CONTINUOUSLY VARIABLE DUROMETER 3D PRINTER

By

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In Partial Fulfillment of the Bachelors degree
With Honors in

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THE UNIVERSITY OF ARIZONA

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Approved by:

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Gary Redford
College of Engineering – ENGR 498 Coordinator

Abstract

The purpose of this project was to develop a 3D printer that can print multiple durometers, or hardness, within one printed part. This project was created by Raytheon so tthey could develop anti-vibration housings for their electronic components that experience vibrations during flight. Team 16077 was successful in developing a printer. To achieve the result, the hardware and software of a commercial 3D printer were modified. The entire existing extrusion system was replaced with a dual extruder system with a tubing design to be able to extrude multiple filaments (a soft and a hard filament) at once. The nozzle was replaced with a mixing nozzle so that the two filaments can create a range of durometers. The firmware of the printer had to be rewritten to accept G-Code commands to run both the extruders at once at varying ratios. A standalone graphical user interface (GUI) was developed to give the user an easy way of modifying their existing G-Code file to include the mixing ratios and commands. The results show that the printer can achieve a range of durometer from 84A to 75D Shore hardness. Furthermore, the printer was successful in printing a multi-durometer part that mitigated vibrations.

Roles and Responsibilities

David Picazzo (Systems Engineer) was the team lead for the project. He handled the paperwork, the electronics, and modifying the printer's firmware. Tim Leach (Biomedical Engineer) handled the materials analysis and helped write the GUI. Rachel Lindley (Mechanical Engineer) handled the hardware design and assisted in rewriting the printer firmware. I handled the hardware design and the GUI design. Ziqiang Wang (Industrial Engineer) handled the paperwork and assisted in the electronics.

Team 16077

Final Report

Continuously Variable Durometer 3-D Printer

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Rachel Lindley
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Ziqiang Wang

May 4, 2017

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Scope

Shock and vibration mitigation is a growing concern when dealing with sensitive electronics, especially those electronics that are placed in fast moving vehicles or projectiles. As a result of this problem, there is in an increasing demand for cheap, successful mitigation methods. Current methods of mitigation have been shown to be both time consuming and expensive, thus Team 16077 has been tasked with the development of a Variable Durometer 3D Printer that can facilitate the implementation of shock and vibration mitigation in its prints. The printer shall vary the durometer of its designed prints by printing a mixture of two variable durometer thermoplastics at specified rates through a single extruder head. The prints will be able to mitigate vibrations to electronics placed within them, based on the varying durometer sections.

Due to time constraints and the expertise of the team, the team and sponsor decided to modify an existing printer design with the variable durometer capabilities. After simplifying the design it was determined there were three components for this project: printing material optimization, print head mechanical design, and software development. Determining thermoplastic filaments for the prints were based on research in the following areas: compatibility, printing temperature, and tensile modulus/Shore hardness. The software package was a combination of modifications to the current printer's firmware along with an executable file that will modify the G-Code from the slicing program via a graphical user interface (GUI) for simple use. A mechanical modification to the extruder head will also be necessary to accommodate for the mixing of two different materials. As a result of these modifications, the technical data package (TDP) attached contains the necessary software/firmware implementations, mechanical Solidworks designs for the extruder head modifications, and materials analysis. The end result of the design will allow for a user to computational slice a desired printing design into sections of varying durometer and print the final product.

The following statement of works (SOW) was developed for the 2016-2017 year:

1. Team 16077 shall perform a **Functional Requirements Review*** (FRR) and develop a system concept for completing the goals of this proposal. The team will construct a Concept of Operations document in order to supplement the FRR to be performed on or before September 20th, 2016.
2. Team 16077 shall compile the given requirements from the Functional Requirements Review as well as create a more in-depth list of deliverables. At the conclusion of this analysis, the team shall complete a **System Requirement Document** (SRD) by October 20th, 2016 to be approved by mentor and sponsor.
3. Team 16077 shall conduct a concept design synthesis for the software and physical 3D printer hardware. Concurrently, the team will conduct experiments and review current

research in order to investigate and determine the best materials to be used for mixing/melting capabilities for various durometer syntheses. At the conclusion of these activities the team shall present a **Preliminary Design Review*** (PDR) on or before November 22nd, 2016.

4. Printer assembly and initial testing of the commercial printer will begin prior to the designated break period starting on December 8th, 2017. The goal is to gain familiarity with 3D printer functions and software.
5. The finished detailed design **Critical Design Review*** (CDR) will be completed by January 24th, 2017 to approve the final design for the specified project.
6. Printer modification period begins on February 1st, 2017 - nozzle modification, software/firmware development, and incorporation of chosen thermoplastic filaments.
7. **Test Readiness Review*** (TRR) on or before March 7th, 2017 to review and approve designed tests to analyze final product.
8. Begin integration of developed software and firmware updates.
9. Begin system testing for approved functional requirements, such as durometer and vibration reduction, on April 3rd, 2017. Most testing can occur at any location, while vibration reduction will be tested at Modular Mining Systems.
10. **Final Acceptance Review*** (FAR) on or before April 20th, 2017 to review final testing and results to be presented on Design Day.
11. Update final Technical Data Package (TDP) prior to the final report.
12. Presentation of project via a detailed poster for **Design Day** on May 1st, 2017.
13. **Final Report** and System Delivery to Raytheon on May 4th, 2017.

System Description and Diagram

The overall system design is a variable durometer 3D printer that is connected to a computer with a Windows 7 platform via standard USB. Provided below are two block diagrams outlining the functional and system components of the printer (Figures 1 and 2). The current design proposed and approved is a printer with the capability of mixing two thermoplastics (soft and hard) to achieve prints with variable durometer. There are essentially three subassemblies to this design: thermoplastic material, mechanical mixing design, and software design. The thermoplastic sub-portion of this project was primarily determined via research and testing to ensure an accepted durometer range along with efficient mixture of the two materials. The testing also aided in determining percentage relationships between the thermoplastics for a final print with a certain desired durometer. Based on research literature and melting of the plastics, three materials were chosen for a possible final material: thermoplastic polyurethane (TPU), polylactic acid (PLA), and nylon (carbon-infused vs. normal). The final thermoplastic chosen for the design was PLA.

As mentioned previously, the main 3D printing software and mechanical design was purchased in the form of a current commercialized 3D printer. Based on a trade study, the Lulzbot TAZ5 was chosen and was modified via software and mechanical additions. As shown in Figure 2, the majority of the main system is provided with the TAZ5. The TAZ5 is a standard plastic 3D printer with multi-axis movement (X,Y, Z) powered by motors attached at the appropriate axes. Additionally, the printer has a heatable borosilicate glass bed printing platform that moves along the y-axis that is covered in a printer-friendly PEI surface. It is important to note that sometimes additional coverings are necessary, such as painter's tape, to aid in print adhesion. The final component provided by the TAZ5 is the standard power supply (100-240VAC) and the internal RAMBo hardware and Marlin firmware. After trial and error, it was determined that the optimal software to develop the G-code from the STL files should be Slic3r, which is open source.

Beyond the main printer mainframe there are additional components, both purchased and fabricated, that contribute to the mechanical components of the design. The purchased components include the dual extruder, diamond hotend, and Bowden tubes. The fabricated components of the mechanical design include the extruder/motor mounts and Bowden couplers. Additionally, a modification was made to the dual extruders by

enlarging the output holes slightly with a drill to accommodate the Bowden couplers. The diamond hotend and dual extruder were purchased to allow for mixture and extrusion of the two thermoplastics simultaneously. Due to weight constraints, mounts were fabricated for both the dual extruder and the diamond head to separate the components in order to not diminish the movements of the extruder during printing. Additionally, there would have been extra vibrations with the movement of the print head, resulting in poor prints. The Bowden tubes and couplers were utilized to maintain a clean and sleek transfer of the filaments from the extruders to the hotend head.

The second major component of the design is the software component that alters the printing G-code to allow for variable printing by extruding the filaments simultaneously at varying rates. An important component of the software is that it must be compatible with Windows 7, so it was decided to package it is an executable file as shown in Figure 2. As mentioned above, the design calls for a secondary open-source software (Slic3r) that allows the user to slice the STL file and generate the preliminary G-code, which includes all printing parameters. The preliminary G-code is then used as an input into the fabricated software to pair desired durometers with certain parts of the print via toolhead number. The fabricated software has been designed to provide the user a graphical user interface (GUI) for ease, and to avoid any issues of incorrect inputs. A secondary portion of the software included a change to the printer’s firmware to allow both extruder motors to run simultaneously, as the original firmware stopped this as a precautionary action.

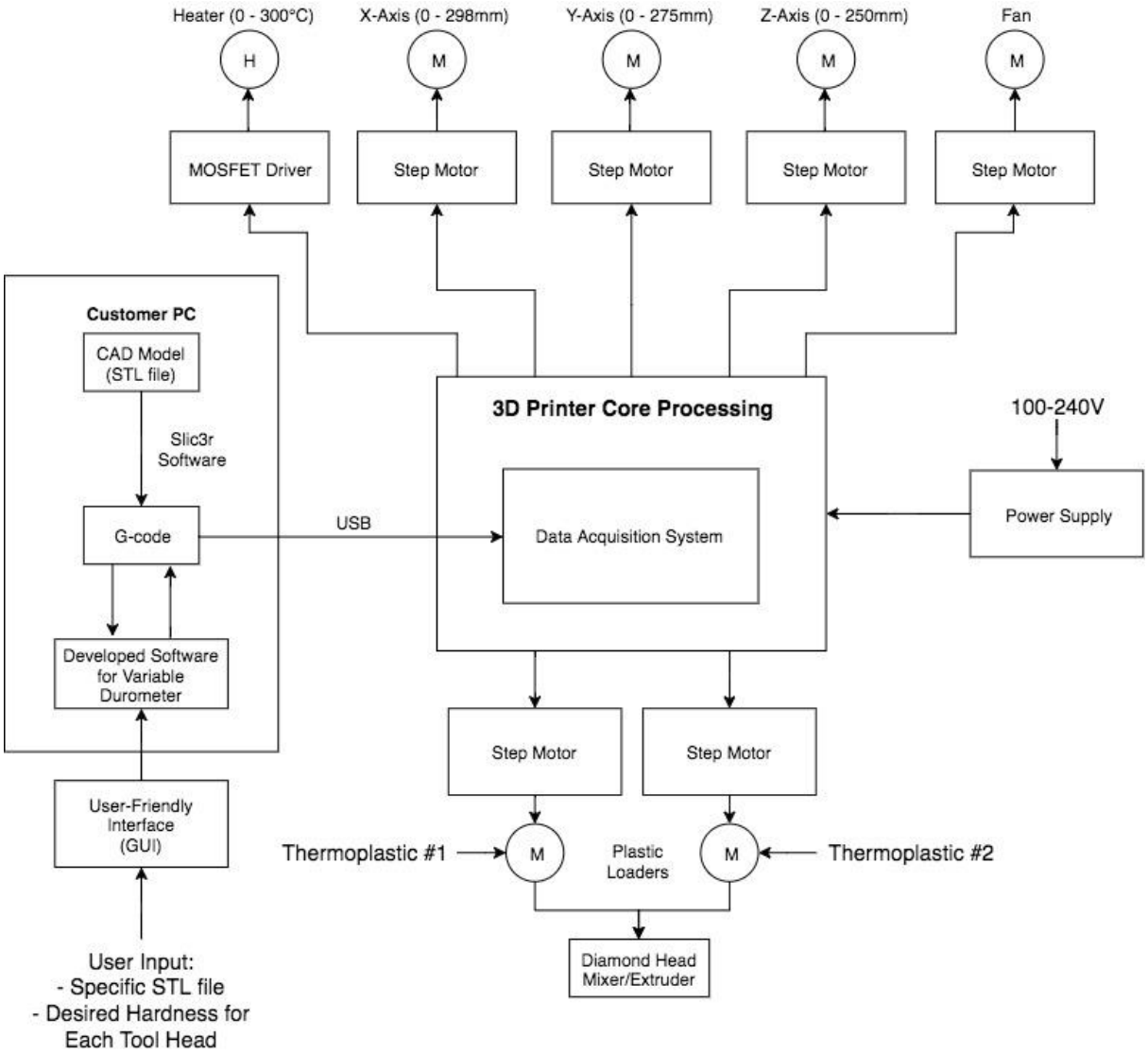


Figure 1. Functional Block Diagram of Printer System.

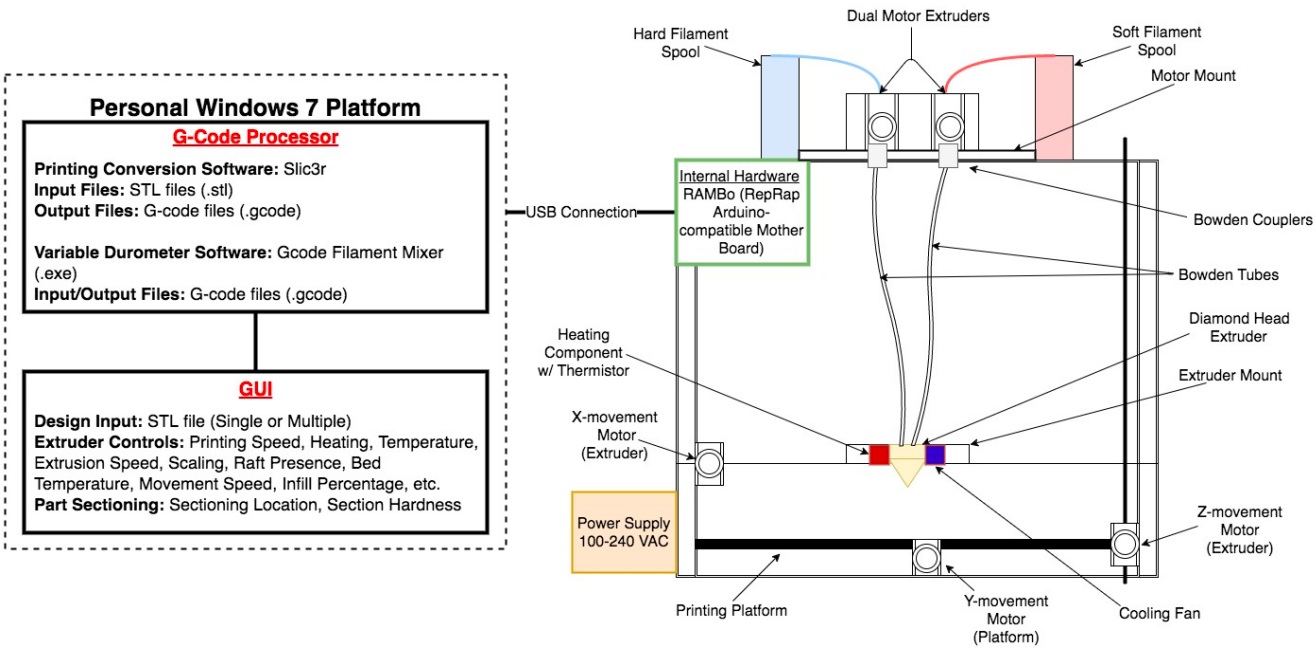


Figure 2. System Block Diagram of Printer System.

Drawings

There were three drawings for the modifications of the printer: the diamond hotend mount, the dual extruder mount, and the bowden guide. For the actual testing of the design, there were 4 drawings of printed parts: the dog bone, control vibe tester, simple ring vibe tester, and advanced reduction vibe tester. All drawings can be found in Appendix 1.

Indentured Drawing List		
ID	Part	Quantity
1	Dual Extruder Mount	1
2	Diamond Hotend Mount	1
3	Bowden Coupler	2
4	Dog Bone	1
5	Control Vibe Tester	1
6	Simple Ring Vibe Tester	1
7	Advanced Reduction Vibe Tester	1

1. **Dual Extruder Mount** - The dual extruder mount was designed to encase the dual extruder itself. It is a shallow tray with an indent to encompass the dual extruder, and a sturdy frame around the edge to keep it in place. It has four “legs” to hang over the edge of the printer and hold it firmly in place against the printer frame. There is a small hole in every corner for zip ties to access. There is also a hole at the edge of the indented tray to secure the dual extruder to both the mount and frame with a zip tie.

