and major components of the TAZ 5.

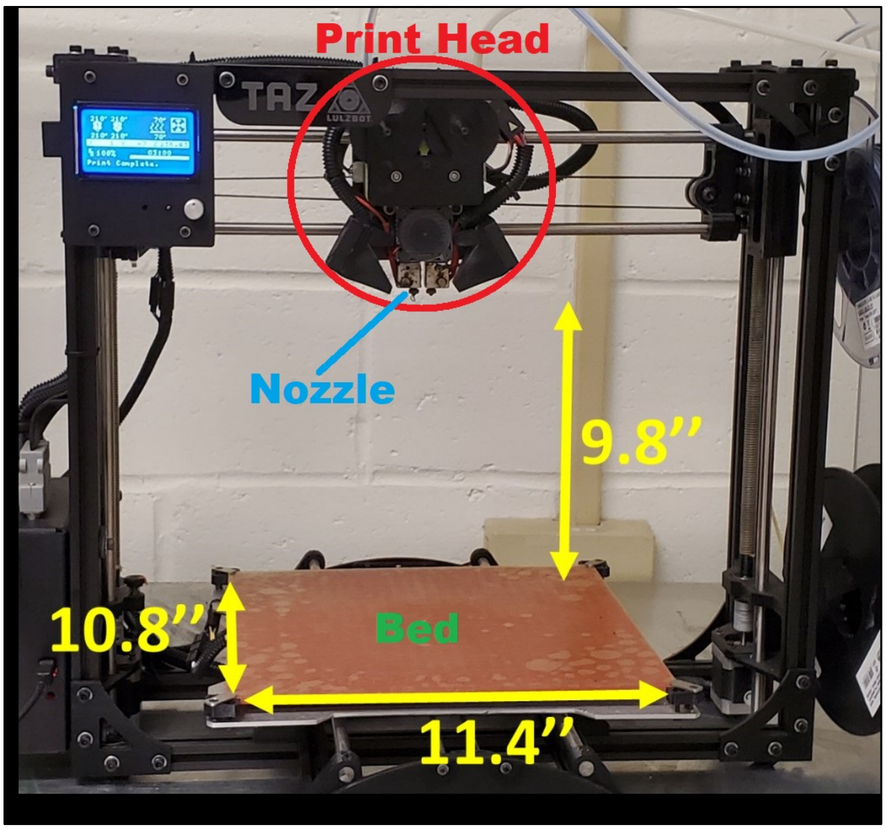

Fig. 2 Printer layout

The Dual Extruder v3 print head is equipped with two nozzles that have 0.5-mm openings. The width of the bead that is laid cannot be less than 0.5 mm. If a detail is required to be less than 0.5 mm wide, laying the piece on the table so that the width is equal to the layer height is the only option aside from postmachining the part after it has been printed. Smaller aftermarket nozzles can be fitted to the print head for better accuracy but the smaller openings would allow for less volume flow. At this time, the speed of the 0.5-mm nozzle is the best option for EEB.

The printer can print a single bead width. However, one bead width is typically not ideal since it has little structural integrity. Nonuniform filament diameter can affect how much filament is extruded since the linear feed rate remains unchanged as varying volume is extruded. Inconsistent extrusion can produce an incomplete bead. The LulzBot TAZ 5 User Manual[3] recommends regularly measuring the diameter of filament samples so the average diameter can be set in the Cura control software and allow the program to adjust the feed rate accordingly. This is generally not a procedure EEB follows since most printed pieces do not require fine detail. Two neighboring beads add strength and if one bead is not laid completely, the other bead can compensate.

The initial nozzle height above the table is manually set by raising or lowering the thumb screw that contacts the contact switch on the print head. When the contact switch is closed, the software believes the nozzle is in the vertical home position. The user should measure the height of the first laid bead with micrometers and adjust the thumb screw so the bead matches the set height in the printer host software. The height value of the first layer can also be altered in the printer host software to match the bead printed by the printer. Figure 3 shows how a first laid bead can be affected by the height of the nozzle without adjusting the set height in the printer host software. Subsequent layers are produced at the correct height due to the vertical travel increments of the nozzle set in the printer host software.

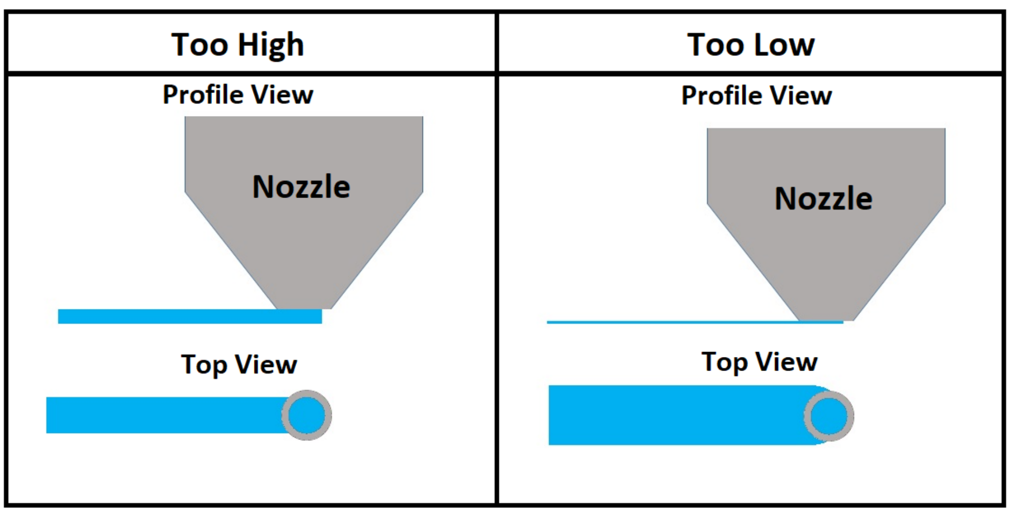

Fig. 3 First bead thickness compared to nozzle height

An important consideration as the print head moves laterally in two dimensions is the level of the print surface relative to the plane of travel. According to TAZ Bed Leveling[4], when leveling the bed, a piece of paper should be able to slide between the nozzle and print bed at all table corner locations, which is approximately 0.1 mm but for a "smooth slide", 0.2 mm is preferred. The thumb screw can then be adjusted so the nozzle height matches the set bead height. It is best to print several test parts before printing the final parts to assure a desired fit without having to postprocess the final part extensively after printing.

It is difficult to obtain a smooth part when printing with the FDM process. When the cylindrical bead of material is extruded from the nozzle, it is pancaked against the build table or other layers. The hemispherical edge of each bead results in a corrugated surface when stacked with other layers. More numerous thinner layers can make a surface smoother, but corrugation will always exist. Figure 4 illustrates how an FDM 3-D printed surface can have a rough texture.

