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The Innovation Station: A 3D Printing Vending Machine for UT Austin Students

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The Innovation Station: A 3D Printing Vending Machine for UT Austin Students

by

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Thesis

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Dedication

To my beautiful wife and wonderful sons. They give my life meaning and their support has made this achievement possible.

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I would like to thank my advisor, Dr. Carolyn Seepersad, for all support on the Innovation Station project and for all of her help revising my thesis.

I would also like to thank Dr. Matthew Green who led the Innovation Station project for the half of its duration. He was instrumental in researching the most reliable way to create an automatic part removal systems, discovering customer needs, and learning how to program MakerBot g-code.

Sanjai Bashyam played a vital role in the circuit design and implementation that runs the external fan and motor for the part removal system. He also contributed considerably with the manufacturing and assembly of the vending machine.

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George Garcia, Jack Mohajer, and Jordon Wahl each contributed to advance this project. George helped with the aesthetic design and assembly of the enclosure, Jack helped with the retrieval bin design, and Jordon helped establish heating and cooling cycles as a viable part removal option through testing.

Nathan Selman helped set up the Innovation Station in the lobby of the Mechanical Engineering building.

Finally, I would like to thank Harvest/Stratasys for their generous donation of $10,000 to help fund TAs to run the Innovation Station for the first year of its implementation.

Abstract

The Innovation Station: A 3D Printing Vending Machine for UT Austin Students

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The University of Texas at Austin, 2015

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The Innovation Station is designed to provide on-demand, web-enabled 3D printing securely in a public space. The overarching goal is to lower the barriers to 3D printing at a university, to facilitate innovation and creativity, and to inspire future engineers. Both hardware and software innovations were required to realize this capability. From the hardware side, the design team invented a process to automatically remove parts from the 3D printer and sweep them into a bin from which users can retrieve them without directly accessing the 3D printer. From the software side, in partnership with the Faculty Innovation Center (FIC) at UT Austin, the design team created a web portal that allows students to upload parts remotely and access detailed directions for creating parts. It also allows administrators to remotely manage the queue and initiate builds. Together, the hardware and the software innovations enable printing multiple jobs continuously without user intervention and remote cancellation of jobs. Plans for the entire station, both

hardware and software, are intended to be open source, with a startup cost of less than $4,000, plus the cost of the printers, for recreating the station at a new location.

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Chapter 1: Introduction

1.1 Motivation

Additive Manufacturing is an emerging method of making parts that opens many doors to designers. "Additive Manufacturing (AM) is an automated technique for direct conversion of 3D CAD data into physical objects using a variety of approaches [1]." Most manufacturing processes are subtractive in nature; starting with a large block of material, the part is formed by removing material from the original block of material. Additive manufacturing builds parts layer by layer, which drastically reduces material waste and facilitates part complexity.

Some additive manufacturing processes include Stereolithography (SLA), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), and Fused Deposition Modeling (FDM). Stereolithography uses a vat of liquid photosensitive resin that is hardened selectively by ultraviolet light, forming objects layer by layer. This technology was invented by Charles W. Hull in 1984 [2]. Selective Laser Sintering creates parts out of powder. In a SLS machine powder is selectively fused by a laser in thin layers until parts are fully formed. This technology was created at the University of Texas in Austin by Carl Deckard and Joe Beaman in the mid 1980s [3]. DMLS is a similar technology that uses metal powder instead of plastic powder. Direct Metal Laser Sintering is often used for complex, functional parts [4]. In FDM printing, plastic in wire form is loaded into a heated extrusion nozzle, which deposits the molten plastic onto a build surface. This nozzle is mounted on a printer head that moves in the X/Y plane to create shapes. After a layer is built, the build plate is lowered incrementally in the Z axis until the part is completed [5].

Manufacturers have been using these technologies to reduce development cycle times and get their products to market quicker, more cost effectively, and with added value due to the incorporation of customizable features [1]. Other advantages of AM include the ability to process multiple materials or functionally graded materials, in some cases, and the ability to fabricate complex parts without significantly increasing cost [3]. For industries like the aerospace industry that depend on lightweight parts produced in small volumes, the cost savings of using additive manufacturing are especially lucrative.

Although this technology has existed for decades, the cost of Additive Manufacturing has prohibited widespread public use until recently. For example, a stereolithography machine costs between $180,000 and $800,000 while a SLS machine costs between $29,000 and $320,000 [6]. In the past five years, there has been an explosion of low-cost, personal 3D printers, such as the Replicator Series from MakerBot, which build parts with inexpensive, off-the-shelf materials, low-cost hardware, and open-source software. An example of a 3D printer that uses FDM technology can be seen in Figure 1. With the introduction of these inexpensive, personal versions, 3D printers are rapidly making their way into engineering curricula. Several universities now offer courses in which undergraduate engineering students build their own 3D printers [7].

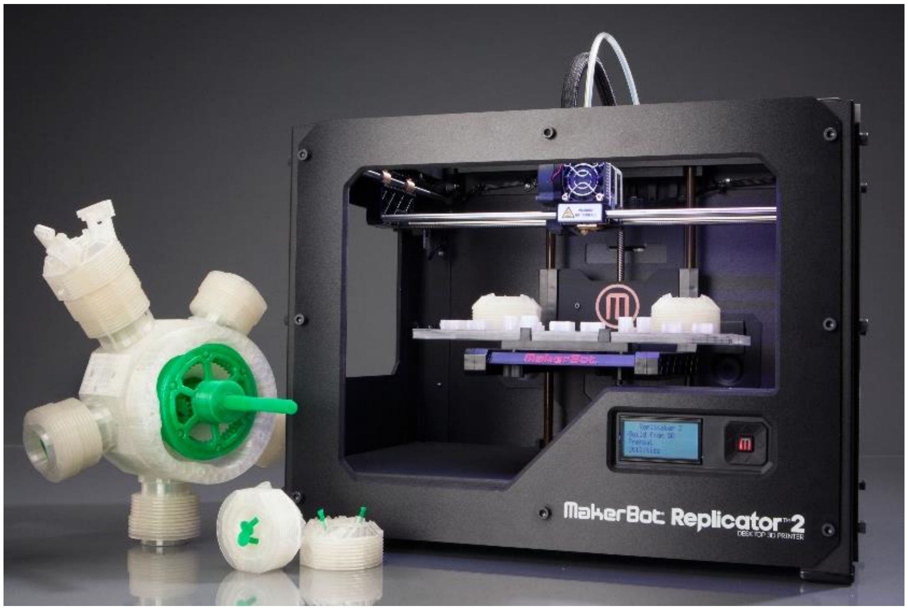


Figure 1: MakerBot Replicator 2 3D Printer used as the heart of the Innovation Station [8]

Even with the recent popularity of 3D printing and the expansion into new markets, most students do not have access to these machines. Even though 3D printers are now located in many universities, special access to a lab is often required to use them.

The goal of the Innovation Station, a 3D Printing Vending Machine, is to allow students at The University of Texas at Austin to fabricate almost any part they can imagine, automatically, in a public university space. Anyone with a UT ID can create 3D models of their parts using standard CAD (computer-aided design) software, upload the virtual models into the Innovation Station's online portal, and then watch as the 3D printers build the parts behind clear acrylic windows and drop them into an open retrieval bin—much like a soda is dispensed from a traditional vending machine. Placing the machine in a public space lowers the barriers to accessing 3D printers so that students can use them in the design process for classes or for personal use. Also, the public nature of the printing process is likely to inspire students to actively create and provides opportunities for future engineers to get excited about the engineering process. In addition, it allows students to become more deeply engaged in the process of designing parts for manufacturing and to become more entrepreneurial.

1.2 PREVIOUS 3D PRINTING VENDING MACHINES

The concept of a 3D printing vending machine originated with Professor Christopher Williams and his students at Virginia Tech, who created a machine called the DreamVendor that prints 3D models for students [9]. This idea of placing 3D printers in a public space has given many students the opportunity to create parts who never would have

Figure 2: The DreamVendor created by Christopher Williams and his students at Virginia Tech as a way for students to have access to 3D printers [10]

had that opportunity. The DreamVendor includes four Thingomatic 3D printers from MakerBot as can be seen in Figure 2. Students upload their files by inserting SD cards into the machine and retrieve their parts from slots in the front of the machine. Along with the vending machine, they have created online design tips to help students who do not have experience designing parts for 3D printing. Dr. Williams and his students have recently launched a second version of the DreamVendor, which includes a built-from-scratch 3D printer and a novel part removal system. By creating their own printer Virginia Tech's design team was able to significantly increase their build volume, incorporate the part removal system into the printer design, and decrease their reliance on industry printers that are constantly upgrading, leaving older versions without support, as with MakerBot's Thingomatics.