2. **Diamond Hotend Mount** - The diamond hotend mount was designed as the support for the diamond hotend nozzle, to support the weight of the nozzle on the printer carriage. It is a thick plate with a rounded triangular hole for the insertion of the diamond hotend and three tabs to hold the part steadily in place. There are three small holes on the ends of the triangular hole for the threading of zip ties to

attach the hotend. There are also two holes in the back of the model sized for a .18’ screw to be inserted (for attachment to the printer carriage).

3. **Bowden Coupler** - The bowden coupler was created for the purpose of guiding the bowden guide out of the dual extruder to the printer. It is a simple design, a cylinder with a thinned section in the middle to fit the tabbed frame of the dual extruder. It has a hollow section down the length of the cylinder for the bowden tubing to be threaded through.

4. **Dog Bone** - The dog bone design was utilized for measurement of the varying durometer capabilities of the final 3D printer. The design was sliced into 5 sections of varying hardness (0%, 30%, 50%, 70%, 100%) to be measured by the handheld durometer testers.

5. **Control Vibe Tester** - The control vibe tester was designed to be fixed onto the vibration table as a control for vibration reduction. It was composed entirely of hard PLA to determine the peak frequency and G-force.

6. **Simple Ring Vibe Tester** - The simple ring vibe tester was designed exactly the same as the control, but with a ring in the middle for vibration reduction. This design was composed entirely of hard PLA, except for the ring, which was composed of soft PLA. It was utilized to determine vibration reduction from integrating soft PLA within the design.

7. **Advanced Reduction Vibe Tester** - The advanced reduction vibe tester was designed similarly to the other two testers, except it utilized a unique design recommended by the Raytheon sponsor for vibration reduction. The core design remained the same, except the ring in the middle was widened and included circular holes evenly spaced throughout it. This design was composed entirely of hard PLA, except for the ring, which was composed of soft PLA.

SW Design Documents

Two major software developments took place in the project. The first was the development of the GUI, which allows the user to manipulate the print GCODE to specify their desired durometers on their printed object. The second was the modification of the latest Marlin firmware used by the printer, which allowed for the mixing tool commands.

1. **GUI**

   1a. Scope.

   The VD3DP G-Code Mixer Guided User Interface is a MATLAB standalone executable that modifies a .gcode file for multi-durometer 3D printed part.

   1b. Identification.

Identification Number	Title	Abbreviation	Version Number	Release Number
1	VD3DP G-Code Mixer	GUI	3	1

   1c. System overview.

   The purpose of the GUI is to give the user (Raytheon) of the VD3DP an easy method of modifying the G-Code for their 3D part to allow for filament mixing to create different durometers within the part. The GUI is a standalone MATLAB executable that was created in MATLAB using the MATLAB GUIDE tool. The program started as a simple search and replace text algorithm. User inputting and controls were added. It was later transformed into a graphical user interface (GUI) to allow for ease of use and simplicity. To run this program, the user must have MATLAB Runtime installed (MATLAB Runtime is a free software provided by MathWorks). Upon opening the program, the user will see the main GUI screen which is pictured in Figure 2 in Appendix 2. Next the user clicks “Choose G-Code File” which then allows the user to navigate to their desired input file using File Explorer. Next the user inputs the desired hardness ratios. Then the user clicks “Create Edited G-Code”. This creates the modified .gcode file. The user then clicks “Close” to end the program.

1d. Document overview.
The purpose of this document is to detail the design of the VD3DP G-Code Mixer.

2. CSCI-wide design decisions.

a. The GUI accepts an input of either a .gcode or a .txt file. While the program is running, the program accepts a user input of integers to indicate the hardness ratios. The user may also click the “Close” button to clear and end the program at any time. It produces a .gcode file. This decision was made because the files used to communicate instructions to 3D printers are .gcode files, and .txt input was allowed because a G-Code can be written in a .txt format.

b. The first input is the “Choose G-Code File”. When the user clicks this button, the File Explorer pops up and allows them to navigate to their desired .gcode or .txt file. If the user does not select a file and clicks cancel, they are returned to the main GUI page. When the user inputs a file, the program first reads through the file and counts the tool changes which appear in the file in the format “T#”. The tool counting algorithm is a simple loop which goes line by line and looks for matches to the regular expression 'T\d'. The program only allows for a file with less than or exactly 10 tool changes. If the user attempts to input a file with more than 10 tool changes, the program notifies them with an error and allows the user to input a different file. The GUI will then show text input boxes for the user to input the desired hardness ratios for each tool head that was counted. The program will report an error if the user inputs anything that is not an integer from 0 to 100 and allow the user to re-enter the desired hardness ratios. When the user clicks “Create Edited G-Code”, the program inserts lines of G-Code to the original file and outputs a new file to the user’s Temp folder.

c. To allow for flexibility within the program, MATLAB was chosen as the programming language because of its extensive library of functions and capabilities. To allow for availability, the program was packaged as an executable so that it could be run on computers that do not have MATLAB installed.

3. Requirements traceability.

a. The GUI complies with the requirements specified in the VD3DP SRD:

1. (3.3.2) Operating System Compatibility – The software shall run and be compatible with the Windows Operating System, specifically with the Windows 7 version.
2. (3.3.4) Functionality – The system shall not require the download of a secondary proprietary software or operating system in order to run on any given Windows compatible computer.

4. Notes.

a. GUI - Graphical User Interface.

2. Marlin Firmware Modification

1a. Scope.

The Marlin Firmware is what drives the operation of the VD3DP. It processes the G-Code commands and parses them to the printer.

1b. Identification.

Identification Number	Title	Abbreviation	Version Number	Release Number
2	Marlin_WorkingCopyFIX2	Firmware	1	1

1c. System Overview.

Modifying the firmware was an unexpected part of the project. The stock TAZ 5 firmware currently does not support simultaneous dual extrusion. As a result, the latest release of Marlin was modified to be able to process the simultaneous Dual Extrusion commands from the G-Code. The purpose of these modifications is to allow the firmware to process the different G-Code commands from the modified G-Code files that the VD3DP GUI produces.

1d. Document Overview.

This document will outline the modifications made to the Marlin firmware for compatibility with the VD3DP system.

2. CSCI-wide design decisions.

a. Note: Three files were modified for the VD3DP. They are the configuration.h, configuration_adv.h, and the pins_RAMBO.h. These three contain the parameters that apply directly to the TAZ 5. The modifications made are listed

in Figures 3-7 In Appendix 2, in order for the Firmware to be compatible with the TAZ 5, these parameters must be set in their respective files.

b. The First File is Configuration.h, This file contains the configuration parameters that will enable the use of the TAZ 5. They contain information for the LCD controller support, the RAMBO board specification, and most importantly the Mixing Extruder Definition. Refer to Figures 3 - 11 for the proper configuration settings. The Mixing Extruder definition allows us to use the commands M163 and M64 to create virtual extruders which control the feeding ratios for our printer's extruder motors.

c. The second file in question is the configuration_adv.h file. For the most part, this file is not heavily modified and should only be manipulated by someone familiar with the firmware. There is only one section that was modified here, the thermal settings. These settings were adjusted through careful fine tuning of the printer. Before they were adjusted, the printer would constantly error when pre-heating. These parameters were changed to fix some of the preheating and temperature polling issues which were causing undesirable behavior.

d. The third file is the pin configuration for the RAMBO board and is called pins_RAMBO.h. This file sets the inputs and outputs for the board. In order to achieve proper functionality they should be set according to figures 13-16 In Appendix 2. The Marlin configuration for the RAMBO board was correct for the most part. They were compared to the stock TAZ 5 Marlin Firmware pin configurations to ensure accuracy.

e. The Modifications were made and flashed to the controller using the ARDUINO IDE.

3. <u>Requirements Traceability.</u>

a. The GUI complies with the requirements specified in the VD3DP SRD:

    1. (3.4.5) <u>Variable Printing</u> –The printer shall be able to print multiple durometers within the same printed part.

Acceptance Test Procedures

Procedure 1

Durometer Testing

The purpose of this test is to find the durometer of various printed ratios. This test will prove the functionality of the Variable Durometer printer.

The test piece is a printed part which is sectioned by hardness ratio (100%, 70%, 50%, 30%, 0%). Each section is a flat plane a few millimeters thick and an inch wide, which will allow the testing device to measure a solid area of the given durometer.

The required test is to ascertain with a hardness tester that our printer will print various durometers within a single part. It will also ensure that our prints will encompass the stated range of shore hardness 85A-70D.

The test equipment we will be using are handheld Shore A and Shore D Digital Hardness scales. Shore A will be used on the softer prints and Shore D on the harder prints (determined by if the Shore A reading exceeds 100). To use, the user simply turns on the scale, and presses it vertically into the material in question. The value is then read from the digital screen and recorded.

Procedure:

1. Lay the test piece on a flat surface
2. Turn on the Digital Hardness Scale
3. Press the scale vertically into the test area with a constant force (Figure 1 in Appendix 4)
4. Record value - If Shore A scale exceeds 100, Shore D scale is used (a conversion can be completed)
5. Repeat 10 times
6. Average result

See Appendix 5 for ATP Data Sheets.

Procedure 2

Vibration Reduction Testing

This test is designed to determine the overall viability of the printer to produce vibration reduction mounts/enclosures using variable durometers.

Three vibration reduction mounts were designed to test the limits of the printer. The design drawings can be found in Appendix 1, drawings 5-7:

1) Control Vibe Tester: The control is printed entirely of Hard PLA, it is important to test against the control to see how our vibration reduction efforts in the later models perform.
2) Simple Ring Vibe Tester: This model incorporates a thin ring of soft PLA between the center platform, and the outside mounting ring.
3) Advanced Reduction Vibe Tester: This design made use of the relationships between frequency, mass, and material stiffness. Frequency is inversely proportional to mass and directly proportional to material stiffness, with this in mind, the stiffness of the center ring was reduced by adding holes along the circumference of the middle ring. The mass of the center platform was increased by increasing its thickness.

3.2.3.3 Test requirements.

a. In order to properly analyze the vibration reduction capabilities, a Sine Sweep should be conducted to find the frequency at which the peak force response occurs in the control design. This peak will be used as a base for future comparisons of different designs.
b. The only performance requirement is the reduction in vibration.

3.2.4 Required test equipment. Includes the following for each piece of test equipment required to perform the procedure:

1) Electrodynamic Shaker (Appendix 4 Figure 2)
    a) The vibration platform is used to vibrate the test piece at different frequencies.
    b) Model S452
    c) UNHOLTZ-DICKIE CORP
    d) Required frequency range 0-2000 Hz
2) Accelerometer (Appendix 4 Figure 3)
    a) Accelerometers are used to measure the G-Force experienced by whatever object they are attached to.
    b) Model number N/A
    c) For this Experiment we will need three accelerometers: one on the outer mounting ring, one in the center platform, and one on the vibration table to use as a control.
3) Signal Conditioner (Appendix 4 Figure 4)
    a) The signal conditioner processes the signal from the accelerometers attached to the device.
    b) Model CVA-4

    c) Manufacturer UPHOLTZ-DICKie CORP
4) Loctite Instant Adhesive (Appendix 4 Figure 5)
    a) Loctite instant adhesive was used to fasten the accelerometers to the test piece.
    b) Part No. 12292
    c) Manufacturer: Loctite
5) Loctite Accelerant (Appendix 4 Figure 6)
    a) This is used as an accelerant in the bonding of the accelerometers.
    b) Part No. 7452
    c) Manufacturer : Loctite

3.2.6 Step-by-step procedure.

1) Begin by placing the device under test (DUT) directly on the vibration platform in the desired position. (Appendix 4 Figure 7)
2) Use a transfer punch to mark the location of each mounting hole on the vibe table.
3) For this test, we used 6-32 screws to mount the DUT. Drill the previously marked holes using an appropriately sized drill bit. (Appendix 4 Figure 8)
4) Use a 6-32 screw tap to tap the drilled holes.
5) Mount the DUT using 6-32 screws of an appropriate length and torque to 8.75 in-lbs. (Appendix 4 Figure 9)
6) The vibration table already has a control accelerometer mounted to it. Decide on the optimal placement for the rest of the accelerometers. For this test, they should be placed on the outside mounting ring, and the center platform. Ensure the accelerometer wires do not lie directly on any sharp edges or corners. (Appendix 4 Figure 10)
7) Perform a resonance search at 0.5 G sweeping a range of 0-2000 Hz using the computer software.
8) After the Resonant frequency is found, use the same test parameters to test the other two vibration dampening models. Record the peak force experienced by the center accelerometer and the frequency at which it occurs.

See Appendix 5 for ATP Data Sheets.

Models/Analyses

Due to the design of this project, there were three analyses performed: one for the mechanical sub-assembly, one for the materials sub-assembly, and one for the weight requirement. The major component of this project was software, which could not provide

an analysis, while most mechanical adjustments could not be verified by any of the specified requirements.

1. **Stress Analysis:** This analysis was to confirm that the diamond hotend mount would pass a stress analysis and not bend with the weight of the diamond hotend attached. The mount was treated as a cantilever beam with a hole in the middle, and the weight of the hotend was the force, applied at the center of the hole of the mount. It was found that all stresses were less than .2 psi, much much smaller than the ultimate strength of the ABS plastic material (~5 psi). Calculations can be found in Appendix 3.

2. **Materials Analysis:** The materials analysis was completed to confirm which of the possible thermoplastics would be the best to incorporate into the variable durometer printer. The main method of determining the thermoplastic material arises from testing various materials for not only variable hardness but similar printing parameters and their mixing abilities. The analysis outlined important printing parameters along with their respective shore hardness calculated from the provided equations (if not provided). The analysis showed that the Nylon mixture would not be able to encompass the required range of hardness, while the TPU or PLA mixture could. After testing the two filaments, it was determined that PLA provided the best mixture, and was able to reach both the soft and hard thresholds, despite the calculations provided in the analysis. Data can be found in Appendix 3.

3. **Weight Analysis:** The weight analysis was performed to verify that the weight of the printer and modifications would fit the desired requirement (< 50 lbs). Our analysis included the weights of the dual extruder, diamond hotend, filament, mounts, and bowden tubes. This totaled to ~35 lbs, much less than the maximum weight. If desired, the personal computer (PC) can be added to the total weight analysis, but it is unlikely that the entire design would pass the maximum threshold of 50 lbs with the PC since a standard desktop weighs 10 lbs and a standard laptop weighs 3.5lbs. Calculations can be found in Appendix 3.

Acceptance Test Results

Since the design of the project was mostly proof of concept, there were only two test procedures and results as outlined above: one for durometer and one for vibration reduction. The durometer results (ATP Data Sheet 1) show that the printer was able to achieve a range of hardness from 84.2A to 73.4D Shore Hardness. Based on the values, there is a linear relationship between percent hardness and durometer. For a 20% increase in hardness, there was an increase in

hardness of 4. For a 30% increase in hardness, there was an increase in hardness of 5. The vibration results (ATP Data Sheet 2, 3, and 4) show that a multi-durometer part successfully reduced vibrations. Between the Control Vibe Tester and the Simple Ring Vibe Tester there was a 1/3 reduction in vibration in the center ring. Between the Simple Ring Vibe Tester and the Advanced Reduction Vibe Tester there was also a 1/3 reduction in vibration in the center ring. Overall, there was a 1/9 reduction in vibration between the Control Vibe Tester and the Advanced Reduction Vibe Tester. This shows that varying designs with the different hardnesses can have significant effects on the vibration of a printed object.