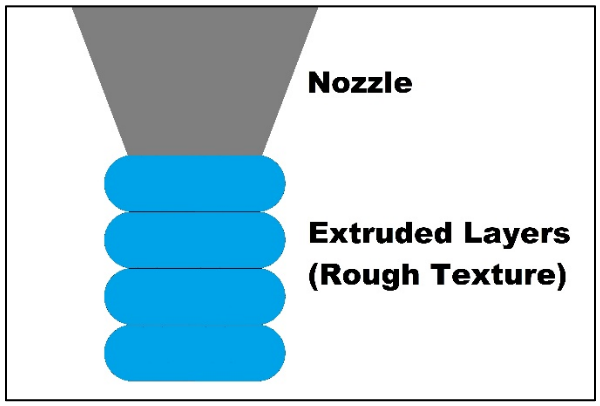

Fig. 4 FDM printed pancaked layers

It is possible to generate one smooth and flat surface using the FDM method by exploiting the surface of the print bed. When a surface requires a smooth or flat finish, it is often best to place that surface against the print bed rather than allowing it to be a side or the top of the printed part. Even the top surface can have an uneven finish due to the path of the print head. When the heated filament is extruded onto the smooth surface of the print bed, the matching part surface will be smooth as well.

Part orientation is an important feature to remember when printing using the FDM method. The printer has a higher chance of making a circular hole if the circular area of the hole is parallel with the print bed. If the circular area of the hole is oriented perpendicular to the print bed, the layers of the print will alter the precision of the hole and become corrugated, as can be seen in Fig. 5.

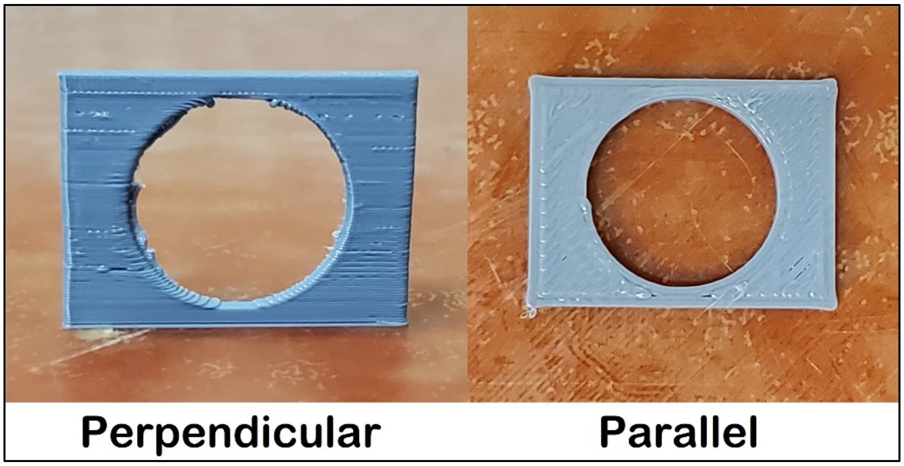

Fig. 5 Hole formation

Webbing can also affect print quality. Webbing occurs when material oozes from a nozzle and is stretched from the last-laid bead to the location where the next bead is started, creating the appearance of a spider's web. The print head can retract filament in an attempt to prevent webbing but this is not always effective. Figure 6 shows an example of webbing.

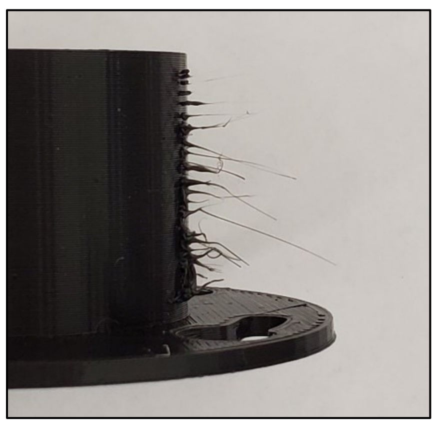

Fig. 6 Webbing

2.2 Filaments

Filaments used in the EEB TAZ 5 have included polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), t-glass polyethylene terephthalate (PETT), polyvinyl acetate (PVA), and thermoplastic elastomer (TPE). PLA is EEB's preferred general-use filament due to its resistance to warping and ease of detailing, such as cutting and filing after removing the part from the print bed. This material is plant based and vapors released during printing are nontoxic. ABS is a very common plastic but has shown significant warping and delamination when used to print on the TAZ 5. Parts printed with ABS that have a footprint of less than 127 × 127 mm

(5 × 5 inches) tend to have the same quality as PLA parts. The warping and delamination are often attributed to larger areas that are allowed to cool between individually printed layers. PETT is a very strong and translucent material that has the highest resistance to warping out of all of the filaments used. This is the preferred material for EEB when strength and durability are required. PVA is a water-soluble material that is often used as a support material. TPE is a rubber material that is useful for making plugs or insulators. The printer can print 3-mm-diameter filaments of thermoplastic materials that do not require a print temperature of higher than 300 °C. The safety settings on the printer will shut it down if the nozzle temperature exceeds this value. In the past, maintaining a print head temperature of 290 °C while printing has become unstable and the temperature jumps to 300 °C, and thus shuts down the printer. Filament will also be covered later in the report since Cura g-code is specific to what filament is loaded into the TAZ 5.

Since the TAZ 5 is currently equipped with the Dual Extruder v3 print head, PVA can be used as a support material that can be dissolved in water. This is the recommended option if a section of the part requires bridging. Very intricate features can be made by supporting the structural material with PVA. EEB tries to avoid using PVA whenever possible because it increases print time and, more importantly, the nozzle extruding the PVA tends to ooze even though the PVA has been retracted. Fortunately, the unwanted PVA can be dissolved from the part with water but it can affect the structural integrity of the finished part since PVA occupies the volume meant for structural material.

The LulzBot TAZ 5 User Manual[3] does an effective job of explaining how to load the print head with filament by heating the print head, removing the old filament, and extruding the new filament. However, the following tips can simplify loading filament.

A new roll of filament comes with the free end taped to the side of the reel. The tape can be removed from the tip or the tip can be cut off and discarded. Cutting the tip is recommended to eliminate the possibility of adhesive being deposited inside the print head. A blunt end is often formed when cutting the filament at a perpendicular angle. The path that the filament travels inside the print head is not perfectly smooth. The filament end must navigate over joints and a blunt end can become lodged. Rounding the edges of the filament end by trimming should eliminate the potential of becoming lodged. The end can also be heated and compressed to make a rounded end. Filament tends to form to the reel that holds it, meaning that it naturally curves to a certain orientation. This curve can guide the end of the filament to become lodged on the gap between the feeder cog and the print-head housing within the print head. The best practice is to straighten the filament before insertion by bending it by hand. Figure 7 shows a diagram of how the filament can become caught inside the print head.