Students at UC Berkley also launched a 3D printing vending machine in May 2013. Their machine, called the Dreambox, prints preloaded parts that vary in cost from $3-15 and also offers the option of building parts submitted by students [11]. Parts are removed by a mechanical arm and pushed into one of four retrieval bins that require a passcode to unlock.

While these vending machines have decreased the barriers of access to 3D printers and are all completely automatic, they still leave opportunities for improvement. The Virginia Tech machines require the user to personally approach the machine to upload their files and start printing, which can create long lines to get access to the printers. None of these options have a way to restrict the printing of dangerous or inappropriate parts. The conveyor belt part removal system of the Thingomatic tended to cause parts to warp significantly while the mechanical arm of the Dreambox uses a brute force method which could break delicate parts. These design opportunities motivated the design team at The University of Texas at Austin to create a new 3D printing vending machine entitled the Innovation Station.

1.3 OPPORTUNITIES FOR INNOVATION

The Innovation Station at UT Austin is unique in a number of ways. First, UT students upload their parts via an online portal that streamlines the user experience, allowing users to place their parts in a queue (and administrators to manage the queue) and to share files, tips, and inspiration with one another. In contrast, users of other vending machines must physically queue and upload their parts at the machine itself, sometimes waiting hours in the hallways for the machine to become available. Second, the Innovation Station utilizes a customized process for automatically and reliably removing parts from the build platform. Finally, the Innovation Station is constructed with commercially available parts, with construction and assembly plans to be made available to other educators online, so that other schools can replicate the machine.

1.4 OVERVIEW OF INNOVATION STATION

As shown in Figure 3, the Innovation Station is built around two personal 3D printers, MakerBot Replicator 2s, which serve as the heart of the station. While personal 3D printers typically build parts on platforms, which serve to anchor the parts as they are being built, the Innovation Station replaces the standard platform with an automatic part removal system which detaches the parts from the build plate, using thermal cycling, and sweeps them into a retrieval bin. The entire machine is housed within an enclosure that secures the printers and the associated hardware, while simultaneously allowing users to retrieve their parts, so that the Innovation Station can be located in a public space. Also, while most personal 3D printers accept input files from SD cards, USB drives, or the hard drive of a connected PC, the Innovation Station includes an online portal through which students upload their files and queue them for printing. The online portal (created in collaboration with the Faculty Innovation Center in the Cockrell School of Engineering at UT Austin) provides a vast array of educational materials related to 3D printing, such as a designer's guide with tips for preparing parts for 3D printing (dimensioning, tolerancing, examples of features that can or cannot be built), educational tutorials on 3D printing technologies, and links to relevant research in the field. A monitor next to the Innovation Station informs students where they can upload their parts for printing and download free CAD files for printing, and shows example parts that have been printed in the vending machine.

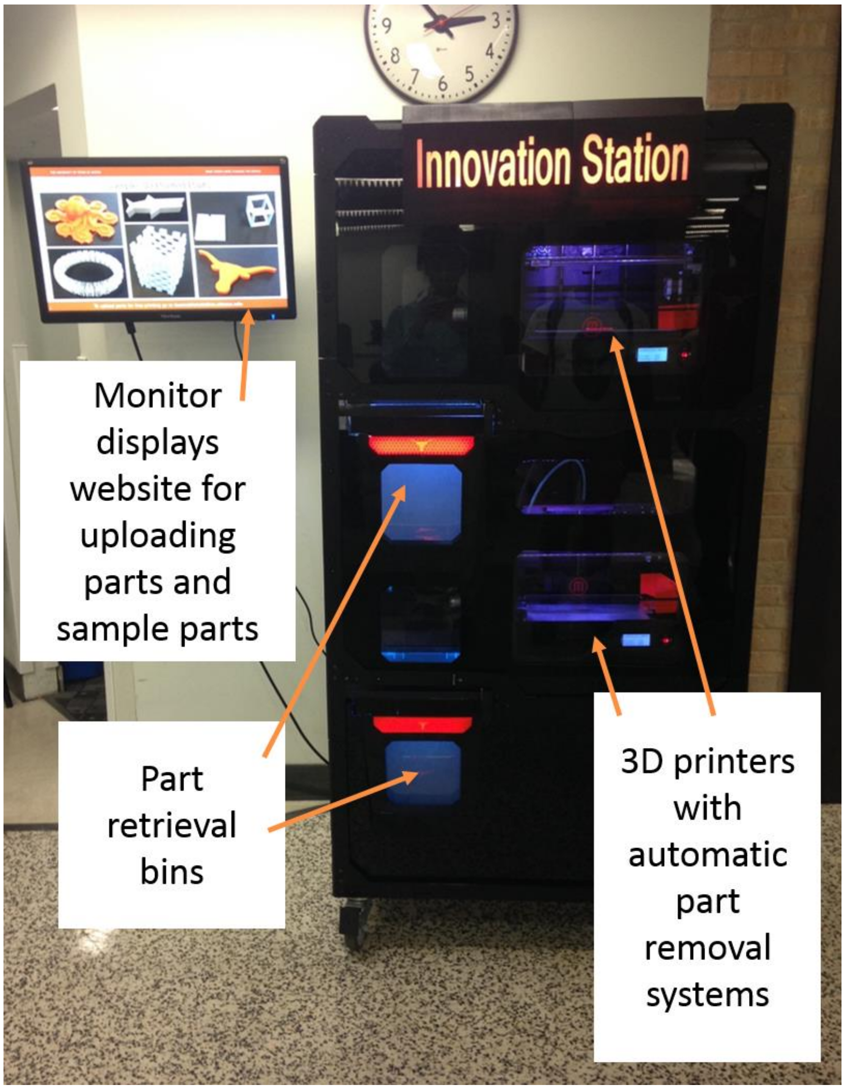


Figure 3: The Innovation Station

1.5 OVERVIEW OF THESIS

This thesis describes the design and development of the Innovation Station. The following chapters outline each of the components of the vending machine. Chapter 2 discusses the part detachment system that is used to completely detach parts after they are printed on the build plate. Chapter 3 describes the automatic part removal system unique to the Innovation Station, and focuses specifically on how parts are removed from the 3D printers into the part retrieval bins. Chapter 4 documents the design of the part retrieval bin and how it is integrated into the vending machine system. The functionality and aesthetics of the vending machine and the measures taken to maintain security of the Innovation Station are discussed in detail in Chapter 4, as well. Chapter 5 describes the online resources for the Innovation Station including the online portal for submitting parts, managing the queue, and providing designer guides to help users with little or no experience designing parts for 3D printing. Chapter 6 summarizes the innovations embodied in the vending machine, as well as the possibilities for future work.

Chapter 2: Part Detachment

To house 3D printers in a vending machine, they must be fully automated so that no human interaction is required between print jobs. There are currently no FDM 3D printers on the market that automatically remove parts from the build plate after printing. To make this project a reality, the primary challenge was reliably removing all parts from the build platform so that the entire build process could be automated. Over the course of this project an automatic part removal system was created that is now patent-pending. This chapter discusses the part detachment phase of the automatic part removal system, while the following chapter details how the parts are swept into a retrieval bin so that users can remove their parts without accessing the 3D printers directly.

2.1 DESIGN PROCESS

The design process for the automatic part removal system began with customer needs analysis to determine the required performance characteristics for the system. Hours of research on maker forums yielded many useful insights. In addition, interviews were performed with graduate students who are familiar with additive manufacturing and undergraduate students who serve as the primary intended users of the machine. The interviews showed that students were uncertain of what they wanted in a 3D printing vending machine because they have never had the opportunity to use one. A condensed version of the performance characteristics and their associated design specifications is shown in Table 1. The full analysis of customer needs is documented in Appendix A.