Final Budget

Purchased			
Item	**Quantity**	**Cost**	**Supplier**
Lulzbot Taz5 3D Printer w/ Dual Extruder	1	$1,968.19	Amazon
Diamond Hotend Kit	1	$92.73	eBay
Printer Filament	8	$424.40	Various
Bowden Tubes	1	$7.75	Amazon
Materials & Tools	--	$112.10	Various
Design Day Materials	--	$45	ART Print Services
Fabbed			
Item	**Quantity**	**Cost**	**Fabrication Method**
Bowden Couplers	4	--	3D Printing
Dual Extruder Modification	2	--	3D Printing
Dual Extruder Mount	1	--	3D Printing
Diamond Hotend Mount	1	--	3D Printing
Test Constructs	3+	--	3D Printing
Total = $2,657.50	**Margin = $4,000 - $2,650.17 = $1,349.83**		

Lessons Learned

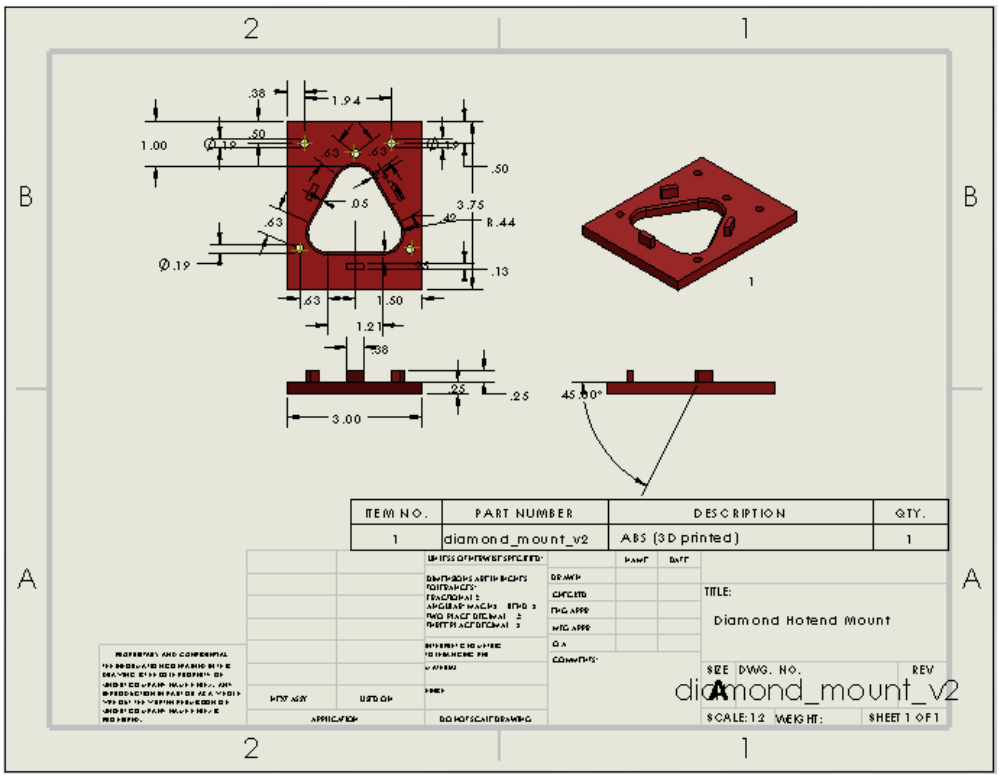
After completion of the senior design project and final report, there were many lessons learned that would be taken into account if the project were repeated or a similar project completed in the future. The most important lesson from this year-long project was the importance of early planning along with enforcing strict deadlines on the team and individuals. Towards the end of the semester many of the tasks needed to be quickly finished in order to meet the deadline. It would have been greatly helpful if modifications of the printer would've started prior to or during winter break since the printer was purchased in late November. Since this project required more of a modification to a system instead of building a system, the most important part was the final acceptance tests. Too many issues arose late in the semester with regards to the mixing of the filaments, so the final acceptance tests were constantly postponed.

Moreover, communication between team members could have aided in the delay of portions of the project. If one team member was struggling with their task, instead of wasting time trying to solve the issue individually, the team could've combined efforts to solve the issue in order not to delay the entire project. Mandatory meetings should have been held by the team weekly, so issues could've been reviewed and solved by the next meeting. Additionally, with the strict deadlines the team could have provided more time to account for errors with design and testing. Allowing time for future complications would also avoid major delays and poor final results.

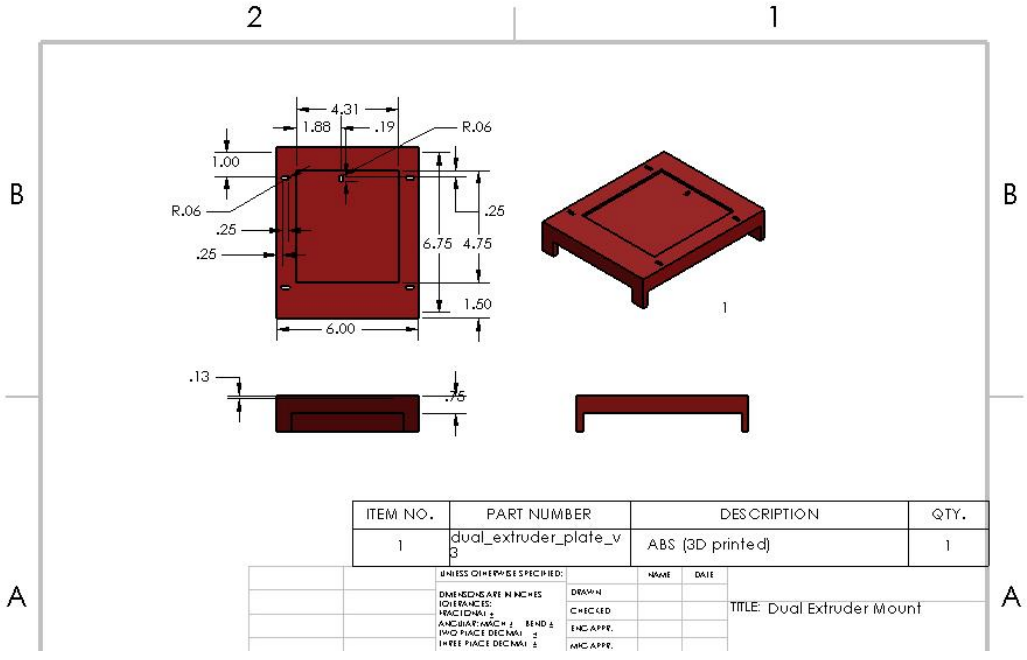
The second major lesson learned from this project was to take advantage of outside sources, especially the resources provided by the sponsor. Due to the backgrounds of the team members, the team lacked experience in software development. This required the team to search for outside sources to aid in this area, especially with regards to the printer's firmware. Due to the background of the sponsor, he was an excellent resource for this issue with the project. It may have been more helpful to ask for his assistance earlier in order to solve the firmware issues in the beginning of the semester and not delay the final acceptance tests. Still, the team was able to solve a handful of issues through forums and the product's provider. Overall, if the project were to be repeated then setting stricter deadlines earlier along with searching for assistance in areas of weakness would've solved many of the issues faced.