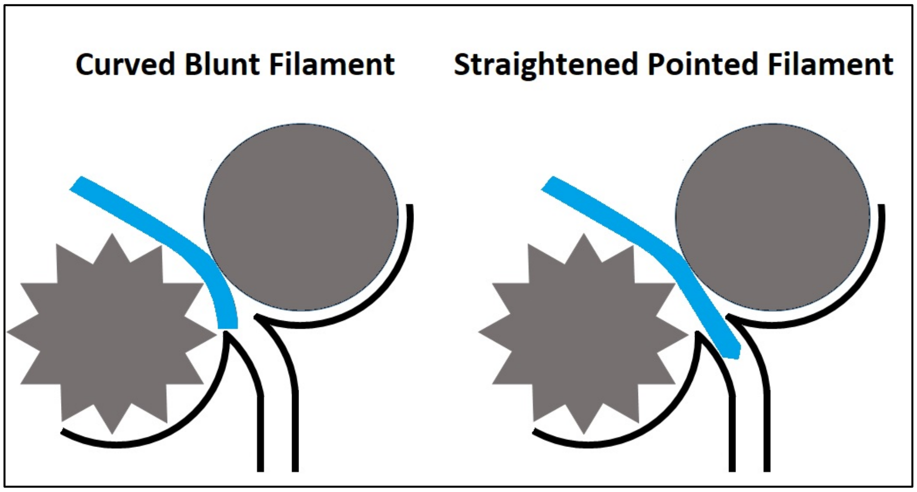

Fig. 7 Proper filament preparation reduces feeder cog lodging

2.3 Slicing and Control Application

After a designer creates the model in a CAD program such as SolidWorks[6], the part file must be converted to a standard format that can be read by the controlling and slicing application. Common file types are stereolithography (.STL), wavefront OBJ (.OBJ), extensible 3-D graphics (.X3D), or 3-D manufacturing format (.3MF) format. The most commonly used file type in 3-D printing is .STL and it is the only one specifically mentioned in the LulzBot TAZ 5 User Manual[3]. A slicing application reads the part file and then determines the intersection of the part with a plane that represents a fixed height of the print head. In this way, the software "slices" the 3-D part to create individual 2-D shapes that are additively stacked on top of each other to make the final part. To make the part, the slicing software converts "slices" into a language that can be understood by the 3-D printer. The slicing software then can control the movements of the printer to create the part.

Although other slicing applications such as Slic3r[7] can be used, the Cura LulzBot Edition[8] software is a custom version for the LulzBot that is distributed by the manufacturer. Usage of Cura is explained in detail in the LulzBot TAZ 5 User Manual.[3] It is an open-source 3-D printer slicing application, available under a GNU Lesser General Public License Version 3.[5] The g-code file that provides the instructions to the printer is a plain-text file with a series of text-based codes and a list of the complete X, Y, and Z axis coordinates used for controlling the movement of the 3-D printer.[3] Cura can convert the .STL-formatted model into g-code once the file is uploaded. The g-code file is typical of many computer numerical control (CNC) files for computer-aided manufacturing.

When opening the Cura software, the user imports the .STL file into the software on the Prepare screen. Many options are not accessible until the part is added. Cura will highlight the model in red if it does not fit within the build volume. Some models that are too long to be printed parallel to an axis may have the ability to be angled diagonally to fit between corners. The model can also be scaled down in Cura.

Once the part is imported and the printer is physically connected to the computer by the USB plug, the Cura software needs to be manually connected using the Connect button on the Cura Monitor screen so the software can control the TAZ 5. The print head and bed temperatures can be preheated while other features are set. Table and nozzle position as well as filament extrusion and retraction can also be controlled on the Monitor screen. On the Prepare screen, an operator can modify the model's position, rotation, quantity, and scale. An operator can also delete or replace a part on this screen. If models are replaced without closing and reopening Cura, the connection to the TAZ 5 does not need to be reestablished via the Connect button.

Cura will automatically slice a model depending on how a user sets the printing preferences. When a user sets variables such as layer height, filament type, speed, and so on, they are telling Cura how to write the g-code to control the printer. Since the TAZ 5 can print a variety of materials, it is necessary to ensure the printer is set up properly for the current job. Cura comes equipped with preset filament profiles that can be found on the Prepare screen. Custom profiles can be set but EEB typically uses PLA (Verbatim), ABS (Village Plastics), HIPS (Village Plastics), PVA, and HIPS (Village Plastics) profiles to print PLA, ABS, PETT, PVA, and TPE, respectively. Some material presets have retraction motions due to the tendency of certain materials to web more than others. Choosing or creating a material preset with a lower print temperature will also guard against ooze. Care must be taken to ensure that the extruded material is still hot enough to fuse to preexisting layers.

Most parts do not require added table adhesion. However, large parts may require a brim to be called for in Cura to keep edges from warping from the table when printing. A brim circles the base of the print while making contact, helping adhere the print to the heated plate. This is only one-layer thick and easily removed when the part is completed.[3] The brim is printed in contact with the part while a skirt is printed around the part not in contact so that the nozzle can extrude filament before printing to eliminate air gaps in the nozzle that would affect the bead uniformity.

The width of the brim and skirt, as well as the distance the skirt is from the part, can be specified in the Custom tab in Cura. The default brim bead width count is 10 while the default skirt bead width is 2 with a skirt distance from the part of 3 mm. The brim and the skirt are only one bead-height tall. EEB uses the default brim and skirt settings unless a part severely peels from the table during printing.

Setting the speed options of high detail, standard, and high speed in Cura controls the layer height. High detail, standard, and high speed have set layer thicknesses of 0.16, 0.25, and 0.38 mm, respectively. Cura also adjusts print speed of the head depending on which speed option and material is selected. By selecting and modifying the custom print option in Cura, the layer height as well as the bottom layer height and top layer height can be set directly. The thinnest layer height printed with the EEB TAZ 5 has been 0.1 mm. When the user selects a 0.1-mm layer height under the custom tab in Cura, the software changes extrusion speed so that the bead width remains unchanged. Figure 8 shows a 1/4 inch-20 thread pattern that was printed with a 0.1-mm layer thickness. Cura will not try to print a CAD model with a wall thickness less than 0.51 mm. EEB prefers to print wall thicknesses of a minimum of 0.75 mm to ensure that two beads are printed across a wall. The layer view in Cura can display if a feature is thick enough to print. If a feature is thick enough to print, the feature is shown when scrolling the layer view while a feature that is too thin will not be displayed.