Table 1: Required Performance Characteristics for Automatic Part Removal System

Required Performance Characteristic	Design Specification
Reliably remove all parts from 3D printer	Fault intervention < 1/week for each printer
Adequately support parts during print	No slipping of parts while printing
Reduce part sticking after print	Safety factor of 3 on all part removal forces
Move finished part to user	Completely transport part out of printer
Keep the design as simple as possible	Limit number and complexity of parts used
Reduce cost of removal system	< $4,000 for all parts excluding printers
Reduce amount of maintenance needed	< 30 min/day
Reduce part removal time	< 15 minutes

The most important requirement is that of reliability. Since the vending machine is in a public place, mechanical failures of any kind would be obvious. More significantly, any mechanical failures related to part removal could cause significant damage to the 3D printer. If parts are not removed from the build plate before the next part starts printing, the machine will jam, which could break it indefinitely. Three other performance characteristics are closely related to the reliability of the part removal system. First, parts must be adequately adhered to the build surface throughout the course of a print job. If not, the parts will slip on the build plate causing a shift in the print job, which in most cases ruins the part being printed. If multiple parts are printed at the same time, one part slipping into other parts that are adhered more securely could cause the other parts to fail as well. Second, after a part is printed, it must be detached from the build surface using some method. Any detachment method must be designed with a high safety factor for a robust design, so a safety factor of three was chosen. For example, once the method of part removal was chosen to be thermal cycling, an additional performance characteristic was defined as limiting the maximum part removal force to two pounds. This performance characteristic, combined with a safety factor of three, means that the final overall system must be able to exert at least six pounds of pushing force. Finally, parts must be completely removed from the 3D printer after printing so that they do not interfere with subsequent print jobs.

The decision to use MakerBot printers was made because, at the start of the project, they were known as some of the most reliable personal printers on the market with some of the best customer support. Also, to increase reliability, the decision to use polylactic acid (PLA) plastic instead of acrylonitrile butadiene styrene (ABS) plastic as the material used in the Innovation Station was quickly made. Although ABS plastic has superior material properties to PLA, it is also more sensitive to printer settings and the environment, thereby decreasing its printing reliability. Using PLA plastic results in a more robust design. Because MakerBot's Replicator 2 printer is optimized for PLA printing it was the natural MakerBot printer to use.

Another way to increase the reliability of the vending machine is to simplify it as much as possible. In addition, the design of the Innovation Station is intended to be open source so that other universities and even high schools can create their own vending machines. To facilitate this goal, a simple yet functional design is needed. For the same reason, the entire vending machine system should be as inexpensive as possible so that more schools could take advantage of the design. Simple designs also tend to be less expensive.

By increasing the reliability of the part removal system, the entire vending machine should require less maintenance. To increase the productivity of the machine and reduce the costs of maintaining it, the required daily maintenance should consume no more than 30 minutes at the beginning of each day by an administrator. This maintenance includes changing the plastic filament, leveling the build plate, and any additional repairs such as unclogging the 3D printers.

To maximize the throughput of the machine, the length of time for part removal per print job should be 15 minutes or less. The lengthy 15 minute time frame reflects the design team's preference for removing all parts without breaking them rather than removing them quickly but more destructively.

With these guidelines in place, extensive brainstorming and review of the online 3D printing community was performed to find as many possible solutions to part removal as possible. In addition, a 6-3-5 concept generation session was performed with graduate students, and interviews were conducted with professors in the additive manufacturing field to expand upon the group of ideas. Some of the leading ideas included:

- Temperature cycling of build plate
- Vibrating the build plate
- Removing parts via a conveyor belt
- Using sacrificial build surfaces
- Changing build plate material/surface
- Applying forces/impact loads
- Mechanically removing parts via rods from underneath
- Rotating rods out of channels in build plate
- Scraping parts off of the build plate
- Warping build surface temporarily
- Modifying printer parameters (nozzle temperature)
- Printing all parts on custom raft profiles
- Printing all parts on water soluble support material

The following section describes the concepts that the design team explored in depth with physical prototypes to investigate feasibility.

2.2 CANDIDATE DESIGNS & FEASIBILITY TESTS

Not all concepts could be thoroughly investigated due to lack of time. The concepts chosen to be explored more in depth are listed below. They were chosen because they were easy to test or were deemed to have the most potential.

- Changing build plate material
- Warp build surface temporarily
- Printing all parts on customized rafts
- Mechanically removing parts via rods from underneath
- Applying impact loads
- Rotating rods out of channels in build plate
- Printing cold, heating surface to remove
- Printing warm, cooling surface to remove

Different build surfaces were investigated to determine which material decreased part removal force the most. The Replicator 2 printer comes with an acrylic build platform. Many 3D printer users recommend covering acrylic build plates with blue painters tape to make parts easier to remove. Tests were performed with both surfaces as shown in Figure 4, and these assumptions were proven to be correct. Test prints were printed directly on cold aluminum as well as anodized aluminum, but the PLA plastic adhered to neither surface. Heated aluminum tests were successful and the addition of blue painters tape to the aluminum again reduced the removal force. Glass was also tested. Parts printed well on heated glass, but would not stick to cold glass. Many 3D printer users prefer glass to aluminum, which is another common heated build plate material, because glass remains a true, level surface that does not warp over time. Glass also gives the bottom of parts a highly smooth surface finish.

Figure 4: Acrylic build plate with test parts printed with and without blue painters tape

Initial 3D printing vending machines at Virginia Tech used a rotating conveyor belt build plate. These Thingomatic printers were designed so that the build plate moved in the X/Y plane while the printer head moved vertically in the Z direction. The Replicator 2 printers are designed so that the printer head moves in the X/Y plane while the build plate moves vertically in the Z direction. Installing a conveyor belt into a Replicator 2 would require adding a conveyor belt and all of its components to a raising and lowering platform, or redesigning the existing printer, both of which were deemed impractical. Also, the conveyor belt is no longer commercially available, and it caused parts to warp significantly. For these reasons, this part removal option was not explored further.

Although a conveyor belt system was not used, it did lead to another idea to be tested. When parts were removed from the conveyor belt, they rotated around the axis of the conveyor belt which helped them to detach. This led to the idea of warping the build surface in order to remove parts. Two 5 x 5 mm test squares were printed on a thin painted aluminum sheet that was covered with blue painters tape. The sheet was bent until one of its edges touched the other (past a U shape) and the small test prints still did not fully detach from the build surface. This amount of deflection without full detachment made this an infeasible detachment method.

Another concept was to build all parts on rafts, which would give administrators more control over the interface between parts and the build plate, ideally making it easier for parts to be removed reliably. Rafts are thin layers of plastic that are printed between parts and the build plate in order to reduce part warping. Many tests were performed by

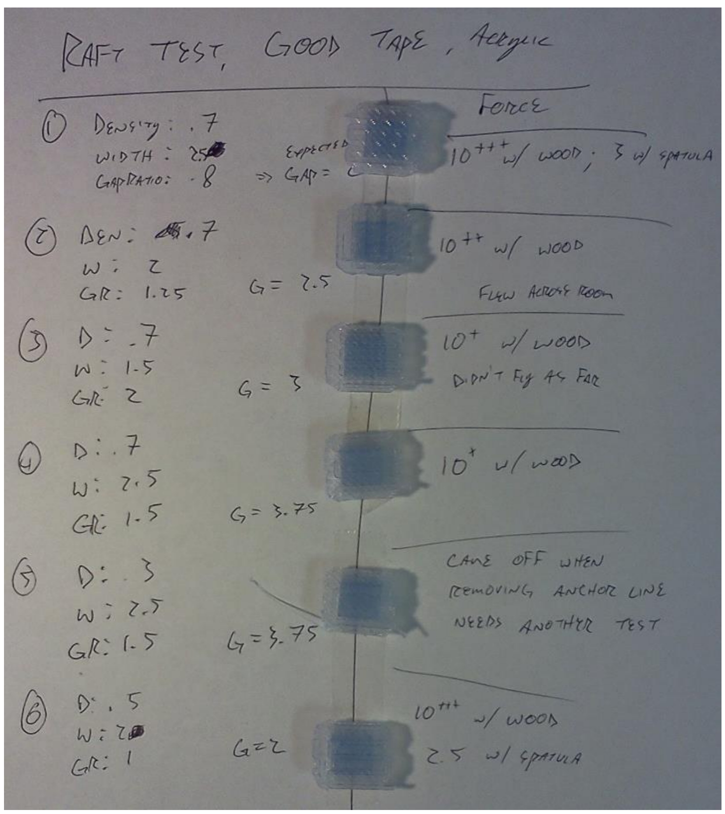


Figure 5: Raft tests with varied parameters and their effects on part removal

modifying the g-code parameters of rafts as can be seen in Figure 5, but from these initial tests the design team could not determine the effects of parameter changes. Because of how difficult it was to understand the behavior of raft parameters and because other methods of part removal appeared more promising, this idea was discarded. After the effects of parameter changes were understood, this idea still was not used for all parts because of the difficulty of removing rafts from printed parts which sometimes leads to part damage.