Appendix 1

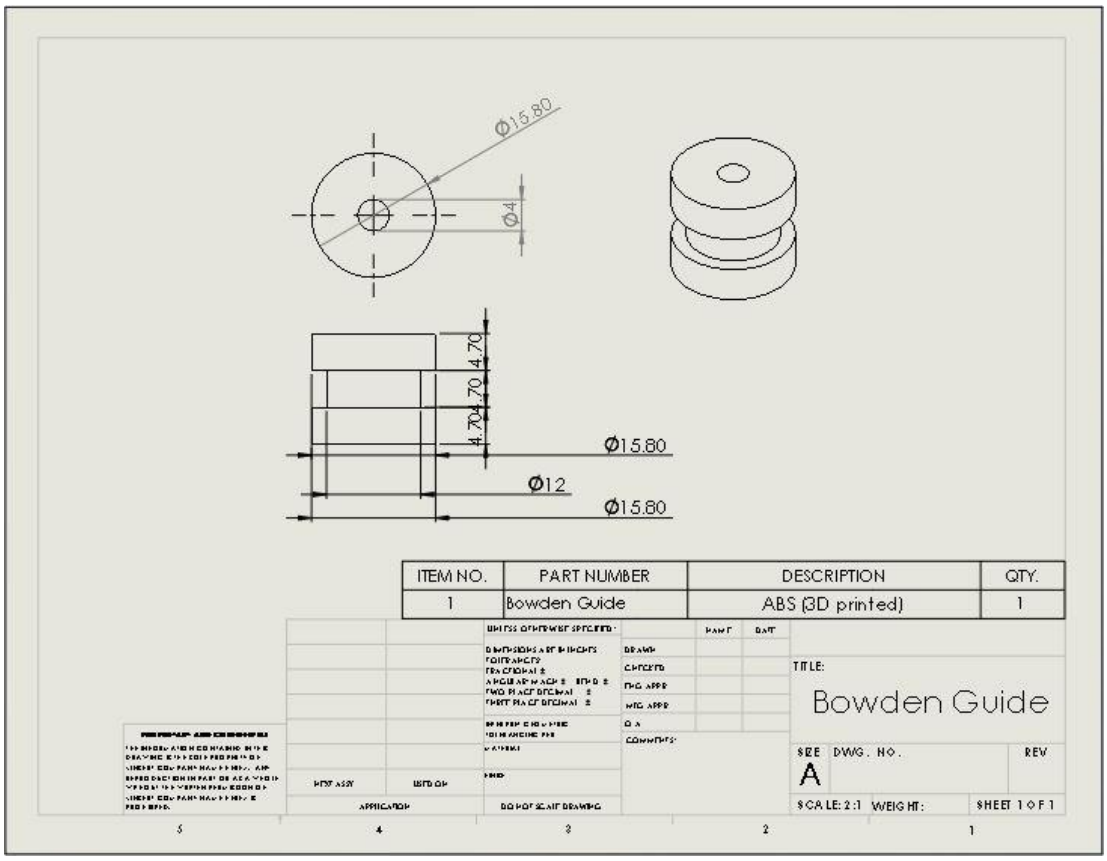
Drawings



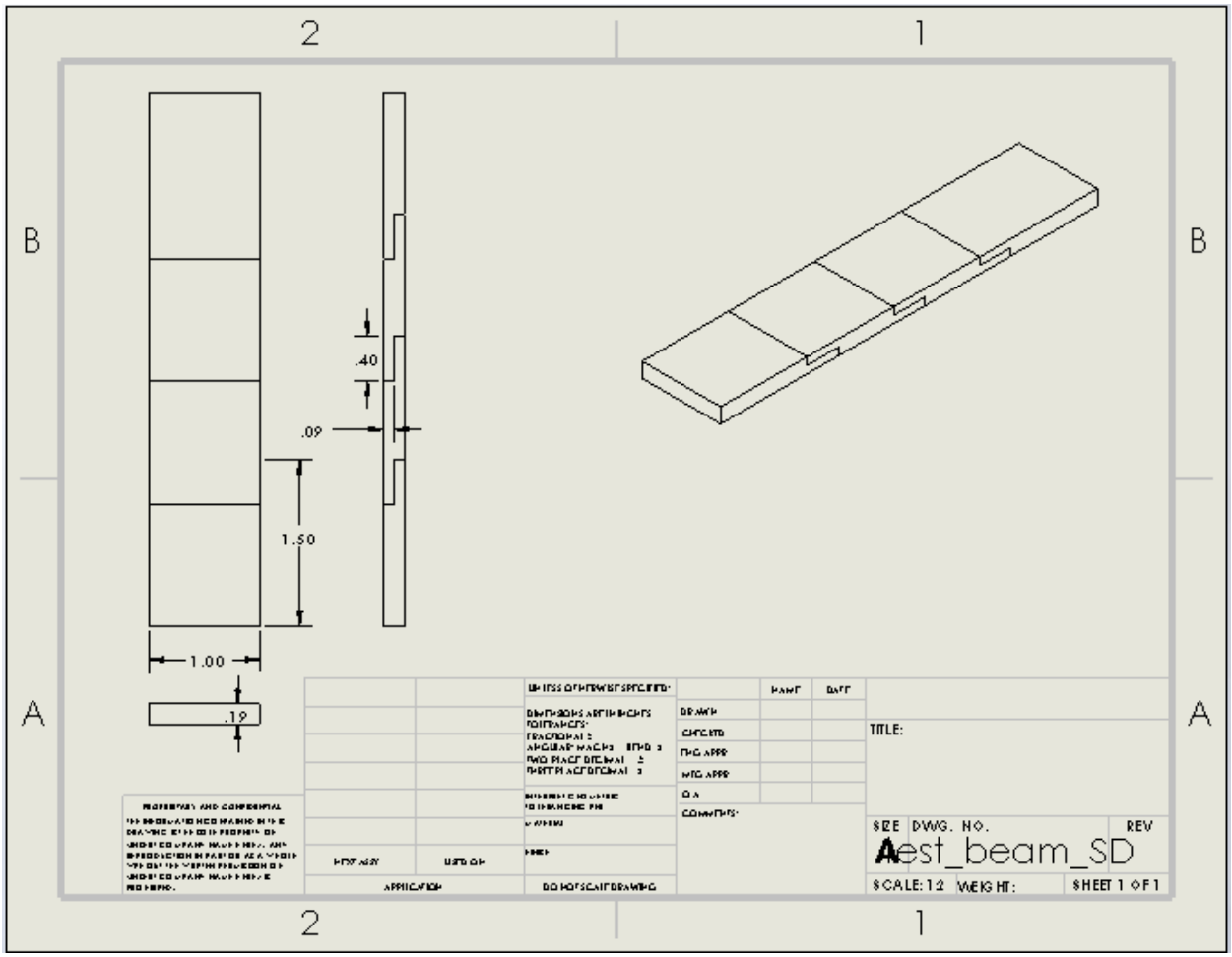
Drawing 1: Diamond Hotend Mount



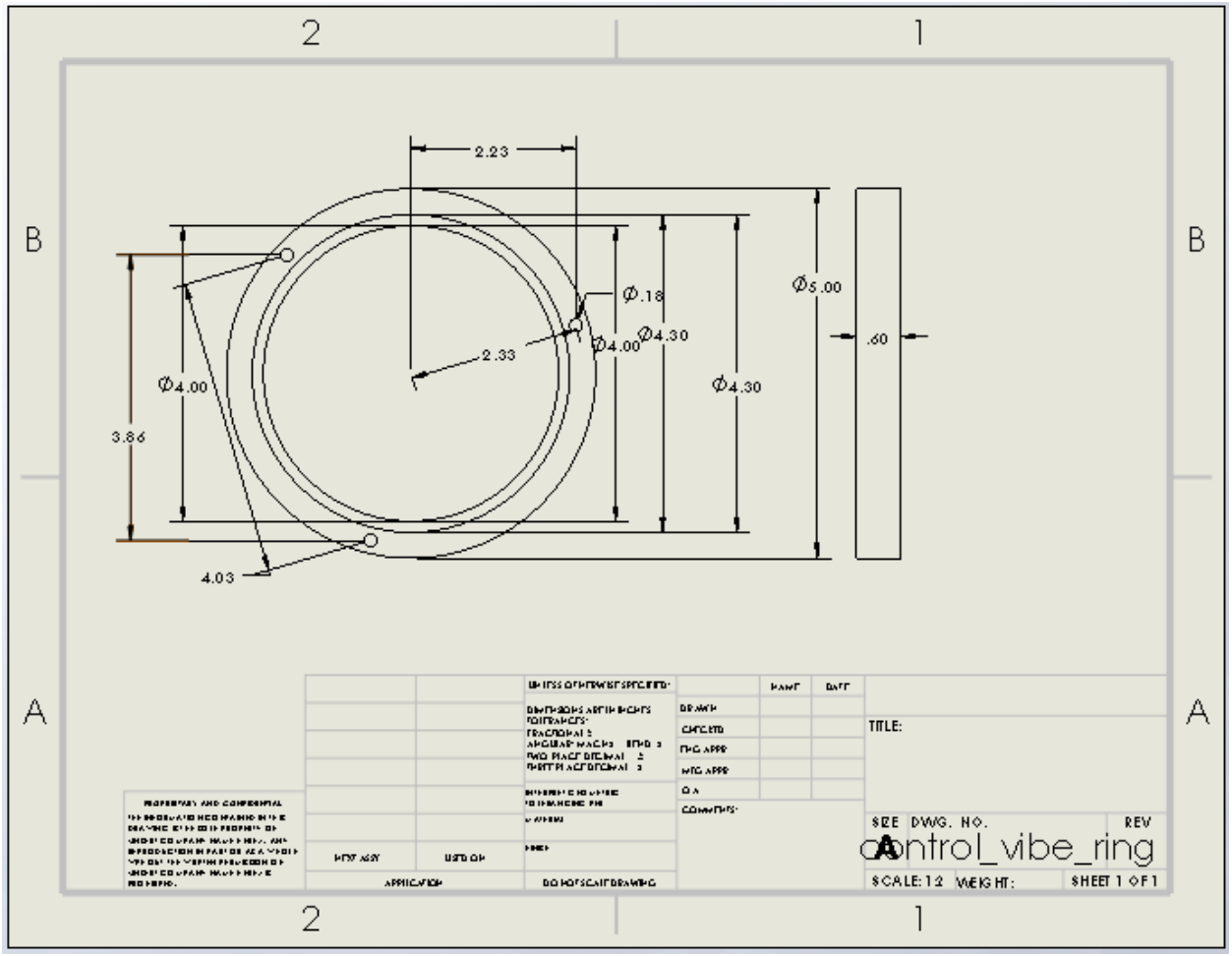
Drawing 2: Dual Extruder Mount



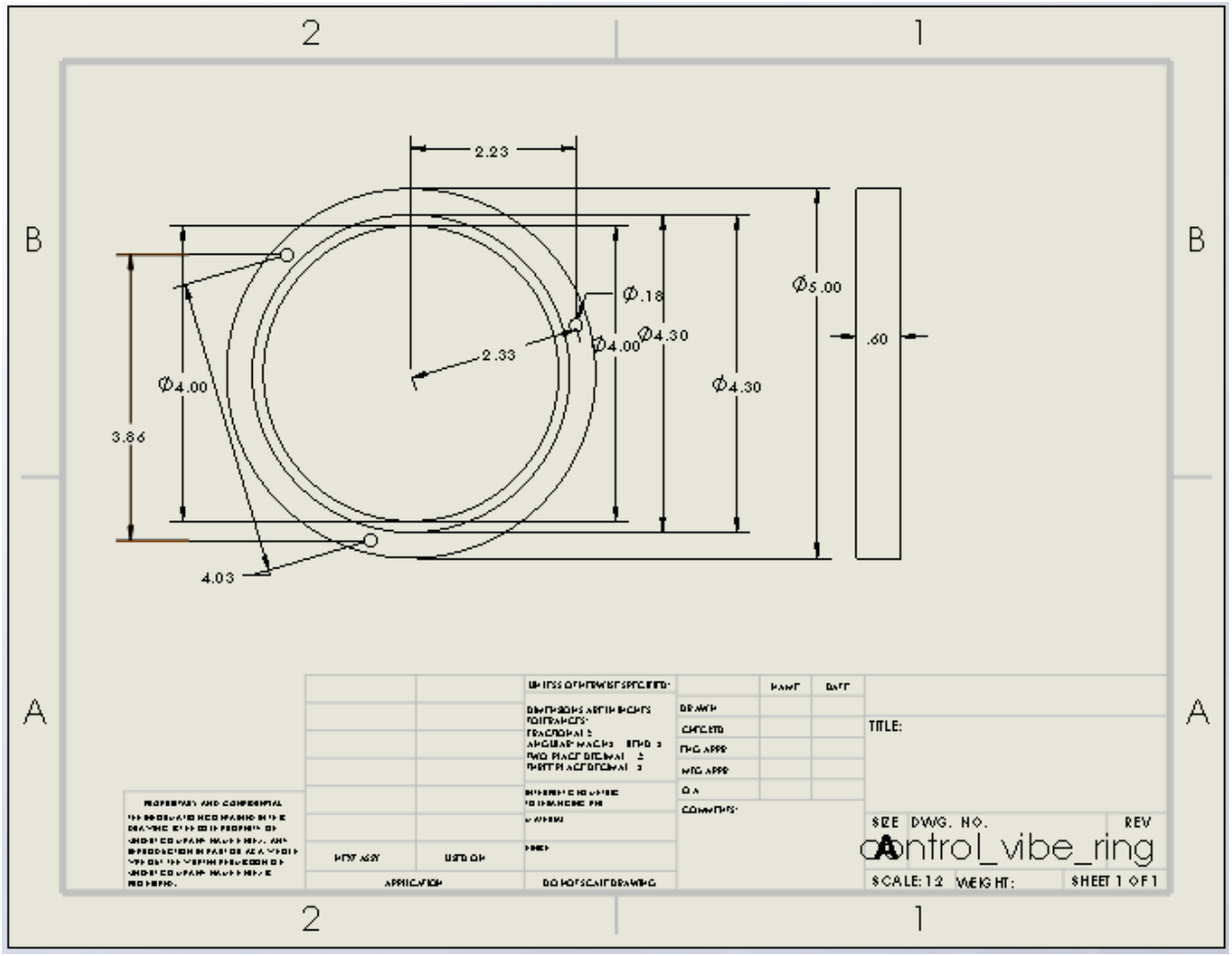
Drawing 3: Bowden Guide



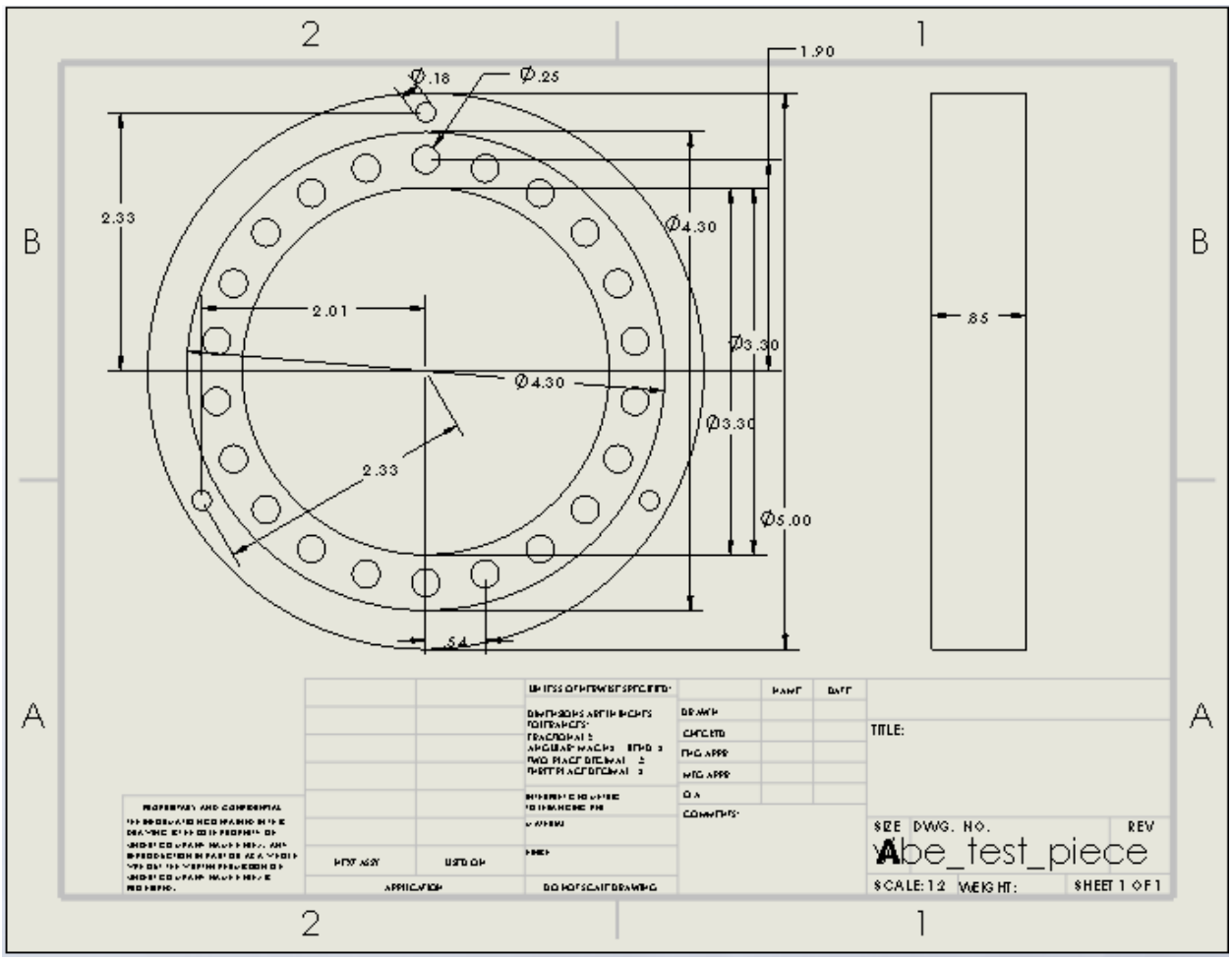
Drawing 4: Dog Bone



Drawing 5: Control Vibe Tester



Drawing 6: Simple Ring Vibe Tester (Same design as Control Vibe Tester)



Drawing 7: Advanced Reduction Vibe Tester

Appendix 2

Software Documents

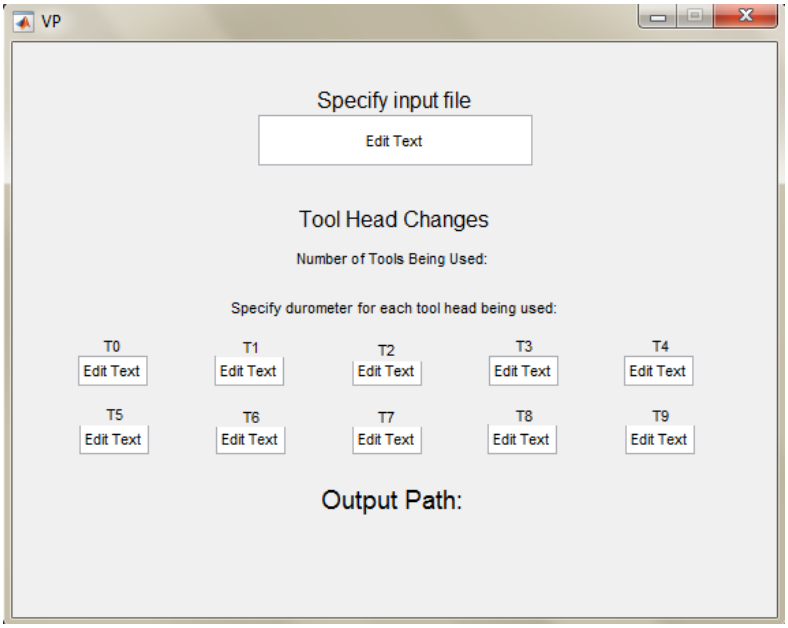


Figure 1. GUI Task Page.

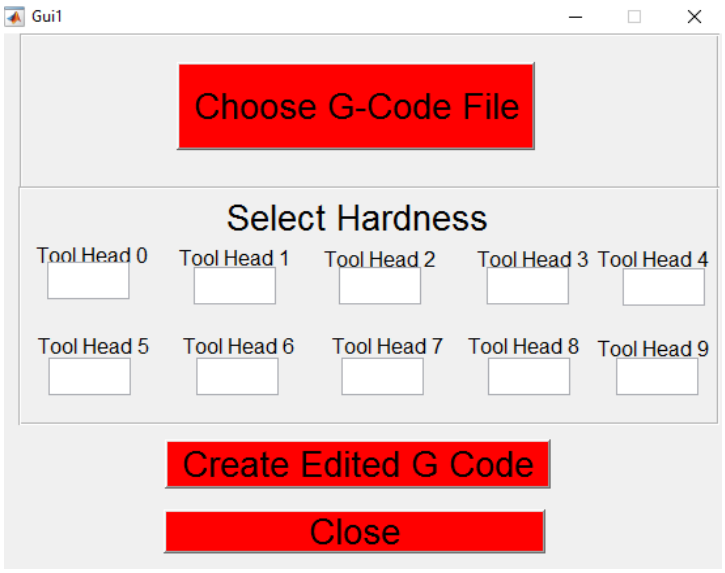


Figure 2. GUI Interface.

Configuration.h Firmware change sections

```
#define STRING_CONFIG_H_AUTHOR "(Raytheon, VD3DP)" // Who made the changes.
#define SHOW_BOOTSCREEN
#define STRING_SPLASH_LINE1 SHORT_BUILD_VERSION // will be shown during bootup in line 1
#define STRING_SPLASH_LINE2 WEBSITE_URL         // will be shown during bootup in line 2
```

Figure 3. Company Information.

```
// SD CARD
//
// SD Card support is disabled by default. If your controller has an SD slot,
// you must uncomment the following option or it won't work.
//
#define SDSUPPORT
```

Figure 4. Uncomment SDSUPPORT.

```
//
// RepRapDiscount FULL GRAPHIC Smart Controller
// http://reprap.org/wiki/RepRapDiscount_Full_Graphic_Smart_Controller
//
#define REPRAP_DISCOUNT_FULL_GRAPHIC_SMART_CONTROLLER
```

Figure 5. Enable the Reprap LCD Controller.

```
// Mechanical endstop with COM to ground and NC to Signal uses "false" here (most common setup).
#define X_MIN_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
#define Y_MIN_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
#define Z_MIN_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
#define X_MAX_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
#define Y_MAX_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
#define Z_MAX_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
#define Z_MIN_PROBE_ENDSTOP_INVERTING true // set to true to invert the logic of the endstop.
```

Figure 6. Endstop Inverting.

```
// The following define selects which electronics board you have.
// Please choose the name from boards.h that matches your setup
#ifndef MOTHERBOARD
  #define MOTHERBOARD BOARD_RAMBO
#endif

// Optional custom name for your RepStrap or other custom machine
// Displayed in the LCD "Ready" message
#define CUSTOM_MACHINE_NAME "RAYTHEON VD3DP"

// Define this to set a unique identifier for this printer, (Used by some programs to differentiate between machines
// You can use an online service to generate a random UUID. (eg http://www.uuidgenerator.net/version4)
//#define MACHINE_UUID "00000000-0000-0000-0000-000000000000"

// This defines the number of extruders
// :[1, 2, 3, 4]
#define EXTRUDERS 1
```

Figure 7. Check Extruder Information.

```
/**
 * "Mixing Extruder"
 *   - Adds a new code, M165, to set the current mix factors.
 *   - Extends the stepping routines to move multiple steppers in proportion to the mix.
 *   - Optional support for Repetier Host M163, M164, and virtual extruder.
 *   - This implementation supports only a single extruder.
 *   - Enable DIRECT_MIXING_IN_G1 for Pia Taubert's reference implementation
 */
#define MIXING_EXTRUDER
#if ENABLED(MIXING_EXTRUDER)
  #define MIXING_STEPPERS 2        // Number of steppers in your mixing extruder
  #define MIXING_VIRTUAL_TOOLS 16  // Use the Virtual Tool method with M163 and M164
  #define DIRECT_MIXING_IN_G1    // Allow ABCDHI mix factors in G1 movement commands
#endif
```

Figure 8. Enable Mixing Extruders.

```
    #define DEFAULT_AXIS_STEPS_PER_UNIT   { 100.5, 100.5, 1600, 830 }

    /**
     * Default Max Feed Rate (mm/s)
     * Override with M203
     *                                    X, Y, Z, E0 [, E1[, E2[, E3]]]
     */
    #define DEFAULT_MAX_FEEDRATE          { 800, 800, 3, 50 }

    /**
     * Default Max Acceleration (change/s) change = mm/s
     * (Maximum start speed for accelerated moves)
     * Override with M201
     *                                    X, Y, Z, E0 [, E1[, E2[, E3]]]
     */
    #define DEFAULT_MAX_ACCELERATION      { 9000, 9000, 100, 100 }

    /**
     * Default Acceleration (change/s) change = mm/s
     * Override with M204
     *
     *   M204 P    Acceleration
     *   M204 R    Retract Acceleration
     *   M204 T    Travel Acceleration
     */
    #define DEFAULT_ACCELERATION          300    // X, Y, Z and E acceleration for printing moves
    #define DEFAULT_RETRACT_ACCELERATION  3000    // E acceleration for retracts
    #define DEFAULT_TRAVEL_ACCELERATION   3000    // X, Y, Z acceleration for travel (non printing) moves

    /**
     * Default Jerk (mm/s)
     *
     * "Jerk" specifies the minimum speed change that requires acceleration.
     * When changing speed and direction, if the difference is less than the
     * value set here, it may happen instantaneously.
     */
    #define DEFAULT_XJERK                 8.0
    #define DEFAULT_YJERK                 8.0
    #define DEFAULT_ZJERK                 0.4
    #define DEFAULT_EJERK                10.0
```