Fig. 8 1/4 inch-20 thread layer height example

Cura offers the option to print with or without supports for overhangs. The second nozzle can print supports from any filament that is loaded in the nozzle. Supports can also be printed by the first nozzle as it is printing the part. The LulzBot TAZ 5 User Manual[3] explains how to set Cura to print supports from the first nozzle. Printing without support is recommended only if an overhang does not exceed a certain degree of inclination. The LulzBot TAZ 5 User Manual[3] recommends using support with an overhang exceeding 45°. EEB has been able to print parts with roughly a 32° overhang without the use of support material (Fig. 9).

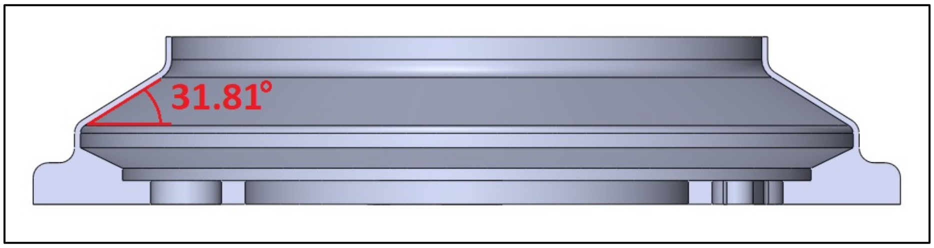

Fig. 9 Maximum unsupported overhang

Overhangs are built differently depending on if Cura believes support will be generated or not. If building without support, the support option must not be selected. If the second nozzle support option is selected with no filament in the print head, Cura will assume filler material will support structural material. If Cura believes support material was printed and it was not, the print path may start printing overhanging structural material away from the existing structural material and print toward it. When no support material is selected, Cura will continue to build from the structural material outward. Figure 10 illustrates how support settings in Cura can affect the path of the nozzle.

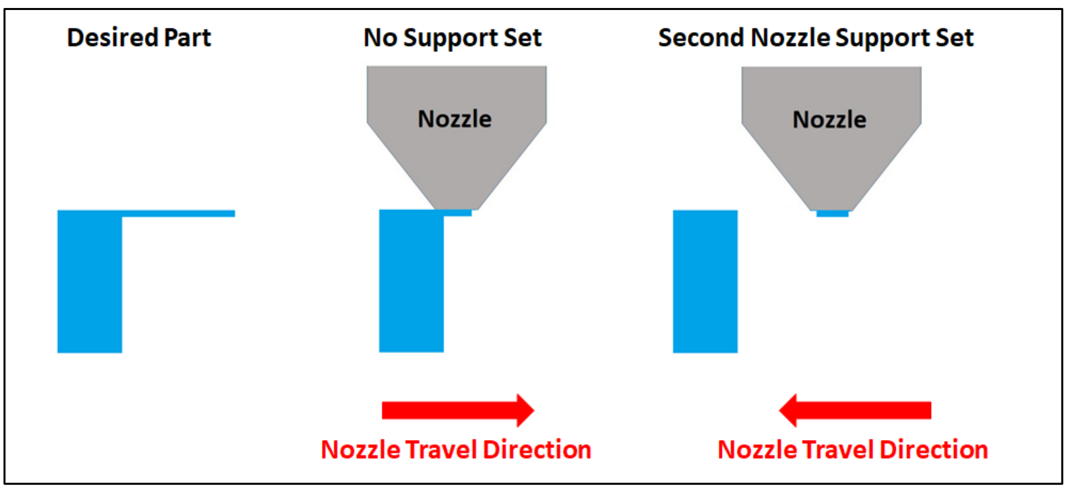

Fig. 10 Support option effect on nozzle path

If a faster print time is the driving factor, several settings can be modified to speed the print process. Changing the percentage of infill or the amount of interior support will decrease the print time without affecting the outer aesthetics of the part. Cura typically optimizes infill as a truss structure. As the infill percentage is increased the trusses become thicker, eventually forming into a solid fill. EEB typically prints with an infill of 20%, and on rare occasion 10%. The optimization algorithm within Cura allows the truss pattern inside the infilled parts to be almost as strong as solid parts. However, no experiments have been performed to prove this optimization. Setting Cura to high speed can cut the print time in half on certain parts depending on the part size. EEB has never adjusted the print speed since most parts can be printed within an acceptable amount of time when the default print speed is selected. The scale can be adjusted if the shape of the part is critical but the size is not, such as a demonstration piece.

2.4 CAD

The CAD software used by EEB is SolidWorks[6], which is owned by Dassault Systèmes. Other software can be used as long as the software can export one of the Cura-supported file types previously listed. When exporting from SolidWorks, a user must select .STL as the file type when saving. This file type consists of a series of triangular facets with a defined normal to identify the material side. Deviation and angle can be modified under options when saving to increase or decrease the detail of the exported .STL file. When creating the .STL file from the CAD file, EEB generally selects the default deviation and angle options since most parts printed do not require fine detail.

Before constructing a CAD model, the designer must decide if the size required can be printed within the build volume of the TAZ 5. If the CAD model cannot be oriented to fit within this volume, the model either needs to be divided into different sections to be printed individually and then assembled, or the entire CAD model can be scaled down. These actions can be performed in the original CAD software. If a model must be broken into sections to be printed, the largest section to be printed will limit the largest available scale the model can be printed to. If certain features of a part must be detailed while other features do not, the model can be separated in the CAD program so that different features of the part can be printed separately at different speeds and then glued or plastic-welded together. Figure 11 shows a comparison of separated component surface finishes that resulted from the selected print speed.

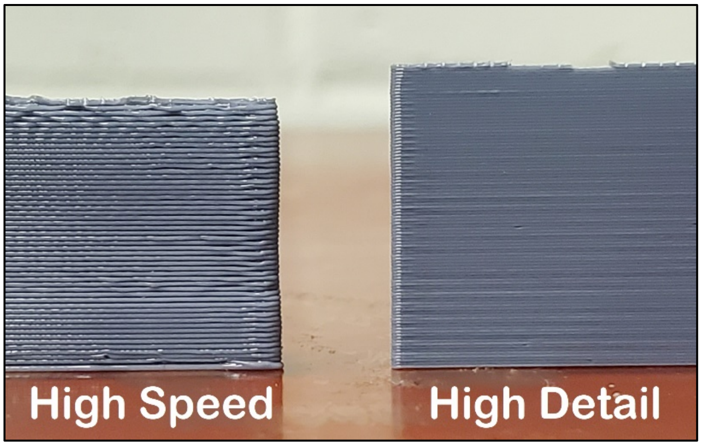

Fig. 11 Surface finish

Some part features cannot be altered with the hardware or slicing application but can only be altered in the CAD program. When printing a part with threads, holes, or corners that need to match an opposing part, it is recommended to make prototypes of the model feature in the CAD software first to investigate only the characteristics of the feature. This allows features of different sizes to be printed to establish a desired fit without wasting material or print time while establishing print parameters, gap spacing, and feature resolution. A safe tolerance to start with between opposing threads or corners is 0.5 mm. If a circular object is to be inserted inside another circular object, a difference of 0.5 mm between the diameters is recommend for a clearance fit. A sliding fit might require a difference of 1 mm. These are just recommendations. Several test prints should be produced and physically examined to establish the desired fit before printing the final component. Figure 12 shows how a part can be cut to check for thread fitment before printing a final part.