Another set of tests was performed by printing parts completely and partially over holes in an aluminum plate. The aluminum plate was heated so that the parts would print and then cooled for at least twenty minutes prior to part removal. Pins were pushed up through the holes by a scale to measure the removal force. As seen in Figure 6, the bottom right part that was completely over the hole did not detach with 5.5 pounds removal force. Further tests showed that the squares that were pushed up from the edge, required less removal force than the parts with the pins directly in the center. Even so, the forces

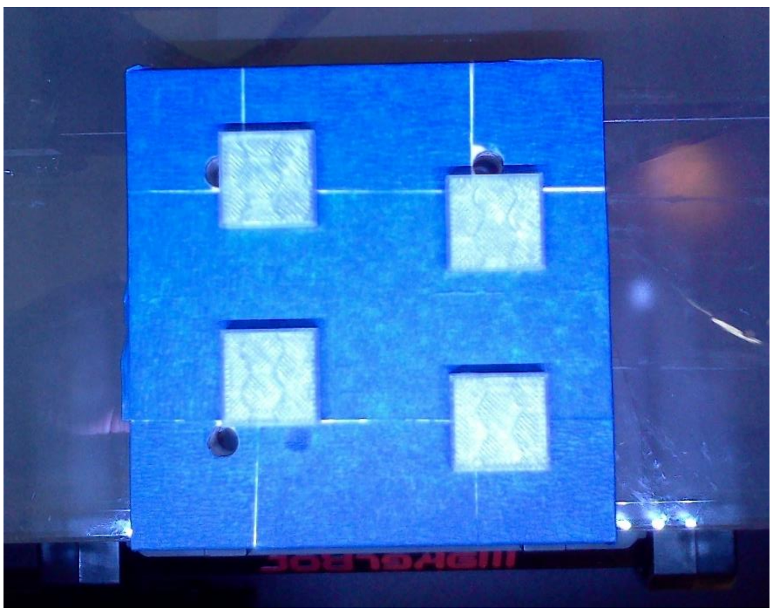


Figure 6: 20 x 20 mm squares printed on heated aluminum plate with holes in it

required to remove parts this way were deemed too high because the force scales directly with the surface area of the parts touching the build surface.

Another set of tests examined the possibility of using blunt force impact to force pins through holes in the build plate as a means of removing parts. As can be seen in Figure 7, a wrench was dropped from 0.5”-1” onto a pin that was directly in contact with a printed square. This impact popped the square off completely. The bond holding the plastic square to the build surface could not absorb the energy from the rapid impact. Although this technique was promising, incorporating impact forces to remove parts was ultimately too complex because it required a custom build plate that would allow pins to penetrate from below. The mechanism for applying the impact loads presented additional complexity. In

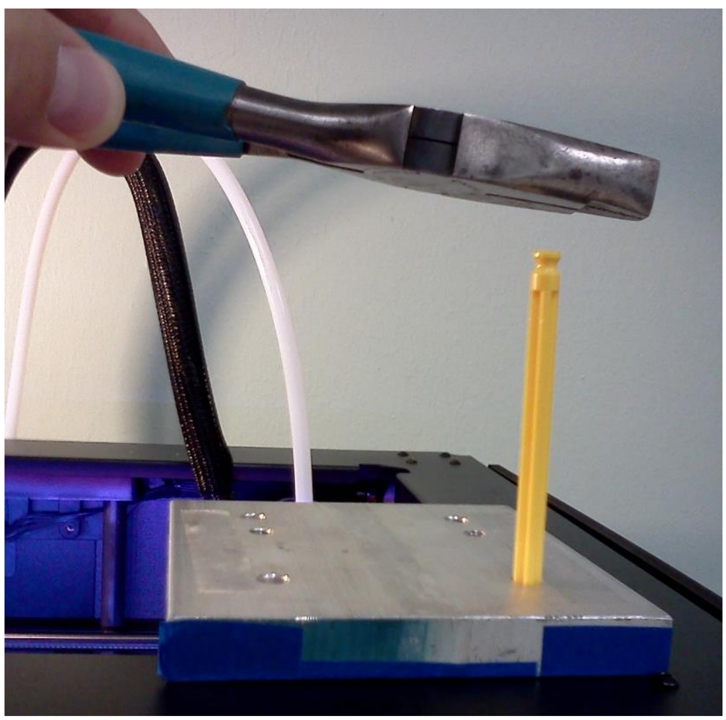


Figure 7: Impact testing using the weight of a wrench to apply the impact load

addition, constant impact forces on the build plate could easily disrupt the leveling of the build plate requiring frequent adjustment.

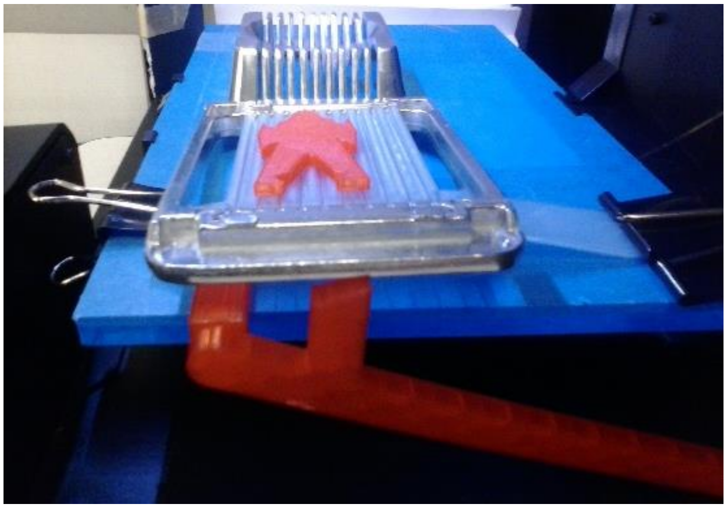


Figure 8: Mechanical part removal system that uses a lever to lift an egg slicer, and thus a part, that rests in the grooves of a 3D printed build platform

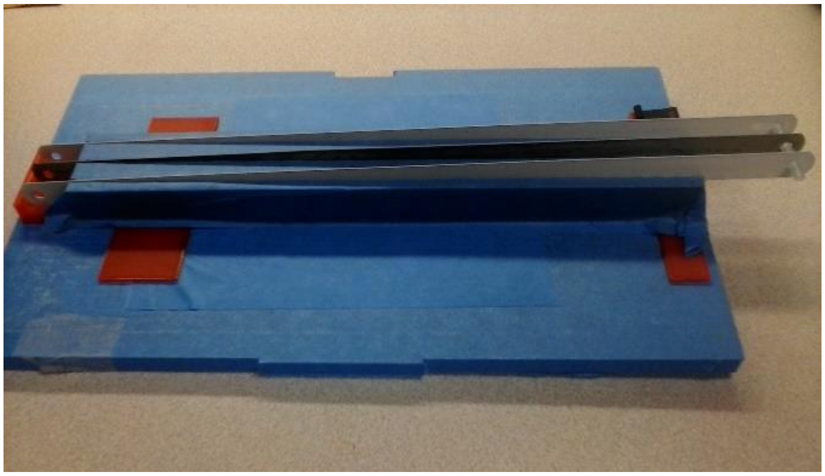


Figure 9: Mechanical part removal system that uses hacksaw blades to lift parts printed on the 3D printed build plate that is covered in blue tape to decrease adhesion

One of the most promising methods of part detachment is illustrated in Figures 8 & 9. It uses rods emerging from channels in the build plate to detach parts. When the build plate lowers, a lever attached to the build plate cause thin wires or hacksaw blades to lift out of slots and pry parts from the build platform. This idea came from the observation that parts are easier to detach when pried from the side. This design takes advantage of the mechanical advantage of the two levers, but because of the difficulty of manufacturing a build plate with slots and the need of blue painters tape to reduce adhesion this design was not selected as the final method for part detachment.

2.3 Heated build plate testing

Two different temperature cycling techniques were explored: (1) printing cold and then heating the build plate to remove parts and (2) printing on a hot build plate and cooling the build surface to remove parts.

2.3.1 Toaster Tests

First, parts were printed on an aluminum plate with blue painters tape on it and then the aluminum plate was placed on a toaster to heat it up as can be seen in Figure 10. This idea was not pursued further because heating the aluminum plate enough for part removal caused the test parts to deform significantly.

Figure 10: Toaster heating up aluminum build plate

This same aluminum plate was heated on the toaster with a glass plate taped to the top. After the plate was heated, it was transferred into the 3D printer and square test parts were printed on it and then left to cool. Once cooled, the square parts slid off the glass without any removal force. Because of the success of this test and the simplicity of the method, this part removal technique was deemed the most promising and worth pursuing further.