Figure 9. Check Movement Settings.

```
//===========================================================================
//============================= PID Settings ================================
//===========================================================================
// PID Tuning Guide here: http://reprap.org/wiki/PID_Tuning

// Comment the following line to disable PID and enable bang-bang.
#define PIDTEMP
#define BANG_MAX 220 // limits current to nozzle while in bang-bang mode; 255=full current
#define PID_MAX 225 // limits current to nozzle while PID is active (see PID_FUNCTIONAL_RANGE below); 255=full current
#if ENABLED(PIDTEMP)
  //#define PID_AUTOTUNE_MENU // Add PID Autotune to the LCD "Temperature" menu to run M303 and apply the result.
  //#define PID_DEBUG // Sends debug data to the serial port.
  //#define PID_OPENLOOP 1 // Puts PID in open loop. M104/M140 sets the output power from 0 to PID_MAX
  //#define SLOW_PWM_HEATERS // PWM with very low frequency (roughly 0.125Hz=8s) and minimum state time of approximately 1s useful for heaters driven by a relay
  //#define PID_PARAMS_PER_HOTEND // Uses separate PID parameters for each extruder (useful for mismatched extruders)
                                  // Set/get with gcode: M301 E[extruder number, 0-2]
  #define PID_FUNCTIONAL_RANGE 10 // If the temperature difference between the target temperature and the actual temperature
                                  // is more than PID_FUNCTIONAL_RANGE then the PID will be shut off and the heater will be set to min/max.
  #define K1 0.95 //smoothing factor within the PID

  // If you are using a pre-configured hotend then you can use one of the value sets by uncommenting it
  // Ultimaker
//  #define  DEFAULT_Kp 22.2
//  #define  DEFAULT_Ki 1.08
//  #define  DEFAULT_Kd 114

  // MakerGear
  //#define  DEFAULT_Kp 7.0
  //#define  DEFAULT_Ki 0.1
  //#define  DEFAULT_Kd 12

  // Mendel Parts V9 on 12V
  //#define  DEFAULT_Kp 63.0
  //#define  DEFAULT_Ki 2.25
  //#define  DEFAULT_Kd 440

  //A0-Hexagon (24V)

  #define  DEFAULT_Kp 28.79
  #define  DEFAULT_Ki 1.91
  #define  DEFAULT_Kd 108.51

#endif // PIDTEMP
```

Figure 10. PID settings.

```
#define TEMP_SENSOR_0 5
#define TEMP_SENSOR_1 5
#define TEMP_SENSOR_2 0
//#define TEMP_SENSOR_3 0
#define TEMP_SENSOR_BED 7

// Dummy thermistor constant temperature readings, for use with 998 and 999
#define DUMMY_THERMISTOR_998_VALUE 25
#define DUMMY_THERMISTOR_999_VALUE 100

// Use temp sensor 1 as a redundant sensor with sensor 0. If the readings
// from the two sensors differ too much the print will be aborted.
//#define TEMP_SENSOR_1_AS_REDUNDANT
#define MAX_REDUNDANT_TEMP_SENSOR_DIFF 10

// Extruder temperature must be close to target for this long before M109 returns success
#define TEMP_RESIDENCY_TIME 0.5  // (seconds)
#define TEMP_HYSTERESIS 10       // (degC) range of +/- temperatures considered "close" to the target one
#define TEMP_WINDOW     10       // (degC) Window around target to start the residency timer x degC early.

// Bed temperature must be close to target for this long before M190 returns success
#define TEMP_BED_RESIDENCY_TIME 1  // (seconds)
#define TEMP_BED_HYSTERESIS 3       // (degC) range of +/- temperatures considered "close" to the target one
#define TEMP_BED_WINDOW     1       // (degC) Window around target to start the residency timer x degC early.

// The minimal temperature defines the temperature below which the heater will not be enabled It is used
// to check that the wiring to the thermistor is not broken.
// Otherwise this would lead to the heater being powered on all the time.
#define HEATER_0_MINTEMP 5
#define HEATER_1_MINTEMP 5
#define HEATER_2_MINTEMP 5
#define HEATER_3_MINTEMP 5
#define BED_MINTEMP 5

// When temperature exceeds max temp, your heater will be switched off.
// This feature exists to protect your hotend from overheating accidentally, but *NOT* from thermistor short/failure!
// You should use MINTEMP for thermistor short/failure protection.
#define HEATER_0_MAXTEMP 305
#define HEATER_1_MAXTEMP 305
#define HEATER_2_MAXTEMP 305
#define HEATER_3_MAXTEMP 305
#define BED_MAXTEMP 150
```

Figure 11. Temperature Settings.

Configuration_adv.h settings

```
#if ENABLED(THERMAL_PROTECTION_HOTENDS)
  #define THERMAL_PROTECTION_PERIOD 100        // Seconds
  #define THERMAL_PROTECTION_HYSTERESIS 10     // Degrees Celsius

  /**
   * Whenever an M104 or M109 increases the target temperature the firmware will wait for the
   * WATCH_TEMP_PERIOD to expire, and if the temperature hasn't increased by WATCH_TEMP_INCREASE
   * degrees, the machine is halted, requiring a hard reset. This test restarts with any M104/M109,
   * but only if the current temperature is far enough below the target for a reliable test.
   *
   * If you get false positives for "Heating failed" increase WATCH_TEMP_PERIOD and/or decrease WATCH_TEMP_INCREASE
   * WATCH_TEMP_INCREASE should not be below 2.
   */
  #define WATCH_TEMP_PERIOD 100               // Seconds
  #define WATCH_TEMP_INCREASE 2               // Degrees Celsius
#endif

/**
 * Thermal Protection parameters for the bed are just as above for hotends.
 */
#if ENABLED(THERMAL_PROTECTION_BED)
  #define THERMAL_PROTECTION_BED_PERIOD 100    // Seconds
  #define THERMAL_PROTECTION_BED_HYSTERESIS 2 // Degrees Celsius

  /**
   * Whenever an M140 or M190 increases the target temperature the firmware will wait for the
   * WATCH_BED_TEMP_PERIOD to expire, and if the temperature hasn't increased by WATCH_BED_TEMP_INCREASE
   * degrees, the machine is halted, requiring a hard reset. This test restarts with any M140/M190,
   * but only if the current temperature is far enough below the target for a reliable test.
   *
   * If you get too many "Heating failed" errors, increase WATCH_BED_TEMP_PERIOD and/or decrease
   * WATCH_BED_TEMP_INCREASE. (WATCH_BED_TEMP_INCREASE should not be below 2.)
   */
  #define WATCH_BED_TEMP_PERIOD 100               // Seconds
  #define WATCH_BED_TEMP_INCREASE 2              // Degrees Celsius
#endif

#if ENABLED(PIDTEMP)
  // this adds an experimental additional term to the heating power, proportional to the extrusion speed.
  // if Kc is chosen well, the additional required power due to increased melting should be compensated.
  //#define PID_EXTRUSION_SCALING
  #if ENABLED(PID_EXTRUSION_SCALING)
    #define DEFAULT_Kc (100) //heating power=Kc*(e_speed)
    #define LPQ_MAX_LEN 50
  #endif
```

Figure 12. Advanced Temp Settings.

```
#ifndef __AVR_ATmega2560__
  #error "Oops!  Make sure you have 'Arduino Mega 2560' selected from the 'Tools -> Boards' menu."
#endif

#define BOARD_NAME "Rambo"

#define LARGE_FLASH true

//
// Servos
//
#define SERVO0_PIN         22 // Motor header MX1
#define SERVO1_PIN         23 // Motor header MX2
#define SERVO2_PIN         24 // Motor header MX3
#define SERVO3_PIN          5 // PWM header pin 5

//
// Z Probe (when not Z_MIN_PIN)
//
#ifndef Z_MIN_PROBE_PIN
  #define Z_MIN_PROBE_PIN  30
#endif

#if ENABLED(Z_PROBE_SLED)
  #define SLED_PIN         -1
#endif

//
// Limit Switches
//
#define X_MIN_PIN          12
#define X_MAX_PIN          24
#define Y_MIN_PIN          11
#define Y_MAX_PIN          23
#define Z_MIN_PIN          10
#define Z_MAX_PIN          30
```

Figure 13. Servo and Limit Switch pin configurations.

```
//
// Steppers
//
#define X_STEP_PIN         37
#define X_DIR_PIN          48
#define X_ENABLE_PIN       29

#define Y_STEP_PIN         36
#define Y_DIR_PIN          49
#define Y_ENABLE_PIN       28

#define Z_STEP_PIN         35
#define Z_DIR_PIN          47
#define Z_ENABLE_PIN       27

#define E0_STEP_PIN        34
#define E0_DIR_PIN         43
#define E0_ENABLE_PIN      26

#define E1_STEP_PIN        33
#define E1_DIR_PIN         42
#define E1_ENABLE_PIN      25

// Microstepping pins - Mapping not from fastio.h (?)
#define X_MS1_PIN          40
#define X_MS2_PIN          41
#define Y_MS1_PIN          69
#define Y_MS2_PIN          39
#define Z_MS1_PIN          68
#define Z_MS2_PIN          67
#define E0_MS1_PIN         65
#define E0_MS2_PIN         66
#define E1_MS1_PIN         63
#define E1_MS2_PIN         64

#define DIGIPOTSS_PIN      38
#define DIGIPOT_CHANNELS {4,5,3,0,1} // X Y Z E0 E1 digipot channels to stepper driver mapping

//
// Temperature Sensors
//
#define TEMP_0_PIN          0   // Analog Input
#define TEMP_1_PIN          1   // Analog Input
#define TEMP_BED_PIN        2   // Analog Input
```

Figure 14. Stepper and Temp Sensor Pin Configurations.

```
// Heaters / Fans
//
#define HEATER_0_PIN        9
#define HEATER_1_PIN        7
#define HEATER_2_PIN        6
#define HEATER_BED_PIN      3

#define FAN_PIN            6
#define FAN1_PIN           8
#define FAN2_PIN           2

//
// Misc. Functions
//
#define SDSS               53
#define LED_PIN            13
#define FILWIDTH_PIN        3   // Analog Input
#define PS_ON_PIN           4

//
// LCD / Controller
//
#if ENABLED(ULTRA_LCD)

  #define KILL_PIN 80

  #if ENABLED(NEWPANEL)

    #define LCD_PINS_RS 70
    #define LCD_PINS_ENABLE 71
    #define LCD_PINS_D4 72
    #define LCD_PINS_D5 73
    #define LCD_PINS_D6 74
    #define LCD_PINS_D7 75

    #if ENABLED(VIKI2) || ENABLED(miniVIKI)
      #define BEEPER_PIN 44
      // NB: Panucatt's Viki 2.0 wiring diagram (v1.2) indicates that the
      //     beeper/buzzer is connected to pin 33; however, the pin used in the
      //     diagram is actually pin 44, so this is correct.

      #define DOGLCD_A0  70
      #define DOGLCD_CS  71
      #define LCD_SCREEN_ROT_180
```

Figure 15. Heater +LCD Pin Configurations.

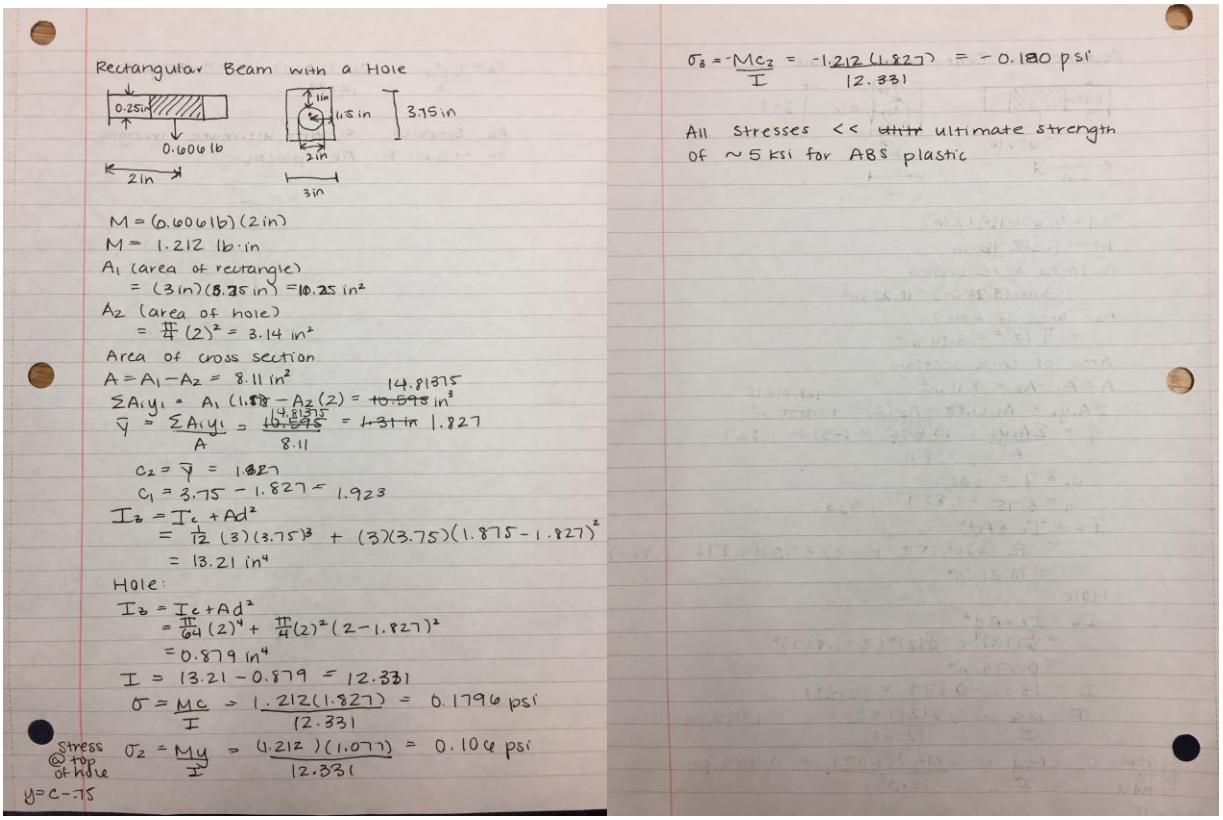
```
      #define BTN_EN1 85
      #define BTN_EN2 84
      #define BTN_ENC 83

      #define SD_DETECT_PIN 81 // Pin 72 if using easy adapter board

      #define STAT_LED_RED_PIN 22
      #define STAT_LED_BLUE_PIN 32

    #else

      #define BEEPER_PIN 79 // AUX-4

      // AUX-2
      #define BTN_EN1 76
      #define BTN_EN2 77
      #define BTN_ENC 78

      #define SD_DETECT_PIN 81

    #endif // VIKI2/miniVIKI

  #else // !NEWPANEL - old style panel with shift register

    // No Beeper added
    #define BEEPER_PIN 33

    // buttons are attached to a shift register
    // Not wired yet
    //#define SHIFT_CLK 38
    //#define SHIFT_LD 42
    //#define SHIFT_OUT 40
    //#define SHIFT_EN 17

    #define LCD_PINS_RS 75
    #define LCD_PINS_ENABLE 17
    #define LCD_PINS_D4 23
    #define LCD_PINS_D5 25
    #define LCD_PINS_D6 27
    #define LCD_PINS_D7 29

  #endif // !NEWPANEL

#endif // ULTRA_LCD
```

Figure 16. MISC Pin Configurations.