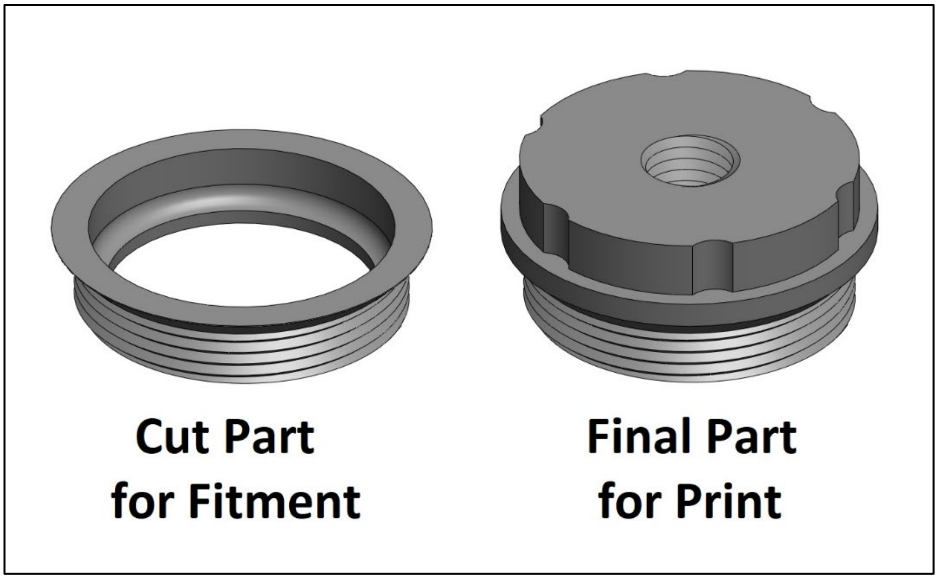

Fig. 12 Prototype part for feature analysis

3. Printing, Troubleshooting, and Postprocessing

Although additive manufacturing is often considered an automated process, a user will need to interact with the TAZ 5 and the print to assure a desired final product. Several steps need to be physically taken to ready the printer before printing. During the automated printing process, some unforeseen events can occur causing the print to fail and the printer to jam or stop. An operator will need to manually troubleshoot these occurrences so that the printer can be restarted. When the final part has finished printing, a user may need to postprocess the part depending on the level of accuracy required.

3.1 Printing

Preparing the table is essential in ensuring a successful print. The table needs to be regularly checked to ensure it is level and that the clearance between the nozzles and the table is acceptable after replacing the print head on the print-head holder. The procedure for checking print-head clearance and if the table is level is explained in TAZ Bed Leveling[4]. Bubbles can form between the print bed and its protective layer. These do not significantly affect height. If removing the bubbles is desired, the bed can be heated to 70 °C and the bubbles can be worked to the edges.

Different filaments adhere to the bed differently. PLA and ABS can be printed directly to a bare TAZ 5 print bed. Oils from skin or previous prints as well as other substances must be thoroughly cleaned from the surface or the parts can warp off of the table. Isopropyl alcohol is preferred for removing oils. Use disposable gloves and a towel when removing oils from the table surface. Other substances must be removed appropriately.

It is recommended to use a glue stick or painter's tape on the bed to promote adhesion of PETT, PVA, and TPE. These materials do not adhere appropriately to a bare table. When applying this added layer one must also adjust the print-head height thumb screw to compensate for the added thickness. The thumb screw must also be reset when the layer is removed. The water-based glue can be removed with a damp rag. If excessive glue is present on the bed, consider removing the bed via the four bed clamps and wiring harness and place the bed under a stream of water. Take care not to allow water to reach the underside of the bed. Allow the bed to thoroughly dry before remounting the bed. Tape adhesive that remains on the bed can be removed with new tape. Unused tape can be used to dab the adhesive residue on the bed to remove it.

When all settings have been selected on the Prepare screen and the nozzle and bed temperatures have reached preset temperatures, the part can be printed. If "Print" is selected without preheating, the nozzles will be rested against the table at the home position and heated there, possibly damaging the table. Both nozzles need to be preheated before printing even if the second nozzle will not be used and filament is not loaded. The current version of Cura does not allow the second nozzle to remain unheated during a single nozzle print.

3.2 Troubleshooting

The nozzles will return to the home position and extrude filament on the table before starting a print. At times, filament can catch on the nozzle or come off of the table. If nothing is done, this material can be deposited on the print. Before the print head starts printing the part, this excess material can be grabbed by tweezers or pliers and removed. Never touch the heated nozzle with unprotected body parts. The print can be paused at any time to address the need to remove excess material from the table printing area.

Even when all precautions are taken, prints still may fail. It is easy to become discouraged when the filament jams, the filament becomes lodged in the print head, filament wraps itself around the print head, or the part delaminates and cracks. Some fixes can be tedious but need to be performed. Since a troubleshooting manual does not exist for the TAZ 5, issues and fixes listed in the following have been developed from first-hand experience as well as from the 3-D printer community and the LulzBot online forum*.

3.2.1 Jamming

A common cause for a failed print is often jammed filament. The reel must be allowed to rotate freely. When opening a new reel or handling a used reel, tension must always be kept on the free end of the filament. If the reel is allowed to unroll, the free end can become crossed under other windings and become caught when being unwound. When storing, it is important that the free end is placed in a hole on the reel so the windings are taut. When the filament is initially wound on the roll during production, an end is locked in the center of the reel for winding. This end may or may not slip out of its hole on the reel when the end of the filament is reached. If the end does not slip out of its hole, the filament will jam. The trapped end must be snipped or removed from the hole when the filament is used to a point where the trapped end can be seen. At times, the filament reel can become angled and lodged on its holder. This can happen when most of the filament has been used and the weight of the filament is no longer applying a significant downward force on the reel. The tension in the filament caused by its curved form will cause the reel to lift and twist. If the reel cannot be straightened by hand, the remaining filament can be removed from the reel and allowed to hang on the reel hanger without the reel. Figure 13 shows the three discussed scenarios of how the reel can be kept from rotating.