2.3.2 Heated Build Plate Prototype

Early part removal experiments proved the feasibility of thermal cycling as a part detachment method, but more tests were needed to perfect the method. For more reliable tests, a consistently heated build plate was needed. The prototype heated build plate is shown in Figure 11. The heated build plate was constructed from resistive heating wire taped with kapton tape to an aluminum plate. The build surface consisted of borosilicate glass, used for high temperature applications and a good surface finish. Underneath the heating wire a thin layer of fiberglass and felt pads were used as insulators and an additional plate of aluminum was used to add weight to decrease the horizontal movement of the heated build plate during print jobs. All the layers were held together using binder clips. The heating wire was powered by an adjustable power supply. The design team set the voltage of the power supply and measured the temperature of the glass during printing and after cooling.

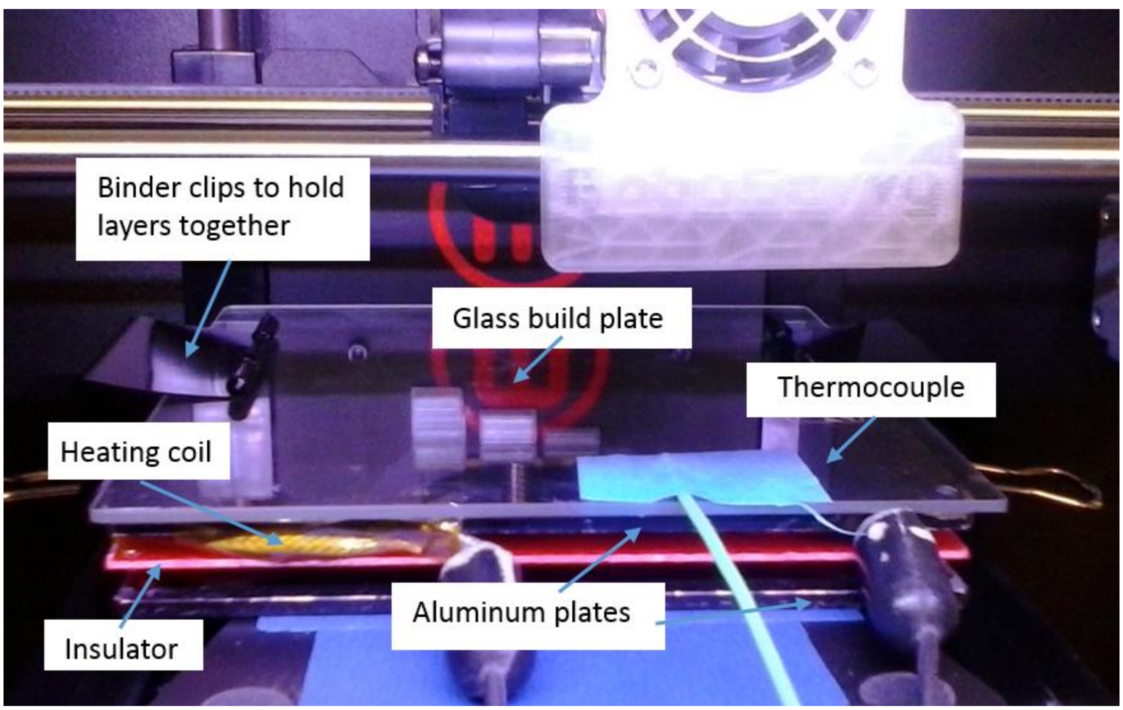


Figure 11: Prototype heated build plate

As shown in Figure 12, squares with a length of 15 mm and cylinders with a diameter of 36 mm were selected as test parts to determine the relationship between part removal force and build plate temperature. These parts were selected because they print rapidly and because the concentric rings in the cylindrical part make it very difficult to stick to the build plate during printing.

Figure 12: 15 mm square and 36 mm cylinder test parts

This functional prototyped yielded the data in Figure 13. From this data, it is apparent that the lower the temperature when the part is removed the lower the removal force. Also, these experiments verified earlier observations that the larger the surface area of a part touching the build plate, the higher the average removal force. These experiments

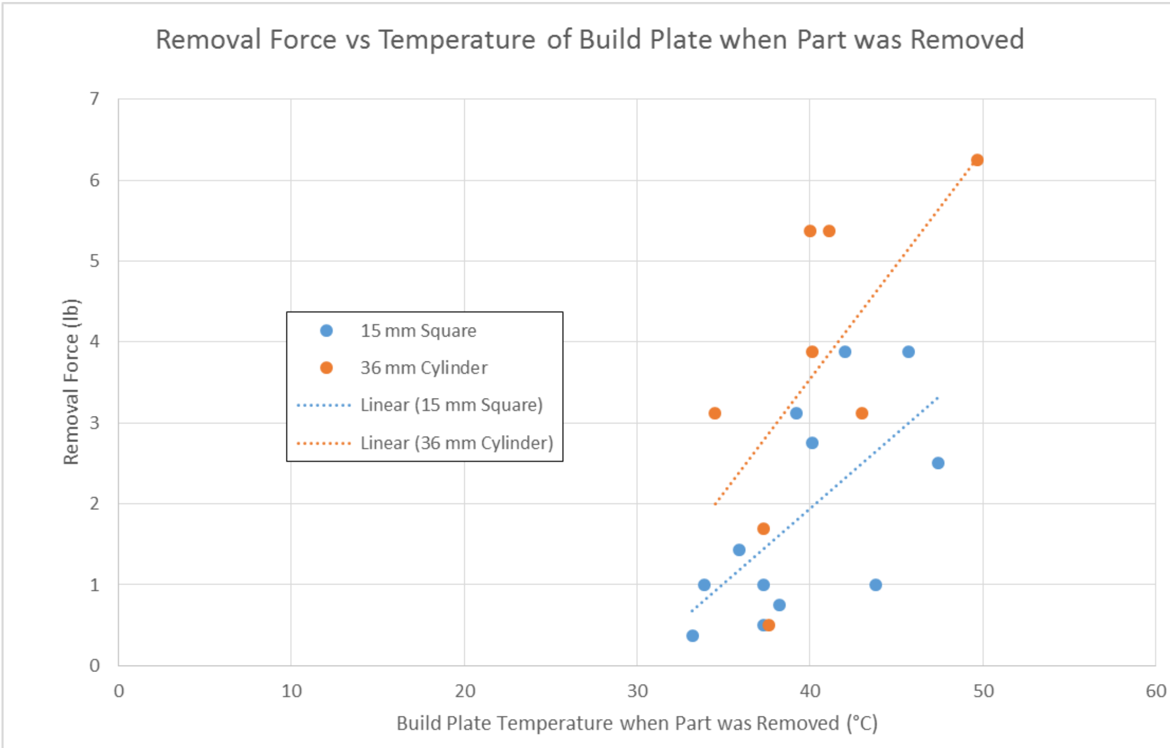


Figure 13: Graph charting how the change in build plate temperature when a part is removed affects part removal force

yielded significantly lower removal forces than any previous part removal method. This increased our confidence that thermal cycling was a viable technique for part removal, but additional experiments were needed to fine tune the process.

2.4 Final Design

Initial tests with a heated build plate to initiate heating and cooling cycles were very encouraging. Not only did the heated build plate significantly reduce the removal force relative to standard acrylic build plates, but it also promised much higher levels of reliability because it is much simpler than the mechanical part removal systems.

2.4.1 Description of Final Heated Build Plate

Additional design requirements were compiled to assure that the heated build plate would work well in the overall system. Table 2 shows these design specifications.

Table 2: Heated Build Plate Performance Characteristics

Required Performance Characteristic	**Design Specification**
Large build plate	> 11.2" x 6"
Uniform temperature for entire build plate	+/- 3°C
Robust performance in different ambient temperatures	Functions reliably from 25-40°C
Durable	Can handle thousands of cycles
Allows for leveling of build plate	Uses existing Rep2 leveling system
Limits reduction of build volume	Height reduction < 1"
Reduce maximum part removal force	Removal force < 2 pounds

A commercially available heated build plate, which is designed for MakerBot printers, was chosen as the heated build plate for the Innovation Station's 3D printers. The build surface of the heated build plate is 1/8" thick glass which is heated from below by a 130 W heater attached to an aluminum plate. The build plate is heated during the build process because PLA parts adhere to a glass build surface only when it is heated. The build plate is 11.125" x 6", slightly smaller than the standard Replicator 2 acrylic plate that measures 11.2" x 6". Because it was designed for MakerBot printers it uses the same leveling system as normal Replicator 2s and is powered directly from the MakerBot's

MightyBoard (microprocessor). A picture of this unmodified heated build plate can be seen in Figure 14. After the build is complete, the glass build surface is raised above the aluminum heating element by 7/8” to increase cooling. This decreases the maximum build height by 7/8” as well.