Appendix 3

Analyses

1. Stress Analysis on Diamond Hotend Mount



Rectangular Beam with a Hole

$M = (0.606\,lb)(2\,in)$

$M = 1.212\ lb \cdot in$

A_1 (area of rectangle) $= (3\,in)(3.75\,in) = 10.25\ in^2$

A_2 (area of hole) $= \pi(2)^2 = 3.14\ in^2$

Area of cross section

$A = A_1 - A_2 = 8.11\ in^2$

$\Sigma A_i y_i = A_1(1.88) - A_2(2) = 14.81375 - 10.598 = 4.31\ in^3$

$\bar{y} = \frac{\Sigma A_i y_i}{A} = \frac{14.81375}{8.11} = 1.827$

$c_2 = \bar{y} = 1.827$

$c_1 = 3.75 - 1.827 = 1.923$

$I_2 = I_c + Ad^2$

$= \frac{1}{12}(3)(3.75)^3 + (3)(3.75)(1.875 - 1.827)^2$

$= 13.21\ in^4$

Hole:

$I_2 = I_c + Ad^2$

$= \frac{\pi}{64}(2)^4 + \frac{\pi}{4}(2)^2(2 - 1.827)^2$

$= 0.879\ in^4$

$I = 13.21 - 0.879 = 12.331$

$\sigma = \frac{Mc}{I} = \frac{1.212(1.827)}{12.331} = 0.1796\ psi$

Stress @ top of hole

$\sigma_2 = \frac{My}{I} = \frac{(1.212)(1.077)}{12.331} = 0.106\ psi$

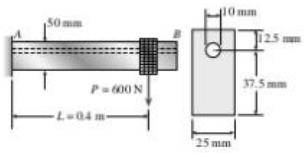
$y = c - .75$

$\sigma_3 = -\frac{Mc_2}{I} = -\frac{1.212(1.827)}{12.331} = -0.180\ psi$

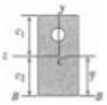
All stresses << ~~ultimate~~ ultimate strength of ~5 ksi for ABS plastic

Problem 5.5-22 A cantilever beam AB with a rectangular cross section has a longitudinal hole drilled throughout its length (see figure). The beam supports a load $P = 600$ N. The cross section is 25 mm wide and 50 mm high, and the hole has a diameter of 10 mm.

Find the bending stresses at the top of the beam, at the top of the hole, and at the bottom of the beam.



Solution 5.5-22 Rectangular beam with a hole



MAXIMUM BENDING MOMENT

$M = PL = (600 \text{ N})(0.4 \text{ m}) = 240 \text{ N} \cdot \text{m}$

PROPERTIES OF THE CROSS SECTION

A_1 = area of rectangle

$= (25 \text{ mm})(50 \text{ mm}) = 1250 \text{ mm}^2$

A_2 = area of hole

$= \frac{\pi}{4}(10 \text{ mm})^2 = 78.54 \text{ mm}^2$

A = area of cross section

$= A_1 - A_2 = 1171.5 \text{ mm}$

Using line $B - B$ as reference axis:

$\Sigma A_i y_i = A_1(25 \text{ mm}) - A_2(37.5 \text{ mm}) = 28{,}305 \text{ mm}^3$

$\overline{y} = \frac{\sum A_i y_i}{A} = \frac{28{,}305 \text{ mm}^3}{1171.5 \text{ mm}^2} = 24.162 \text{ mm}$

Distances to the centroid C:

$c_2 = \overline{y} = 24.162 \text{ mm}$

$c_1 = 50 \text{ mm} - c_2 = 25.838 \text{ mm}$

MOMENT OF INERTIA ABOUT THE NEUTRAL AXIS (THE z AXIS)

All dimensions in millimeters.

Rectangle:

$I_z = I_c + Ad^2$

$= \frac{1}{12}(25)(50)^3 + (25)(50)(25 - 24.162)^2$

$= 260{,}420 + 878 = 261{,}300 \text{ mm}^4$

Hole:

$I_z = I_c + Ad^2 = \frac{\pi}{64}(10)^4 + (78.54)(37.5 - 24.162)^2$

$= 490.87 + 13{,}972 = 14{,}460 \text{ mm}^4$

Cross-section:

$I = 261{,}300 - 14{,}460 = 246{,}800 \text{ mm}^4$

STRESS AT THE TOP OF THE BEAM

$\sigma_1 = \frac{Mc_1}{I} = \frac{(240 \text{ N} \cdot \text{m})(25.838 \text{ mm})}{246{,}800 \text{ mm}^4}$

$= 25.1 \text{ MPa}$ ←

(tension)

STRESS AT THE TOP OF THE HOLE

$\sigma_2 = \frac{My}{I} \quad y = c_1 - 7.5 \text{ mm} = 18.338 \text{ mm}$

$\sigma_2 = \frac{(240 \text{ N} \cdot \text{m})(18.338 \text{ mm})}{246{,}800 \text{ mm}^4} = 17.8 \text{ MPa}$ ←

(tension)

STRESS AT THE BOTTOM OF THE BEAM

$\sigma_3 = -\frac{Mc_2}{I} = -\frac{(240 \text{ N} \cdot \text{m})(24.162 \text{ mm})}{246{,}800 \text{ mm}^4}$

$= -23.5 \text{ MPa}$ ←

(compression)

2. Materials Analysis

Material	TPU (Soft)	TPU (Hard)	Nylon	Carbon-infused Nylon	Soft PLA	Normal PLA
Extrusion Temp (°C)	195-230	195-230	240-270	250-270	210-235	190-220
Bed Temp (°C)	70	70-80	100-110	100-110	50-70	23-60
Glass Transition Temp (°C)	-	-	105	105	60-65	60
Printing Speed (mm/s)	30	30	45-70	50-70	20-50	50-80

Tensile Modulus (MPa)	22.761	109.32	2094	4387	33.240	2865
Shore Hardness	85A	64D	88.5D	92.0D	92A	90.08D
Margin	--	-6D	-53.5A	+22D	-7A	+20.08D

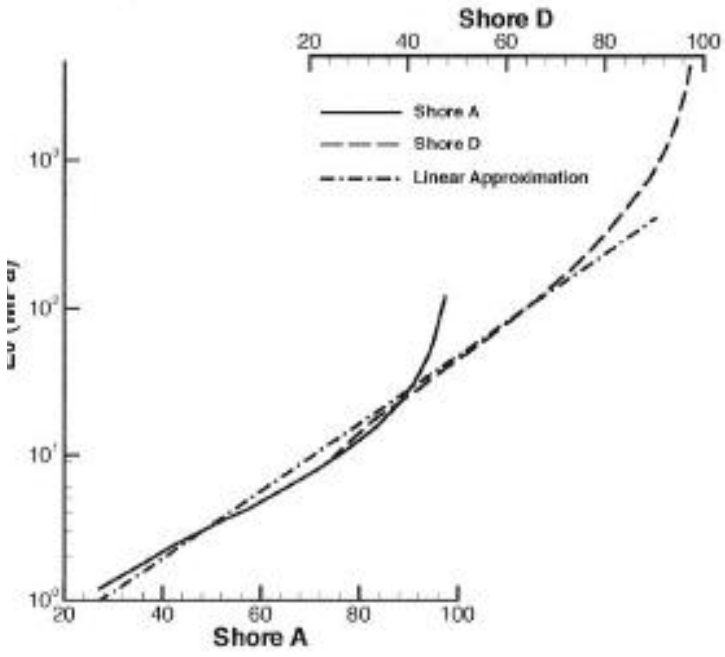
Conversion Equations

$$\log E = 0.0235S - 0.6403$$

$$S = \begin{cases} Shore\ A & 20A < S < 80A \\ Shore\ D + 50 & 80A < S < 85D \end{cases}$$

$$S_D = 100 - \frac{20(-78.188 + \sqrt{6113.36 + 781.88E})}{E}$$

Note: Due to the non-linear relationship of Shore D Hardness, the second equation should be utilized for harder plastics.



3. Weight Analysis

Component	Number	Weight (lbs)	Total Weight (lbs)
Taz 5 Printer System	1	25.25	25.25
Printing Filament	2	2.2	4.4
Dual Extruder	1	3.6	3.6
Diamond Hotend	1	0.55	0.55
Extruder Mount	1	1.14	1.14
Motor Mount	1	0.11	0.11

Bowden tubes	2	0.04	0.08
Total			**35.13 lbs**
Margin			**50 - 35.13 = 14.87 lbs**

Appendix 4

Test Procedures

Figure 1. Shore Durometer testing.

Figure 2. Vibration Platform.

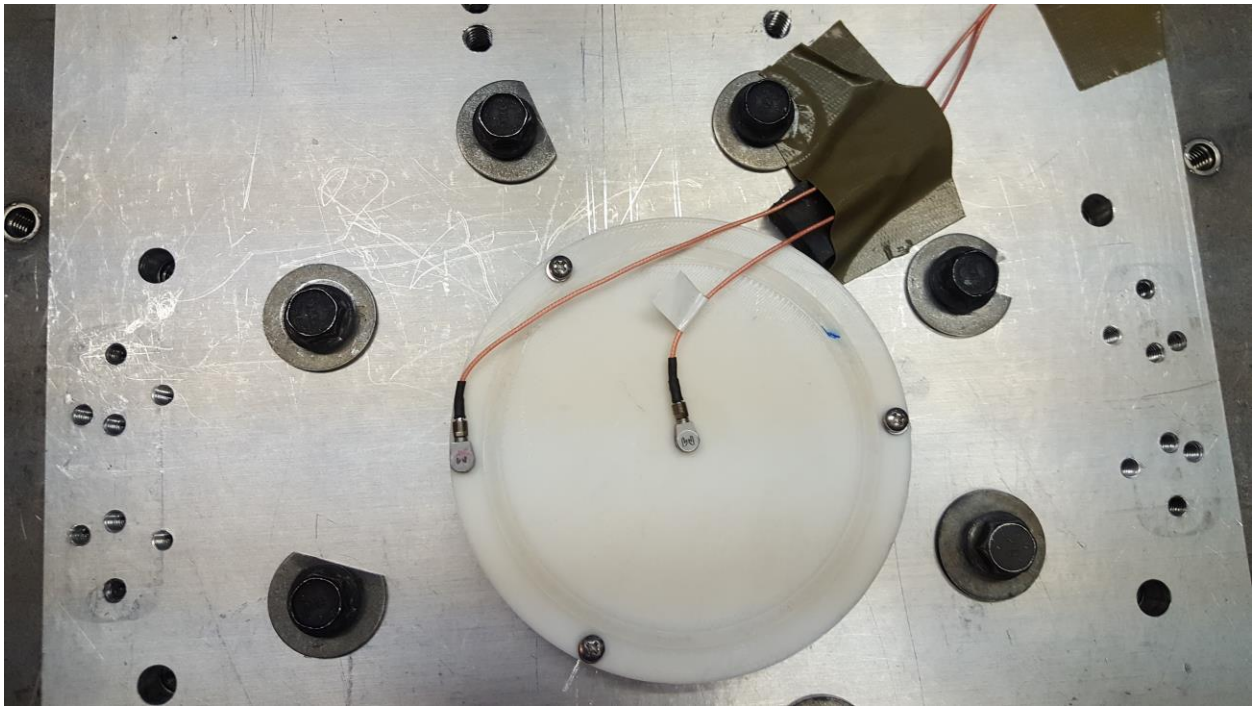


Figure 3. Accelerometers.

Figure 4. Signal Conditioner.

Figure 5. Loctite Instant Adhesive.

Figure 6. Loctite Accelerant.

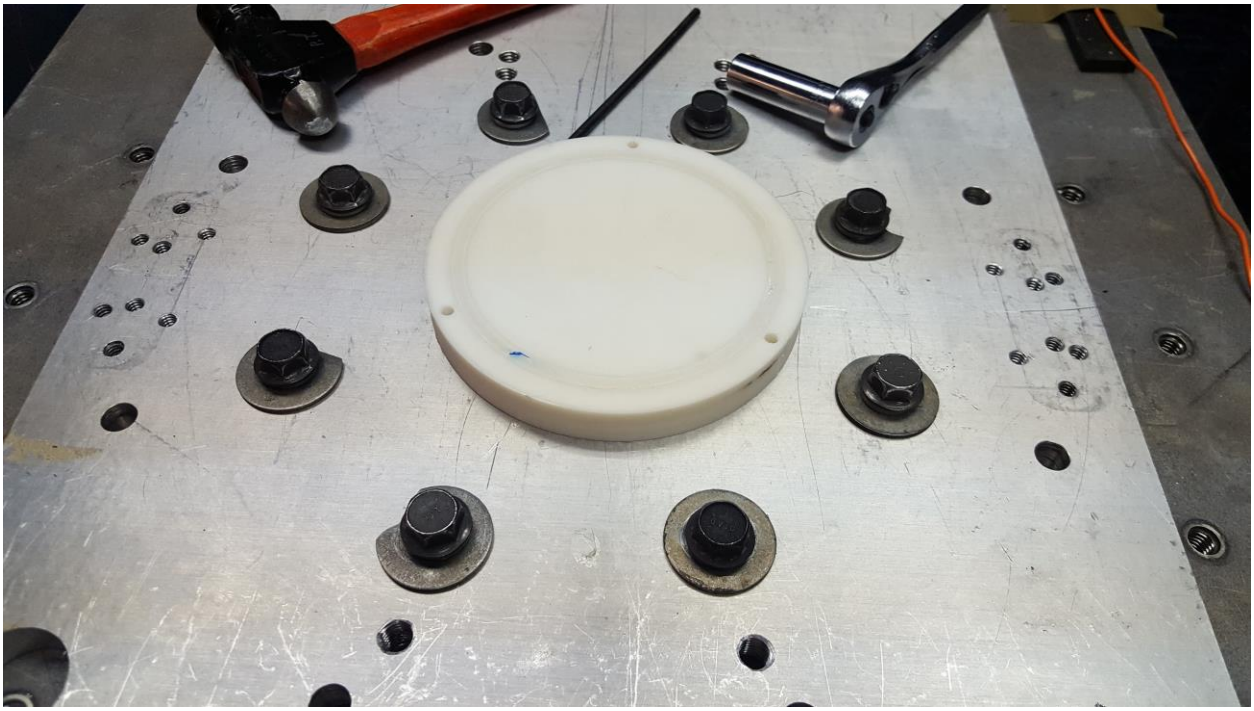


Figure 7. DUT.

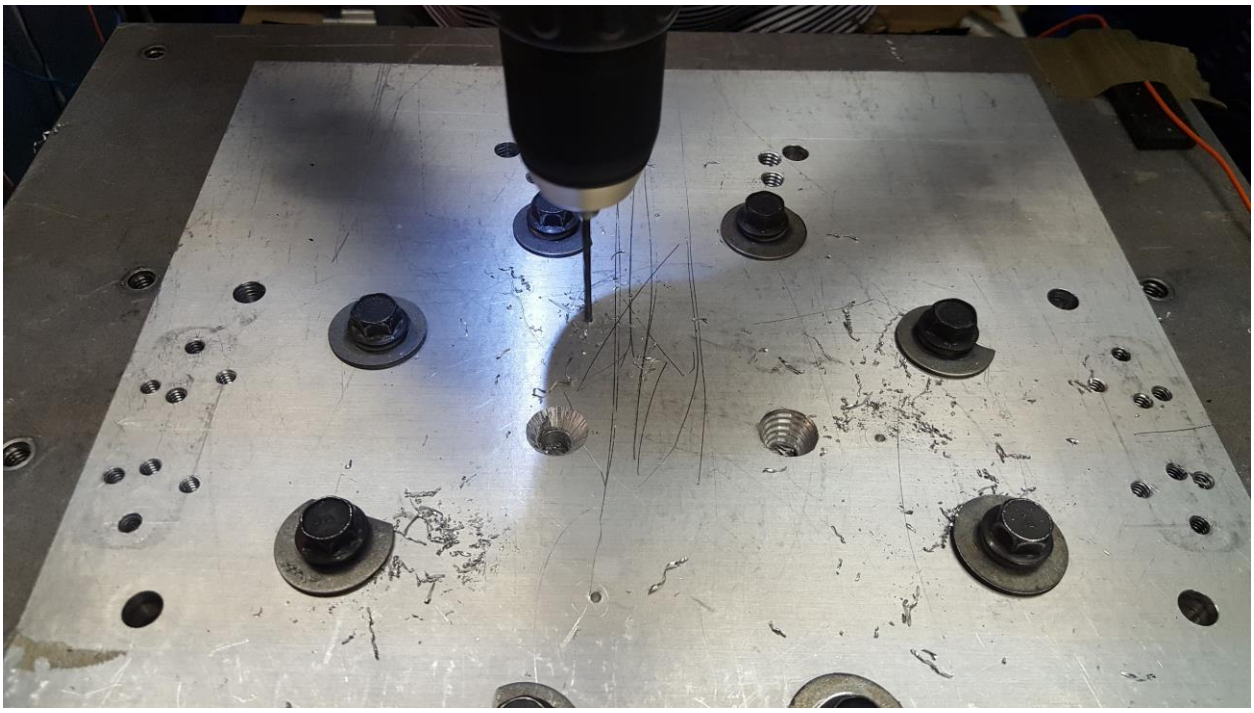


Figure 8. Drilling the transfer punch holes.