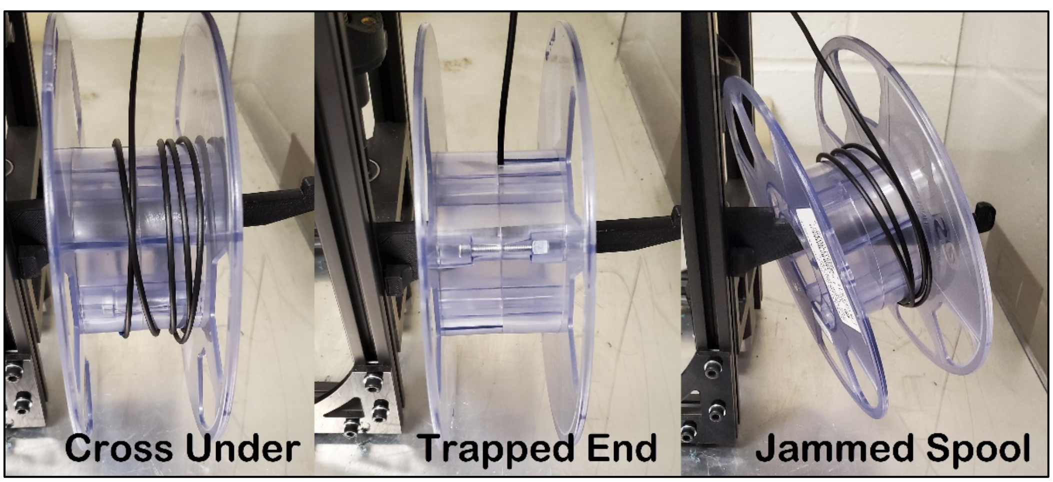

Fig. 13 Scenarios of filament reel becoming jammed

* https://forum.lulzbot.com/.

3.2.2 Clogging

The feeder cog in the print head grinds against the filament whenever filament becomes jammed due to a clogged print head or a binding reel. When this happens, shards of filament deposit onto the teeth of the feeder cog and also fall into the print-head housing. Over time, the feeder cog will begin to lose traction as filament builds up on the teeth. To periodically clean the teeth, the three machine screws must be removed (circled in red in Fig. 14) and then the front-cover plate (circled in green) and drive cog can be removed. The Dual Extruder v3 does not need to be removed from the carriage. The drive cog teeth can be cleaned with a pick or knife and the print-head housing can be blown out before reassembly.

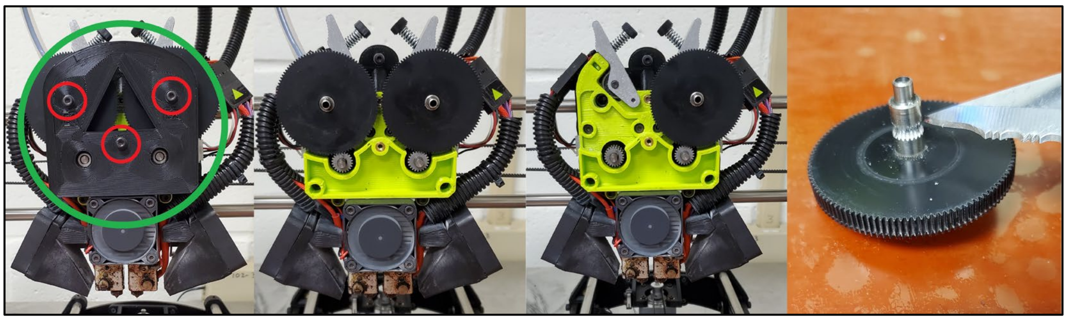

Fig. 14 Drive cog cleaning

A clogged print nozzle can possibly be caused by several factors. The first factor focuses on the second nozzle when it is not in use. The second nozzle primarily prints PVA. When not in use, PVA is removed by retracting the filament from the print head. It is inevitable that some PVA will remain in the nozzle. The second nozzle remains heated regardless if a print requires the second nozzle or not. It would be logical to conclude that the filament remaining inside the second nozzle becomes baked onto the inner surface of the print nozzle. Since PVA is a soft material, attempting to force PVA filament through the nozzle to clear it will bind the filament. The most effective solution is to heat the nozzle to 280 °C to soften the PVA and extrude PETT through it. The drive cog is better able to grip the PETT and force the filament through the nozzle. If the nozzle still cannot be cleared, attempts can be made with a needle. While the nozzle remains heated, a needle held with pliers can be inserted and removed from the outer end of the nozzle as depicted in Fig. 15.

Fig. 15 Nozzle cleaning with needle

It is not uncommon for PLA to become jammed in a nozzle. The filament will not extrude or retract. Even gripping the filament and manually attempting to retract it will fail. Initially, it was believed that PLA absorbed moisture in the air and the filament swelled in diameter causing it to become jammed against the interior walls of the print head. PVA is also known to absorb moisture. Unused filament is stored inside a sealed container with desiccant but the problem may still persist.

Heat creep has been a persistent issue on many FDM printers. As the nozzle remains heated to a certain temperature while printing, heat begins to travel from the heating element at the end of the nozzle up through the other metal parts of the print head. As the filament is pushed down toward the nozzle, the heated walls of the print head soften the filament allowing it to warp and mushroom before being extruded through the nozzle tip, as can be seen in Fig. 16. Previous print heads were built with heat sinks around the nozzle to dissipate the heat but tended to be ineffective. Cooling fans could be retrofitted to the exterior of the print heads to carry more airflow across the heat sinks, which may yield better results. The Dual Extruder v3 is equipped with a small cooling fan to dissipate the heat on the heat sinks. The equipped fan is too small to meet the required air flow. Hence, when printing it is recommended an additional small fan be focused toward the print area when printing to prevent heat creep. This procedure has shown the most success in preventing clogged nozzles. The fan must be turned on after the print is started since the airflow can inhibit the heating of the nozzles and bed.

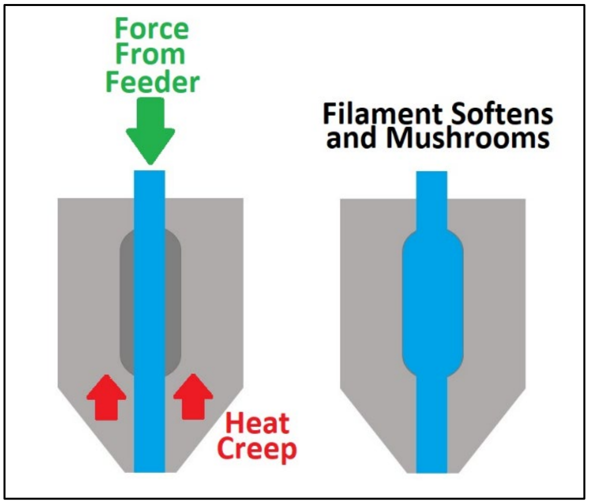

Fig. 16 Heat creep

Another theory as to how filament becomes lodged in the nozzle is that shards of material that result from the drive cog grinding on jammed filament deposit in a cavity in the nozzle. Over time, these shards accumulate and either jam or fuse to the filament causing the nozzle to clog. This also can prevent the filament from being extruded or retracted. Figure 17 shows how shards might become fused to the filament.