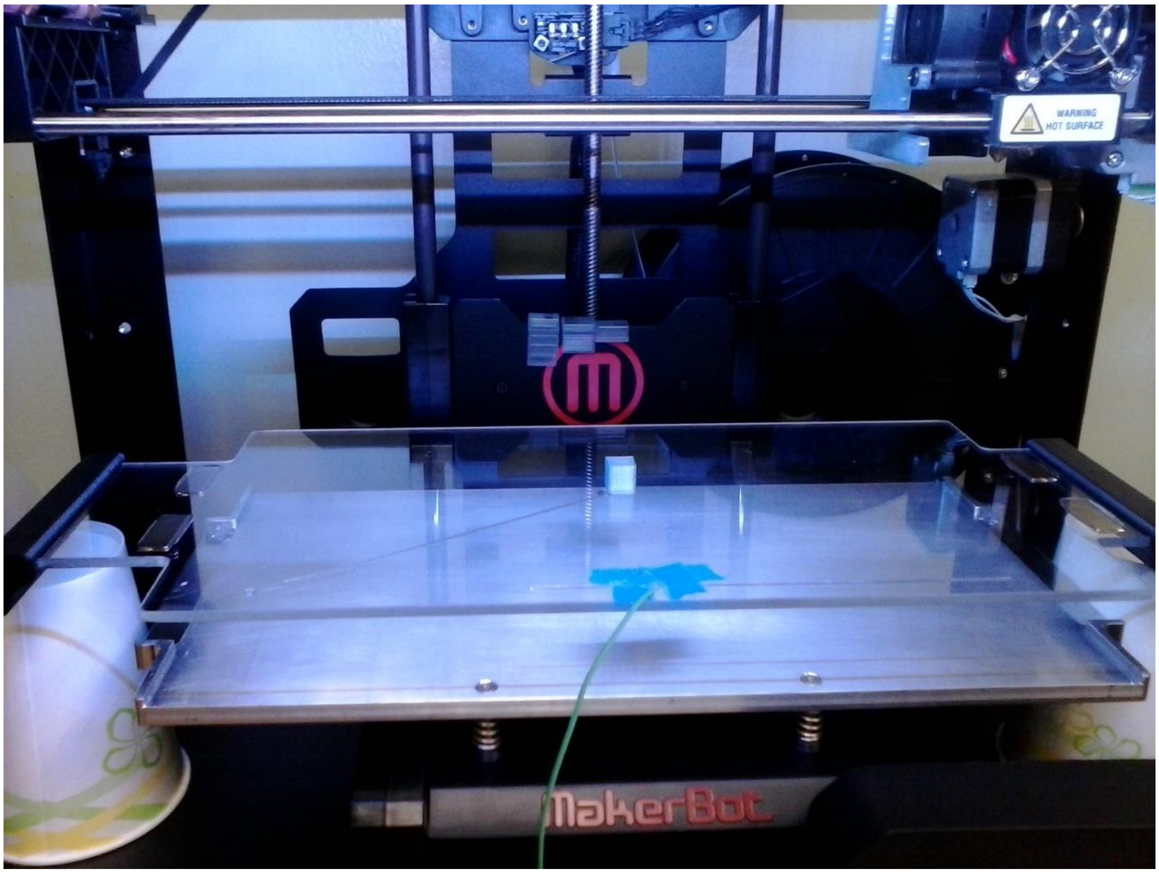


Figure 14: Commercial heated build plate

The heated build plate was integrated into the 3D printer and additional experiments were conducted to determine the optimal build plate temperature, the required cooling rate, and cooling time at the end of the build for ideal part detachment. As shown in Figure 15, the experiments indicated that higher build plate temperatures during printing correlated with higher part removal forces.

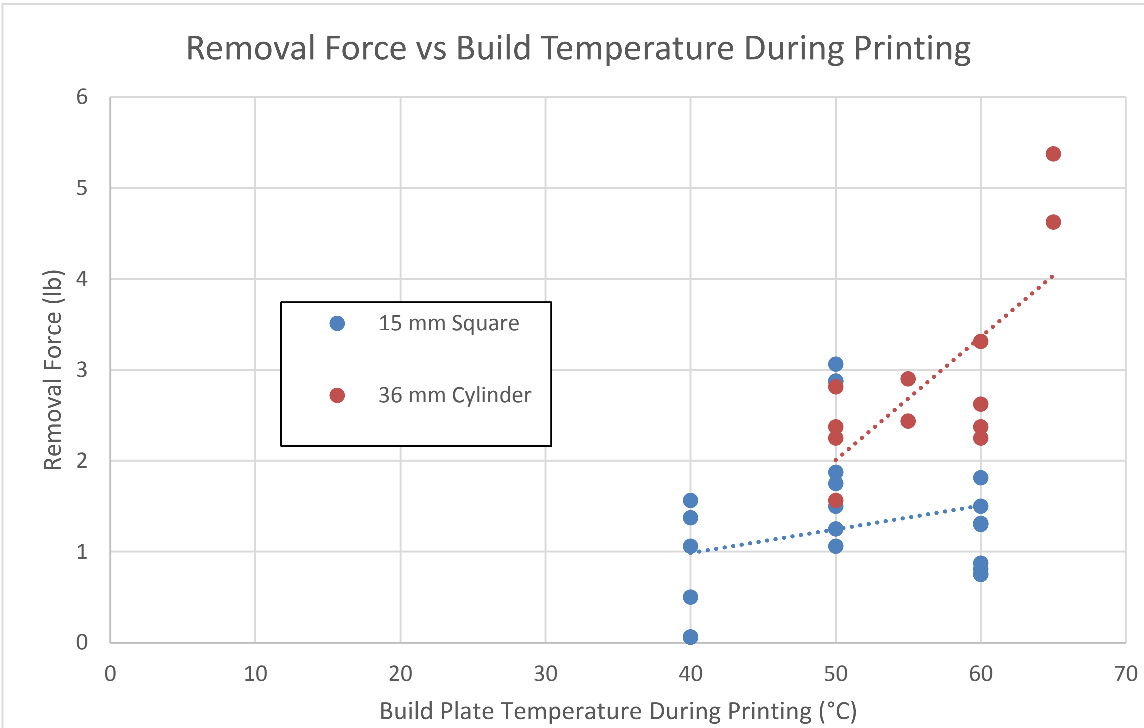


Figure 15: Graph charting how the change in build plate temperature during printing affects part removal force

If the build temperature is too low, the parts will not adhere to the surface during printing; if it is too high, the parts require excessive removal force after printing. Challenging parts were built as part of these experiments, including the tall parts in Figure 16, which are the most difficult to adhere to the build plate during printing because of the small surface area touching the build plate and the large moments applied by the printer head as it builds the uppermost portions of the part. The cylindrical 36 mm diameter part used in previous tests (cf. Figure 12) was reused because it detaches easily during printing.