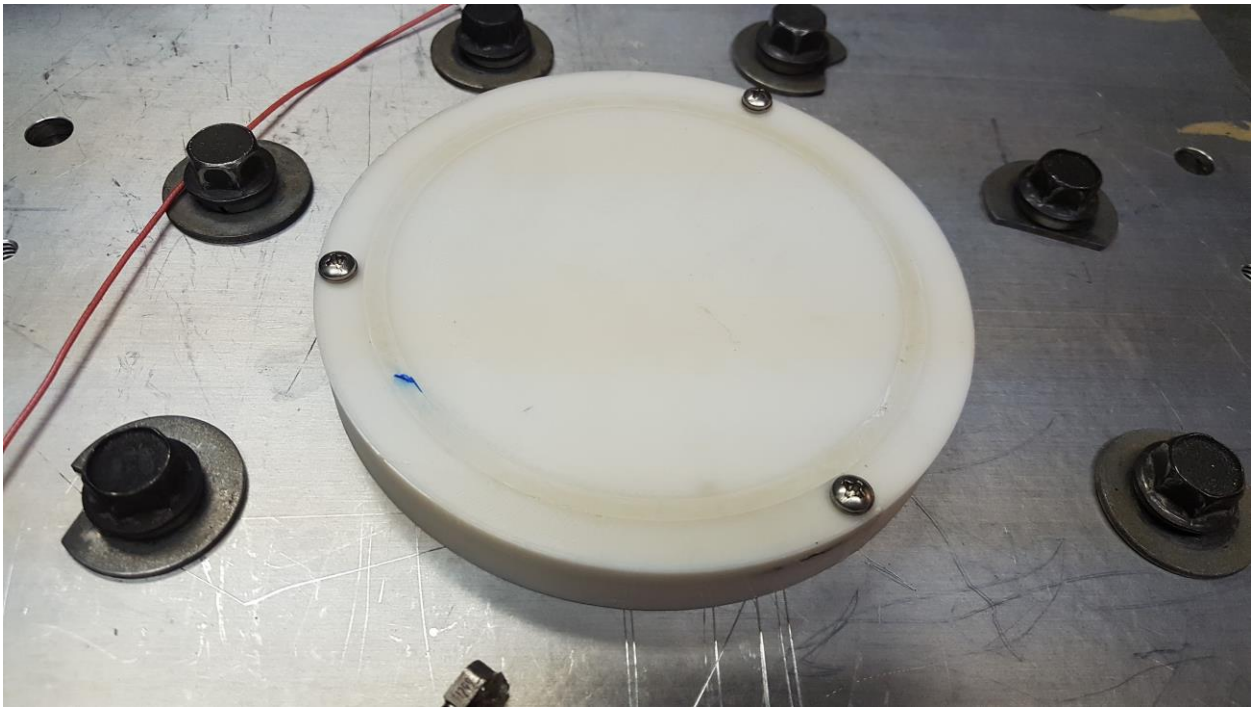


Figure 9. Mounting the DUT.

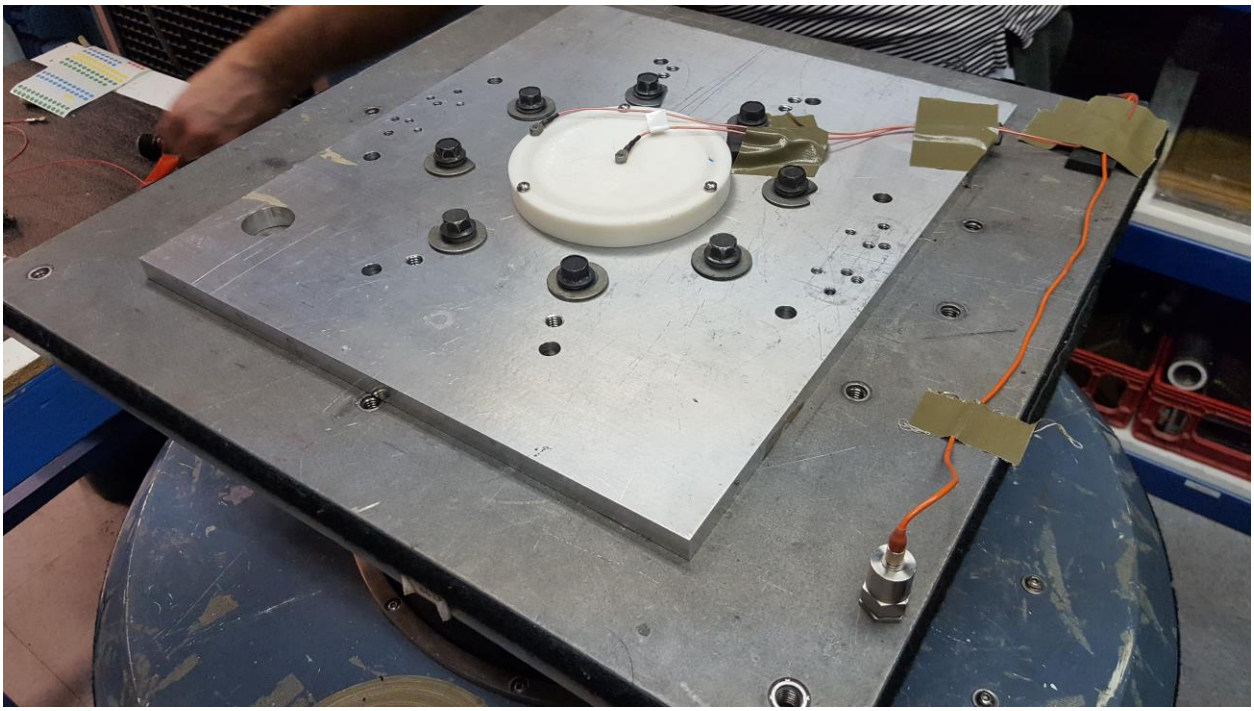


Figure 10. Mounting the accelerometers.

Appendix 5

Test Results

Acceptance Test Data Sheet 1

Referenced ATP Number: **1**

Analysis Referenced (for verification by T/A): **Materials Analysis (2)**

Name of Test: **Durometer Measurement**

Unit Under Test (UUT):
Name: **Dog Bone**
Part Number: **4**
Serial Number: **N/A (Printed)**

Results: **Pass**	Date of Test: **April 17, 2017**

Recording of Test Measurement:	Requirement:	Test Equipment Error:	Adjusted Test Limit:
Handheld Durometer Testers (Shore Hardness A and D)	**4. The printer shall be able to print between 85A-70D shore hardness**	**N/A**	**N/A**

Computations:

Hardness Percentage				
0%	30%	50%	70%	100%
Durometer				
84.2A	102A	64.0D	68.5D	73.5D

Signatures:

Tester _____

Customer _____

Acceptance Test Data Sheet 2

Referenced ATP Number: **2**

Analysis Referenced (for verification by T/A): **N/A**

Name of Test: **Vibration Reduction**

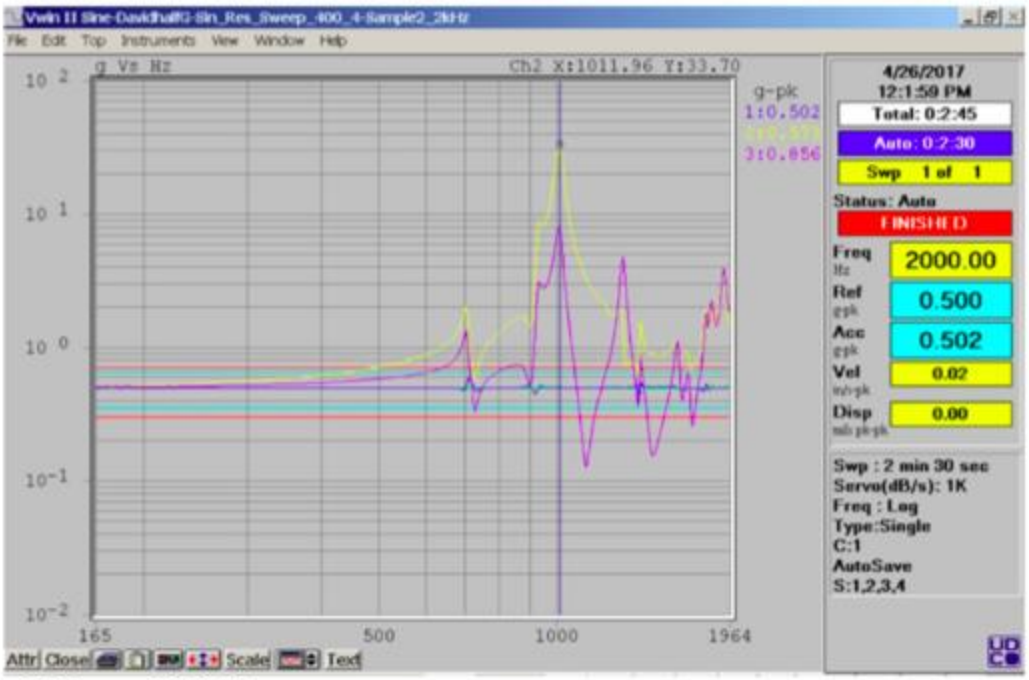
Unit Under Test (UUT):
Name: **Control Vibe Tester**
Part Number: **5**
Serial Number: **N/A (Printed)**

Results: **Pass**

Date of Test: **April 26, 2017**

Recording of Test Measurement:	Requirement:	Test Equipment Error:	Adjusted Test Limit:
Vibration Table with Accelerometers (Acceleration and Frequency)	**5. The products generated by the printer shall exemplify a reduction in vibration in a standard vibration test**	**N/A**	**0.5G at 2kHz**

Computations, (Include Analyses Results, if any):



Peak G-Force: 33.70 G's
Frequency at Peak G-Force: 1011.96Hz

Signatures:

Tester _____

Customer _____

Acceptance Test Data Sheet 3

Referenced ATP Number: **2**

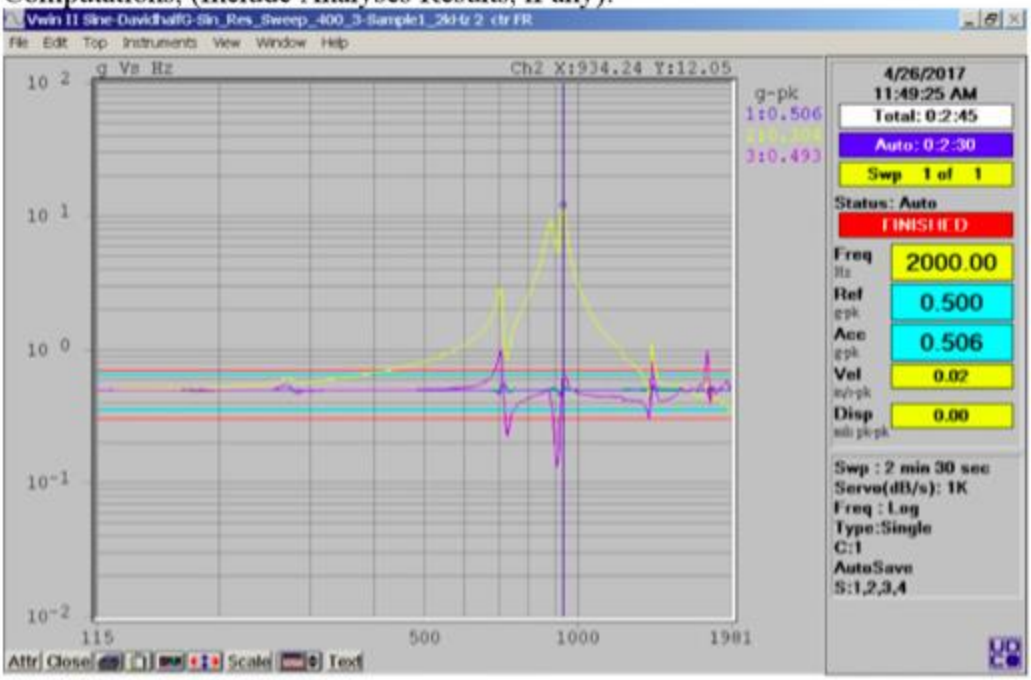
Analysis Referenced (for verification by T/A): **N/A**

Name of Test: **Vibration Reduction**

Unit Under Test (UUT):
Name: **Simple Ring Vibe Tester**
Part Number: **6**
Serial Number: **N/A (Printed)**

Results: **Pass**		Date of Test: **April 26, 2017**	
Recording of Test Measurement: **Vibration Table with Accelerometers (Acceleration and Frequency)**	Requirement: **5. The products generated by the printer shall exemplify a reduction in vibration in a standard vibration test**	Test Equipment Error: **N/A**	Adjusted Test Limit: **0.5G at 2kHz**

Computations, (Include Analyses Results, if any):



Peak G-Force: 12.05 G's
Frequency at Peak G-Force: 934.24Hz

Signatures:

Tester _____

Customer _____

Acceptance Test Data Sheet 4

Referenced ATP Number: **2**

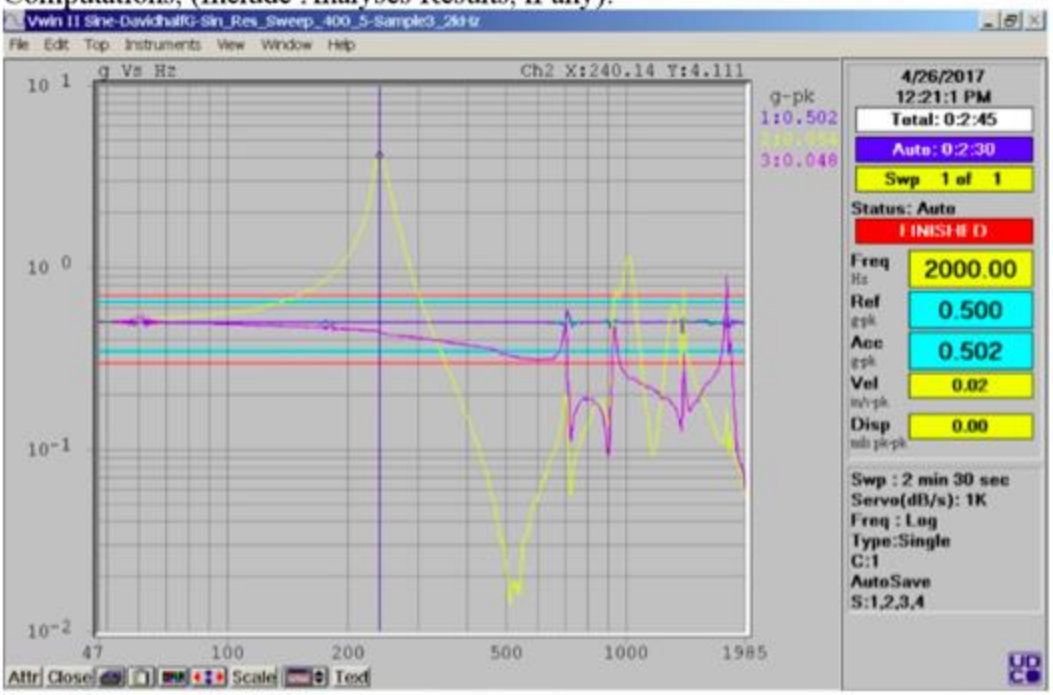
Analysis Referenced (for verification by T/A): **N/A**

Name of Test: **Vibration Reduction**

Unit Under Test (UUT):
Name: **Advanced Reduction Vibe Tester**
Part Number: **7**
Serial Number: **N/A (Printed)**

Results: **Pass**		Date of Test: **April 26, 2017**	
Recording of Test Measurement: **Vibration Table with Accelerometers (Acceleration and Frequency)**	Requirement: **5. The products generated by the printer shall exemplify a reduction in vibration in a standard vibration test**	Test Equipment Error: **N/A**	Adjusted Test Limit: **0.5G at 2kHz**

Computations, (Include Analyses Results, if any):



Peak G-Force: 4.111 G's
Frequency at Peak G-Force: 240.14Hz

Signatures:

Tester _____

Customer _____

Appendix 6

Component Specifications

1. Lulzbot TAZ5 Specifications

(https://download.lulzbot.com/TAZ/5.0_0.5noz/documentation/Manual/Manual.pdf)

Printing

Print Surface: Heated borosilicate glass bed covered with PEI print surface. Separate bed preparation is recommended when printing with flexible filaments, which can be found on the Flexystruder and FlexyDually Tool Head pages respectively.