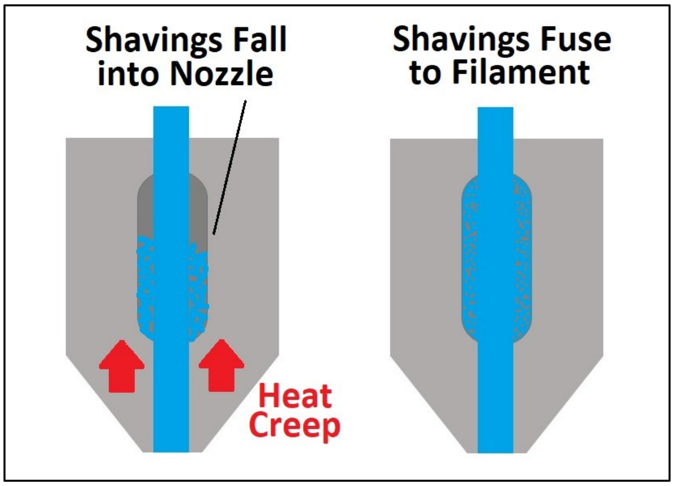

Fig. 17 Shard fusion

Although the nozzle has not been disassembled, the elongated oval shape of the cavity can be deduced based on the shape of the end of retracted filament, as can be seen in Fig. 18.

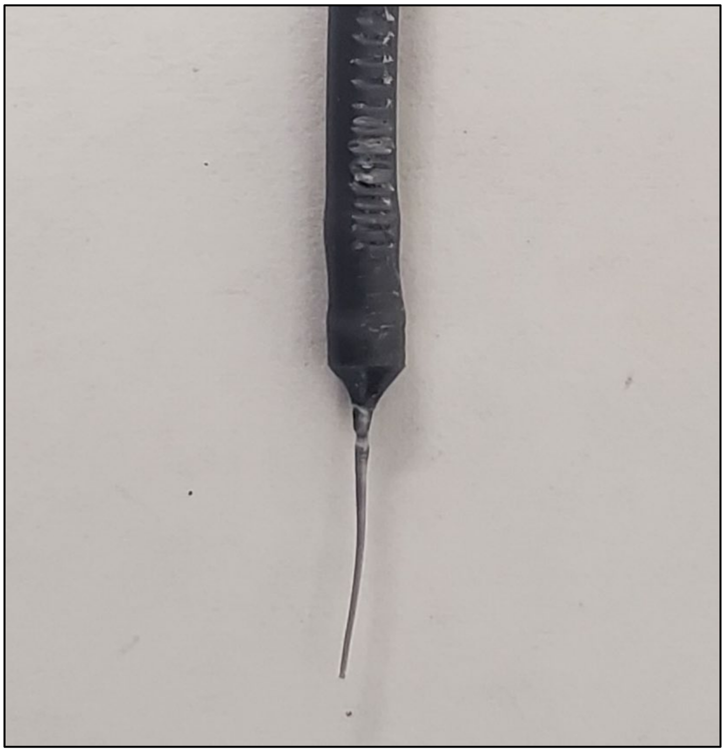

Fig. 18 Filament end

If filament becomes jammed in the print head and the filament cannot be manually retracted, the print head must be separated from the nozzle. Once the nozzles are cooled, the printer must be turned off and unplugged from the wall. The print head can be unplugged from the TAZ 5 wiring harness (circled in blue), the print head mounting screw can be removed (circled in red), and the print head can be detached from the print-head carriage as illustrated in Fig. 19.

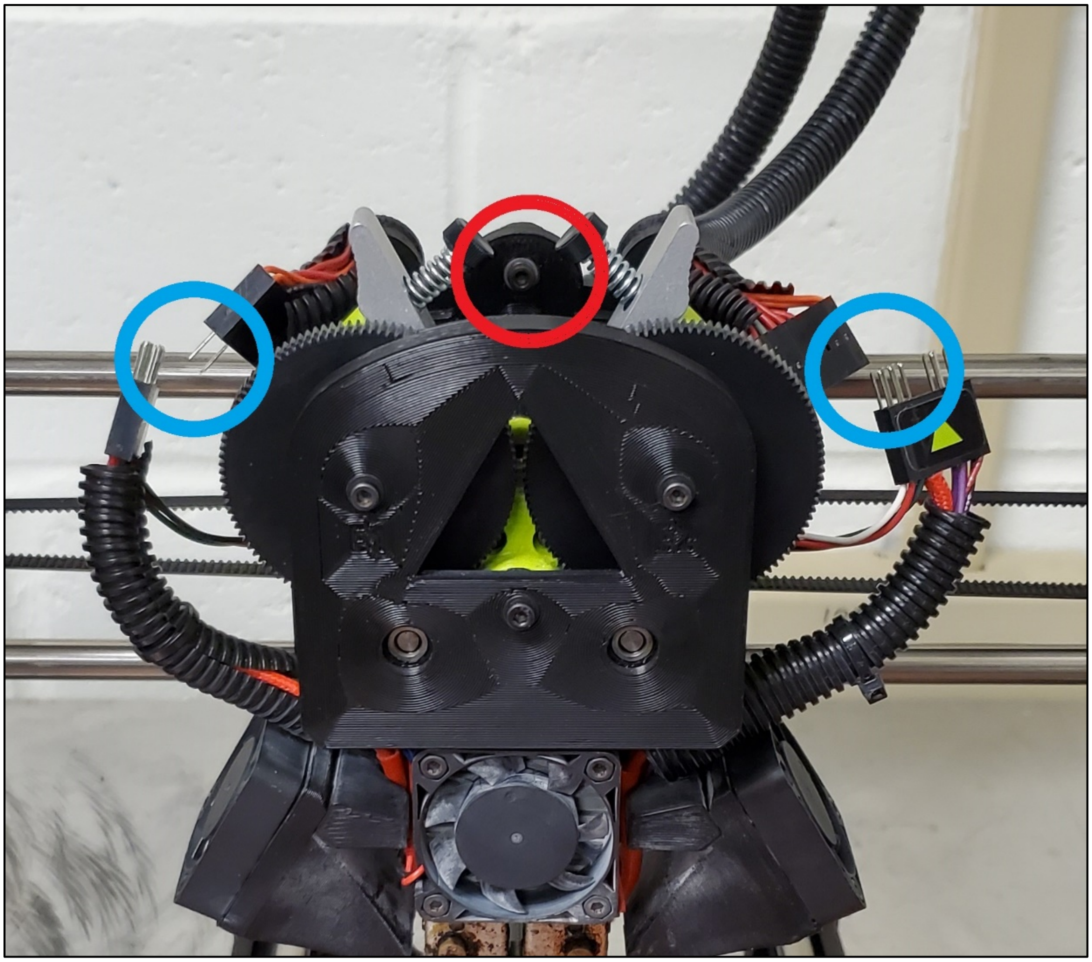

Fig. 19 Removing Dual Extruder v3

For the nozzle to be separated from the print head, the nozzles must be unplugged from the nozzle harness (circled in blue), the three bolts must be unscrewed (circled in red), and the two assemblies can be separated as shown in Fig. 20. Removal of the black 3-D-printed cover plate circled in green in Fig. 14 is not necessary. The print head may have difficulty separating from the nozzle due to the filament connecting the two assemblies. The assemblies can be separated as needed and the filament can be snipped. If the filament cannot be removed from the nozzle with pliers, the filament will need to be drilled. A pin vise with a 3-mm drill bit can be used to gently hand drill into the metal nozzle. Care must be taken not to scratch the nozzle with the drill bit.