Figure 16: Tall part with small 7.5 mm square base. Used for testing adhesion while building parts

2.4.2 Maximizing Cooling Rate

The glass build surface detaches easily from the aluminum surface as shown in Figure 17. As shown in the figure, the glass surface is wider than the aluminum surface. When the build plate lowers, the glass surface rests on 3D printed supports while the

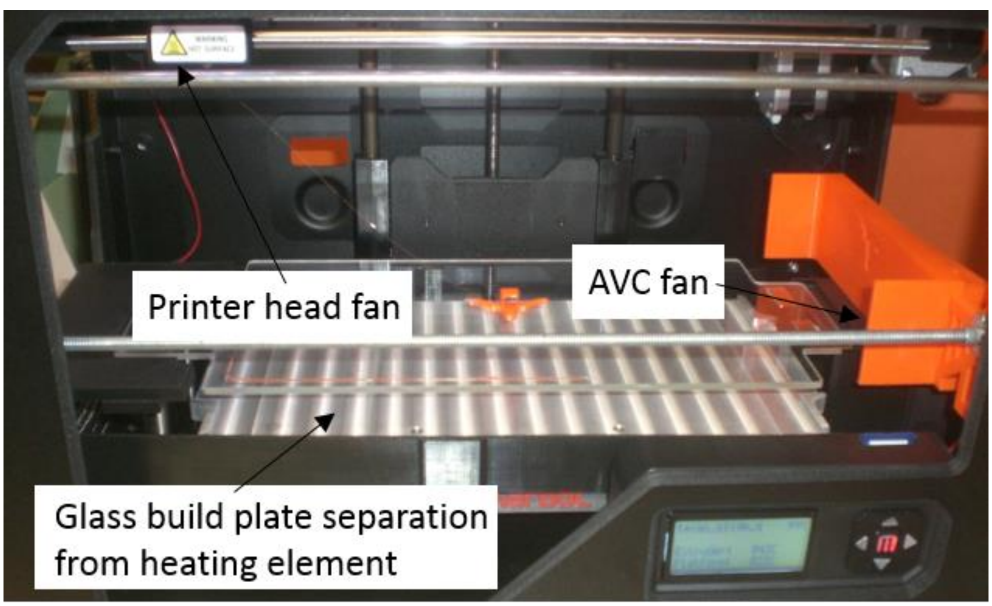


Figure 17: Automatic part removal system

aluminum surface continues to descend, creating a 7/8” gap of separation. The gap facilitates rapid cooling of the glass surface and its attached parts. Rapid cooling causes the parts to detach from the glass build plate. During rapid cooling, the PLA plastic contracts faster than the glass, breaking the bonds holding the parts to the build surface and lowering or even eliminating the force required to remove or scrape the parts from the build surface. The faster PLA is cooled, the more bonds are broken, and the less removal force is required. To maximize the rate of cooling and thereby minimize the part removal force, two fans blow on the part after printing. One fan on the printer head blows air on the top of the glass at the center of the build plate at a flow rate of 4.59 CFM. The other fan is mounted to the right glass support and blows air between the glass and the aluminum heating element at a flow rate of 100 CFM. The fans are activated by the printer head, which pushes switches that are mounted on top of the 3D printer as can be seen in Figure 18. These switches are intended to simplify the design so that no external microcontrollers are needed.

2.4.3 G-code Modifications

The fans and the heated build plate are controlled by a custom build profile, which is a customized set of commands added to the g-code scripts that control the printer during the build. All users of the vending machine are required to use either a “No Raft”, “Raft”, or “Supports + Rafts” profile, each of which incorporates commands to operate the heated build plate and the fans, as well as a sweeper that removes parts. A picture of the printer

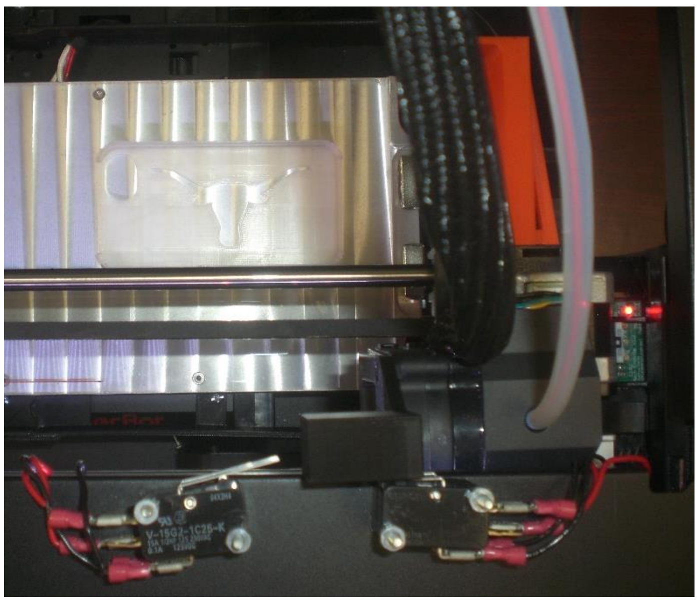


Figure 18: Printer head activating switches that turn on the fan and move the sweeper

head activating switches that move the sweeper can be seen in Figure 18. Two different cooling cycles are used, one for long builds requiring more than 1.5 hours to print, and one for short builds requiring less than 1.5 hours to print. The long versus short profile is automatically selected by the queuing system according to the estimated print time for parts. The long cooling cycle cools for 11.67 minutes with the glass separated from the aluminum heating element. The short cooling cycle cools for 7.17 minutes with the glass separated from the aluminum heating element. The cooling time for short builds is reduced because parts with less surface area touching the build plate need less cooling time to detach completely from the build plate. By using two separate print profiles the throughput of each printer can be maximized.

The distance between the nozzle and the build surface is the other variable that greatly influences part removal force. There are two ways to change the distance between the nozzle and the build plate: changing how tightly the build plate is leveled or adjusting the Z offset in the g-code. This total nozzle Z offset can be seen in Figure 19. To standardize build plate leveling, a 0.06 mm feeler gauge is used instead of the business card that MakerBot recommends. The bolts for leveling the build plate are tightened/loosened so that the feeler gauge barely touches the nozzle. In the profile used to print all parts without rafts, a 0.1 mm Z offset is used. This combination of nozzle distance from the build plate decreases part adhesion for the parts to detach easily from the build surface after a cooling cycle.

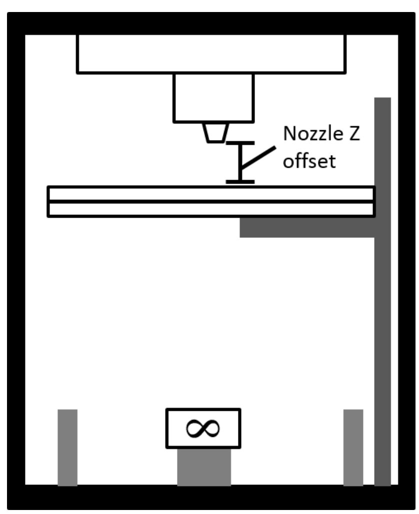


Figure 19: Diagram of total nozzle Z offset between nozzle and build plate

Parts with expansive coverage of the build platform are the most difficult to remove from the build plate after printing. Examples of some of these challenging parts are show in Figures 20 & 21. These parts were tested to fine-tune all of the g-code parameters so that the parts most difficult to detach are removed reliably.

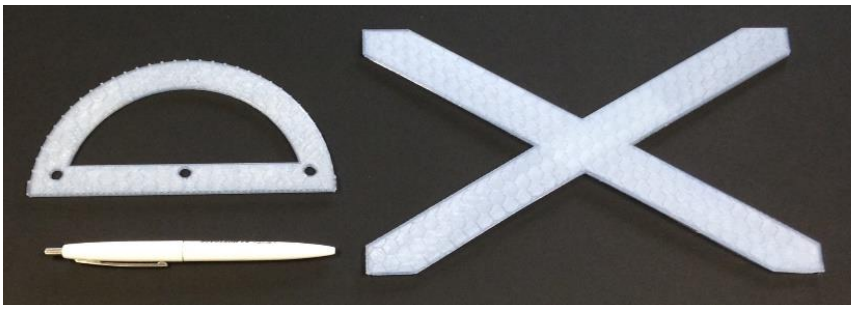


Figure 20: Protractor and large X part used for testing ease of removal after printing

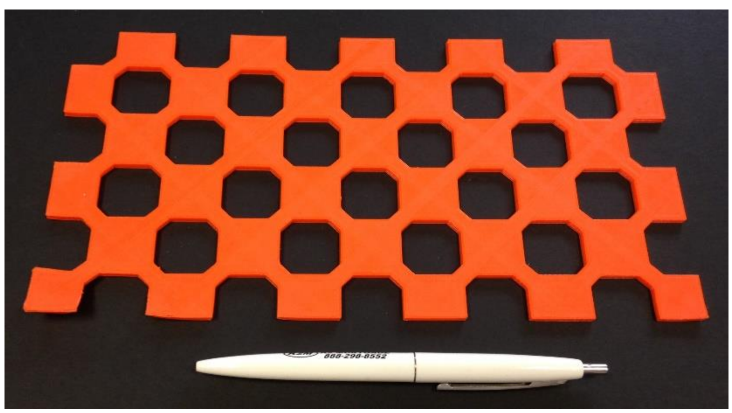


Figure 21: Max size checkerboard part used to determine if build profile parameters were optimized for part removal

By moving the nozzle farther away from the build plate, part removal force is reduced, but part warping increases. To reduce warping, rafts are used. Figure 22 illustrates a standard raft. Traditionally rafts adhere very tightly to the build surface so that parts do not warp. To reduce adhesion, but still maintain their usefulness as tools for

Figure 22: Octopus raft built with rafts to decrease warping

reducing warping, some raft parameters were changed in the print profiles provided to the students. The “raftBaseWidth” parameter was halved to 0.125 mm and the “raftBaseDensity” parameter was lowered from 0.7 mm to 0.21 mm. These changes can be seen in Figure 23. These changes greatly decrease the surface area of the raft touching the build surface. In addition, the Z offset for parts with rafts is increased to 0.25 mm. These changes allow all parts that can be made on the 3D printer to print with rafts and still detach with minimal removal force.