Print Area: 290mm x 275mm x 250mm (11.4in x 10.8in x 9.8in)

Print Volume: 199375 cm3 (1206 in3) of usable space

Top Print Speed: 200mm/sec (7.9in/sec)

Layer Thickness with 0.35mm nozzle: 0.075mm to 0.35mm (0.003in - 0.0138in)

Layer Thickness with 0.5mm nozzle: 0.075mm to 0.5mm (0.003in - 0.0196in)

Capable Materials: ABS, PLA, HIPS, PVA, wood filled filaments, Polyester (Tritan), PETT, bronze and copper filled filaments, Polycarbonate, Nylon, PETG, conductive PLA and ABS, UV luminescent filaments, PCTPE, PC-ABS, Alloy 910, and more every day.

Discouraged Materials: 3D printing with carbon fiber filaments is not recommended at this time because carbon fiber filaments can degrade both the nozzle and hot end of the LulzBot TAZ 5 Tool Head.

Usable Filament Sizes: standard 3mm (0.1in)

Multi-Software Compatible: Freedom to use any number of 3D printing software programs, Cura LulzBot Edition ships standard! Other compatible Free Software options include OctoPrint, BotQueue, Slic3r, Printrun, MatterControl, and many more.

Warranty and Support

30 day money-back guarantee

One-year warranty

One-year customer support

Additional 1, 2, or 3 Year Extended Warranty Available!

Physical Dimensions

Overall Dimensions: 680mm x 520mm x 515mm (26.8in x 20.5in x 20.3in)

Weight: 11kg (24.25lbs)

Electrical

Power Requirements: 100 - 240 VAC

Power Output: 24 volt 500 watts 21 amp

Example Power Consumption: ABS

0.239kWh, 30 minute print

0.450 kWh, 60 minute print

Maximum Draw: 550 watts

Operating Temperature Range

Maximum Tool Head Temperature: 300°C (572°F)

Maximum Heated Bed Temperature: 120°C (248°F)

Your TAZ 3D printer package includes:

LulzBot TAZ 5 3D printer and 24V power supply

30 day money-back guarantee

One-year warranty and support

LulzBot Hexagon Hot End Tool Head with 0.50mm Nozzle

Quick Setup Guide

4GB SD Card

Filament Feed tube

Toolkit bag

15 Piece Metric Hex Key Set

Pliers, Needle Nose

Tweezers

Standard Precision Knife

Dental Pick

Flathead Bristle Brush

Part Removal Knife (clam knife)

Metric Ruler

Complete documentation including a detailed manual with information for setup, downloading and using software, and starting your first print. Also includes an in depth manual on using Slic3r software

Filament is not included, click here to select some to include with your order. We recommend nGen by colorFabb!

2. Lulzbot TAZ Dual Extruder Tool Head v2 Specifications

(https://download.lulzbot.com/TAZ/5.0_0.5noz/documentation/Manual/Manual.pdf)

Parts Included

LulzBot® TAZ Dual Extruder Tool Head v2 (Fully Assembled)

Wade's Accessible Extruder

LulzBot® TAZ Extruder Mount

Specifications

Required filament diameter: 3mm

Hot end temperature range: 120°C - 300°C

Nozzle diameters: 0.5mm

Required power system: 24v

Fans: Heat sink and nozzle fans included

3. Diamond Hotend Specifications

Main features:
1. 3 in 1 out diamond hotend support 3 filaments of different colors and different materials.
2. Creating printings with a wide range of colors and materials in a single object, in one print.
3. Easy to level nozzles make getting started in multi-extrusion easier than ever before.
4. Absolute minimum size and weight, will not weigh down your printer or reduce printing performance
5. All-metal, high performance J-head with efficient heat dissipation for fantastic printing.
6. All-metal accessories to withstand higher temperatures involved in printing process so that you can print with multiple kinds of filament that requires higher temperature such as ABS.

Tips: Different materials of filament has different melting point, when printing with two different kinds of material, please choose those with close melting point.

Specifications:
1. Number of filament: 3
2. Filament material: PLA, ABS
3. Heater cartridge: 40W, 12V (24V is available); size: 6*15mm
4. Heater cartridge wire length: 700mm
5. Thermistor: 100K NTC
6. Thermistor wire length: 1m
7. Working Temperature: 190°-230°
8. Cooling Fan: 40mm x 40mm x 10mm
9. Fan voltage: 12V
10. Filament size: 1.75mm
11. Nozzle size: 0.4mm
12. Net Weight: 175g
13. Shipping weight: 300g

4. Slic3r Specifications

(http://manual.slic3r.org/)

Compatible with your printer too.

RepRap (Prusa Mendel, MendelMax, Huxley, Tantillus...), Ultimaker, Makerbot, Lulzbot AO-100, TAZ, MakerGear M2, Rostock, Mach3, Bukobot and lots more. And even DLP printers.

Fast G-code generation is fast.

Don't wait hours for slicing that detailed model. Slic3r is about 100x faster than Skeinforge. It also uses multithreading for parallel computation.

Lots of input/output formats.

Slic3r reads STL, AMF and OBJ files while it can output G-code and SVG files.

Do you like the graphical interface or command line?

All the features of the user-friendly interface are also available from command line. This allows to integrate Slic3r in your custom toolchain and batch operations as you like.

Open source, open development.

Slic3r is open source software, licenced under the AGPLv3 license. The development is centered on GitHub and the #slic3r IRC channel on FreeNode, where the community is highly involved in testing and providing ideas and feedback.

Dependencies? Nah.

Slic3r is super-easy to run: download, double click and enjoy. No dependencies needed. Hassle-free. For MacOS X, Windows, Linux.

Print with ~~dual~~ multiple extruders.

Print beautiful colored objects, or use your secondary extruder to build support material. Or put a larger nozzle on it and print a faster infill.

Use brim for the best adhesion.

This unique feature improves built plate adhesion by generating a base flange around your objects that you can easily remove after printing.

Microlayering: save time, increase accuracy.

You can choose to print a thicker infill to benefit from low layer heights on perimeters and still keep your print time within a reasonable amount.

Compose a plate but print one object at time.

Use the built-in plating interface that allows to place objects with drag-and-drop, rotate and scale them, arrange everything as you like. The *sequential printing* feature allows to print one complete object at time in a single print job.

Cool cooling strategies.

A very smart cooling logic will regulate your fan speed and print speed to ensure each layer has enough time to cool down before next one is laid on it.

Manage multiple printers, filaments and build styles.

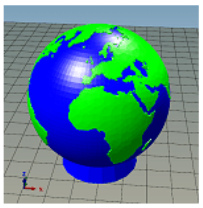
The configuration handling system was designed for people working with multiple machines and filaments: you can save configurations as presets for each category avoiding to multiply your saved configurations.

Enjoy support material.

Automatic generation of support material for overhangs.

5. Repetier Specifications

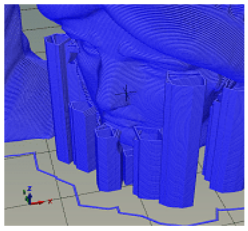
(https://www.repetier.com/documentation/repetier-host/)



Multi Extruder Support

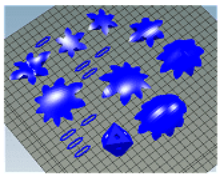
Repetier-Host can handle up to 16 extruders with different filament types and colors simultaneously and visualize the result with individual filament colors, so you can see your result before printing.

Multi Slicer Support



Repetier-Host includes directly **3 different slicers**: Slic3r, CuraEngine and Skeinforge
If that is not enough, you can use any other slicer you want with Repetier-Host.

After slicing you can see all extruder movements and support structures. You control the whole model, a particular area or individual layers and recognize potential problems before printing – this saves a lot of time and money.

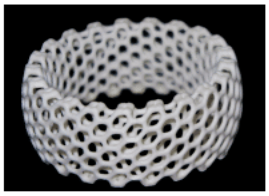


Easy Multi-Part Printing

You can load or duplicate as many models that fit on your build plate and print them simultaneously. The efficient use of the build plate saves a lot of time!

You can arrange them manually or just click the autoposition button and Repetier-Host does the rest.

Gain Full Control over your Printers



Repetier-Host is easy to use, even for beginners, but gives you full control of your printer, slicer and printing process if needed.

This is the reason why you can print any filament in perfect quality like PLA, ABS, PETG, chocolate or metal, if your printer hardware supports it. Biotech companies even print organs with Repetier-Host.

6. Possible Printing Filaments Specifications

3DXTECH Technology... Advanced.

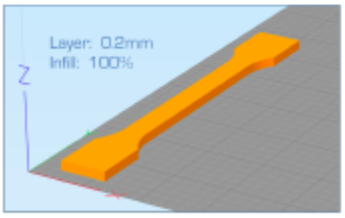
Technical Data Sheet
Rev 2.1

iOn™ NYLON Copolymer 3D Filament

iOn™ Nylon copolymer is an engineering grade 3D printing material that can be used in demanding industrial applications due to its high mechanical, thermal, and chemical performance. iOn™ Nylon has excellent resistance to many chemicals – including solvents, fuels, alcohols, and lubricants. Offering a low gloss matte finish, iOn™ is ideal for technical components that require real-world functional performance. iOn™ Nylon is suitable for use in practically all consumer-grade FDM/FFF printers that have a heated print bed. Made by 3DXTECH® in the USA.

The reported technical data was generated from printed ISO test specimen. The general print parameters utilized are noted below.

- Desktop FDM/FFF Printer
- Nozzle: 0.4mm A2 hardened
- Layer height: 0.2mm
- Infill: 100%, +/- 45°
- Extrusion temp: 260°C
- Bed temp: 110°C
- Bed prep: ABS/Acetone Gel
- Print speed: 50 mm/sec



Disclaimer: The technical data contained on this data sheet is furnished without charge or obligation and accepted at the recipient's sole risk. This data should not be used to establish specifications limits or used alone as the basis of design. The data provided is not intended to substitute any testing that may be required to determine fitness for any specific use.

General Property	Unit	Standard	Typical Value
Density	g/cc	ISO 1183	1.06
Mechanical Property	**Unit**	**Standard**	**Typical Value**
Tensile Strength	MPa	ISO 527	45
Tensile Modulus	MPa	ISO 527	2094
Tensile Elongation, Break	%	ISO 527	8.6
Flexural Modulus	MPa	ISO 178	2206
Flexural Strength	MPa	ISO 178	80
Thermal Property	**Unit**	**Standard**	**Typical Value**
Glass Transition Temperature (Tg)	°C	DSC	105
Heat Distortion Temperature (HDT) @ 0.45MPa	°C	ISO 75	96.8
Electrical Property	**Unit**	**Standard**	**Typical Value**
Surface Resistivity	Ohm/sq	IEC 60093	>10^11

Printing Recommendation	Typical Range
Extruder Temperature	250 – 270°C
Bed Temperature	100 - 110°C
Print Speed	50 - 70 mm/sec

3DXTECH Technology... Advanced.

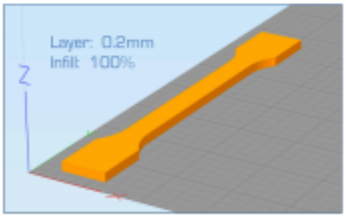
Technical Data Sheet
Rev 2.1

CarbonX™ Carbon Fiber Reinforced Nylon 3D Filament

CarbonX™ Carbon Fiber Reinforce Nylon is a high-performance carbon fiber reinforced 3D printing filament. This grade was formulated utilizing high-modulus carbon fiber and an advanced semi-aromatic polyamide copolymer – making it ideal for applications that require superior chemical resistance, thermal properties, mechanical properties, and dimensional stability compared to other FDM/FFF nylon materials. Suitable for use in practically all consumer-grade FDM/FFF printers that have a heated print bed. Made 3DXTECH® in the USA.

The reported technical data was generated from printed ISO test specimen. The general print parameters utilized are noted below.

- Desktop FDM/FFF Printer
- Nozzle: 0.4mm A2 hardened
- Layer height: 0.2mm
- Infill: 100%, +/- 45°
- Extrusion temp: 260°C
- Bed temp: 110°C
- Bed prep: ABS/Acetone Gel
- Print speed: 50 mm/sec



General Property	Unit	Standard	Typical Value
Density	g/cc	ISO 1183	1.14

Mechanical Property	Unit	Standard	Typical Value
Tensile Strength	MPa	ISO 527	63.9
Tensile Modulus	MPa	ISO 527	4387
Tensile Elongation, Break	%	ISO 527	4
Flexural Modulus	MPa	ISO 178	5650
Flexural Strength	MPa	ISO 178	78

Thermal Property	Unit	Standard	Typical Value
Glass Transition Temperature (Tg)	°C	DSC	105
Heat Distortion Temperature (HDT) @ 0.45MPa	°C	ISO 75	102

Electrical Property	Unit	Standard	Typical Value
Surface Resistivity	Ohm/sq	IEC 60093	>10[11]

Printing Recommendation	Typical Range
Extruder Temperature	240 - 270°C
Bed Temperature	100 - 110°C
Print Speed	50 - 70 mm/sec

3DXTECH Technology... Advanced.

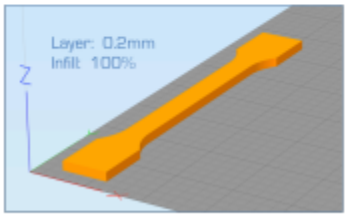
Technical Data Sheet
Rev 2.1

ECOMAX® PLA 3D Filament

ECOMAX® PLA (polylactic acid) is a premium 3D printing filament made using premium Natureworks bio-polymer derived from corn – not petroleum products. ECOMAX® PLA has a sweet smell while printing making it ideal for 3D printers located in public spaces, schools, and offices. PLA is a semi-crystalline resin that has high mechanical properties below it's Tg and is suitable for many general-purpose prototype and production parts. Suitable for use in practically all consumer-grade FDM/FFF printers. Made by 3DXTECH® in the USA.

The reported technical data was generated from printed ISO test specimen. The general print parameters utilized are noted below.

- Desktop FDM/FFF Printer
- Nozzle: 0.4mm A2 hardened
- Layer height: 0.2mm
- Infill: 100%, +/- 45°
- Extrusion temp: 210°C
- Bed temp: 60°C
- Bed prep: Hairspray on glass
- Print speed: 50 mm/sec



General Property	Unit	Standard	Typical Value
Density	g/cc	ISO 1183	1.24

Mechanical Property	Unit	Standard	Typical Value
Tensile Strength	MPa	ISO 527	56
Tensile Modulus	MPa	ISO 527	2865
Tensile Elongation, Break	%	ISO 527	8
Flexural Modulus	MPa	ISO 178	3185
Flexural Strength	MPa	ISO 178	115

Thermal Property	Unit	Standard	Typical Value
Glass Transition Temperature (Tg)	°C	DSC	60
Heat Distortion Temperature (HDT) @ 0.45MPa	°C	ISO 75	54.7

Electrical Property	Unit	Standard	Typical Value
Surface Resistivity	Ohm/sq	IEC 60093	>10[11]

Printing Recommendation	Typical Range
Extruder Temperature	190 - 220°C
Bed Temperature	23 - 60°C
Print Speed	50 - 80 mm/sec