Fig. 20 Nozzle cleaning

3.2.3 Curl Over

It is possible for bulk material to accumulate on the nozzle if a part becomes detached from the bed or layers become delaminated (Fig. 21). This mass is difficult and strenuous to remove. First, the nozzle must be heated to or above the printing temperature of the filament. The mass can then be grabbed with pliers and removed. This will undoubtedly still leave filament deposited on the nozzle. If large deposits need to be removed, it is best to lower the nozzle temperature by half. This allows the material to harden and strips can be removed with tweezers or pliers. Care must be taken to not scratch the nozzle or heating-element wires. If residue remains on the nozzle, a brass bristle brush can be used to safely clean the nozzle.

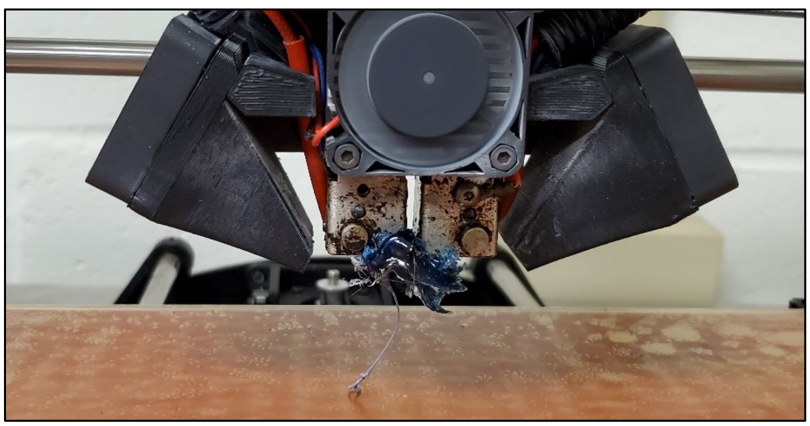

Fig. 21 Bulk material collection

3.2.4 Delamination

Depending on material or wall thickness, printed parts have the potential of delaminating. Certain materials such as ABS succumb to internal stresses and delaminate due to uneven heating during printing. The surface contacting the bed and the surface contacting the nozzle remain hot, but the area in between is allowed to cool. Thin walls can delaminate due to an inadequate fusing of layers. Thicker walls have a larger area for layers to fuse together. The CAD model can be altered to correct this but at times minimal material is desired. If a part needs to be reconnected or two separately printed parts need to be attached, two methods have proven to be successful. Cyanoacrylate (CA) is very successful for attaching PLA or ABS parts. The glue has been used to reattach delaminated layers, attach separate parts, and at times to fill small gaps. However, CA does not bond well to PETT. The preferred repair method is to plastically weld the area if a repair needs to be made to an exterior surface. Initial trials were performed by manually extruding the filament through the Dual Extruder v3 print head onto the part. This process is very cumbersome. The preferred method now uses 3-D print pens to apply the heated filament. The pens add a layer that is just as strong if not stronger than the original layer. Matching filament can be used in the pen and excess material can be sanded off to create a smooth finish. Figure 22 shows the 3-D print pen being used to patch a delaminated part.

Fig. 22 3-D print pen

3.3 Postprocessing

An FDM print will always require postprocessing if a precision part is required. Postprocessing can occur once the table cools and parts can be removed from the printer. Rough surfaces can be sanded with sand paper or emery cloth. Razor blades or hobby knives are good for removing small imperfections. Edges can be deburred or rounded with deburring tools or files. A finishing coating such as Smooth-On XTC-3D can also be applied to smooth the printed surface. This adds material to a part's surface and hence increases mass of a part. Holes may need to be reamed or tapped, which is simple to do with the listed filaments.

4. Conclusion

The LulzBot TAZ 5 with the Dual Extruder v3 print head has proven to be a valuable, cost-effective, and time-saving tool when used properly. As with any machine, the user must understand the inner working to understand its full capabilities. EEB has produced small production runs of explosive containers and surrogate mines that would otherwise be very expensive if they were machined from plastic stock. Many surrogate mines have hollow centers and thin walls that would be impossible to machine. Electronic cases, instrumentation mounts, and scale-prototype displays have been produced on a smaller scale but were manufactured with accuracy in mind.

The size and material selection provided by the TAZ 5 is adequate for EEB small-scale production. Most parts that EEB requires are small enough or coarse enough to be printed in-house. Better precision can be obtained by taking care to properly adjust the printer to match settings in Cura. Parts can also be created with overhangs if proper settings are selected.

Although the TAZ 5 is a reliable machine, it can fail at times. Filament jamming, clogging, delamination, and curl-over can at times plague the printer and need to be rectified. However, with patience, the operator can quickly service the printer and produce repeatable parts with operational experience.

FDM printers such as the TAZ 5 are currently the most cost-effective 3-D printers on the market. The major limitation of these printers is the achievable resolution, limited by the size of the print nozzle. Finer print nozzles can increase the resolution but at a time cost as smaller amounts of material can be deposited. The TAZ 5 used by EEB has a print nozzle of 0.5 mm, which has been sufficient to meet the small-quantity production runs that have been required at a sufficient level of resolution. For higher resolution, it is recommended that an SLA-type printer be considered.

5. References

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List of Symbols, Abbreviations, and Acronyms

.3MF	3-D manufacturing format
.OBJ	wavefront OBJ
.STL; SLA	stereolithography
.X3D	extensible 3-D graphics
2-D	two-dimensional
3-D	three-dimensional
ABS	acrylonitrile butadiene styrene
ARL	Army Research Laboratory
CA	cyanoacrylate
CAD	computer-aided design
CNC	computer numerical control
DEVCOM	US Army Combat Capabilities Development Command
EEB	Explosive Effects Branch
FDM	fused deposition modeling
PETT	polyethylene terephthalate
PLA	polylactic acid
PVA	polyvinyl acetate
TPE	thermoplastic elastomer
USB	universal serial bus

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