Figure 23: Standard raft on right and modified raft on left for easier part removal. The modified raft is less dense and has thinner lines.

Lastly, because 3D printers print parts layer by layer they must have a layer of material beneath them in order to print. Therefore, parts with overhangs usually require supports in order to print correctly. Parts with supports fail to print when they have any Z offset because the supports do not remain adhered to the build plate. To solve this problem, if students need to print their part with supports they have the option of using a printer profile that prints their part with rafts and supports, as shown in Figures 24 & 25.

Figure 24: Cat part printed with supports in order to print its overhangs [12]

Figure 25: Cat part with the support structure removed [12]

2.5 CLOSURE

This chapter discussed the process for designing a part detachment method for fully automating a 3D printer. Ultimately, printing parts on a glass heated build plate, combined with rapidly cooling parts after printing, was the most effective way of detaching any part that could be printed on the Replicator 2 printer. Adjustments to the g-code were made in order to facilitate rapid cooling and decrease adhesion by changing the Z offset and other raft parameters to allow rafts and supports to be used.

Chapter 3: Part Removal

After the thermal cycling process that detaches parts from the build plate, a mechanism must deposit them into a retrieval bin so that users can access their parts. Multiple 3D printed sweepers were tested until a sweeper of sufficient reliability was created.

3.1 Conceptual design, prototyping, and testing

3.1.1 Printer head sweeper

While researching, the design team discovered a sweeper that could be 3D printed and was designed to attach to the front of the printer head. This design was created by a user of thingiverse.com and can be seen in Figure 26. The design was downloaded, printed, and then tested showing that the idea had merit.

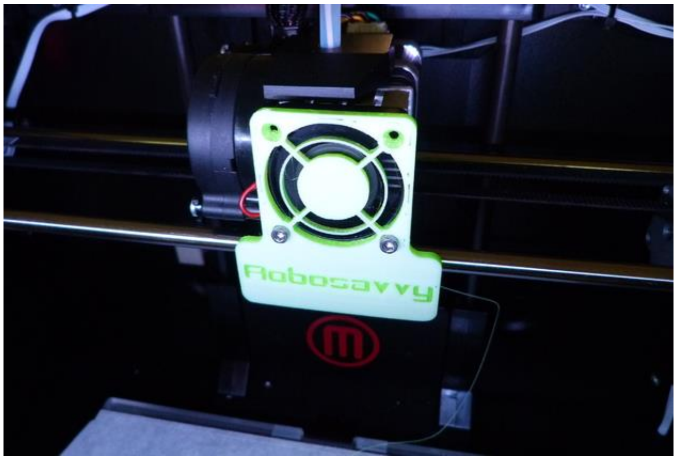


Figure 26: Front mounted printer head sweeper downloaded from thingiverse.com [13]

One of the requirements for the part removal system was to minimize any reduction in build volume. With the sweeper mounted to the front of the printer head the back 2” of the build plate could not be swept, which causes a total build volume reduction of 106 in^3. To minimize the reduction in printable build volume, a 3D printed side sweeper was created. By mounting the sweeper to the side, only 1.5” on the right side of the build plate was inaccessible with a total build volume reduction of 43 in^3, only 30% of the build volume reduction caused by the front sweeper.

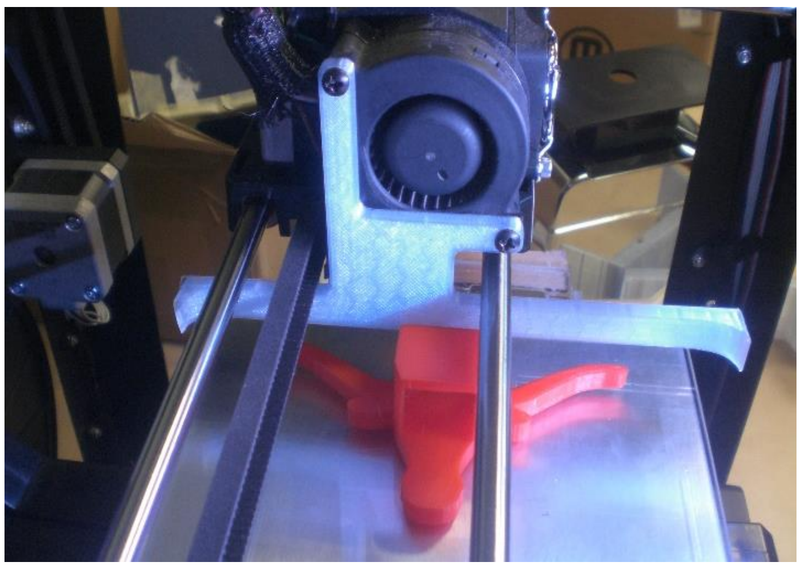


Figure 27: Full length side sweeper mounted to printer head

The side sweeper was originally designed to sweep only one half of the build plate at a time because of the concern of a long moment arm for a longer sweeper, but the reduction of time for a full length sweeper was deemed worth the extra torque. The full length side sweeper can be seen in Figure 27. This sweeper would sweep across the build plate at the highest possible part level, then lower 8 mm and sweep again, and continue this process until it sweeps at the level of the build plate. This sweeper had some significant disadvantages. It sometimes jammed because it required sweeping parts at different heights. It could not sweep parts that required more than 5 lbs of removal force because it was attached to the printer head, and the sweeping process took 3 minutes to complete. Because of these concerns it was determined that a printer head sweeper would not achieve the reliability requirements and that a different method of sweeping would be needed.

3.1.2 All thread sweeper

Many different ideas were generated for sweeping with increased reliability, and a 6-3-5 was performed, which fleshed out these concepts further. A picture of some of these concepts can be seen in Figures 28-31.

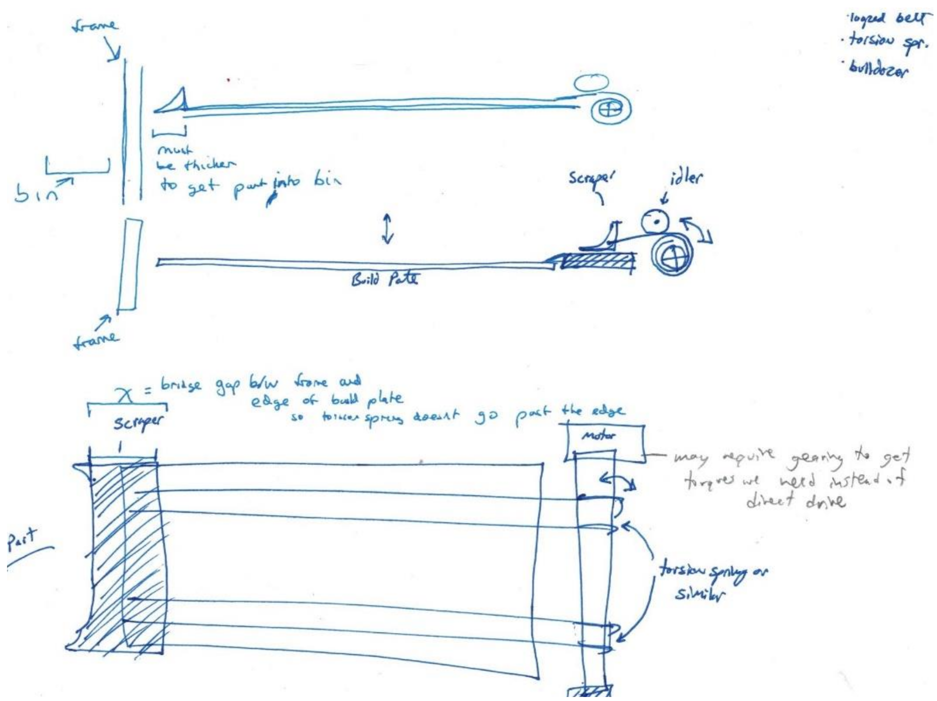


Figure 28: Concept 1-A scraper mounted to a torsion spring actuated by a motor

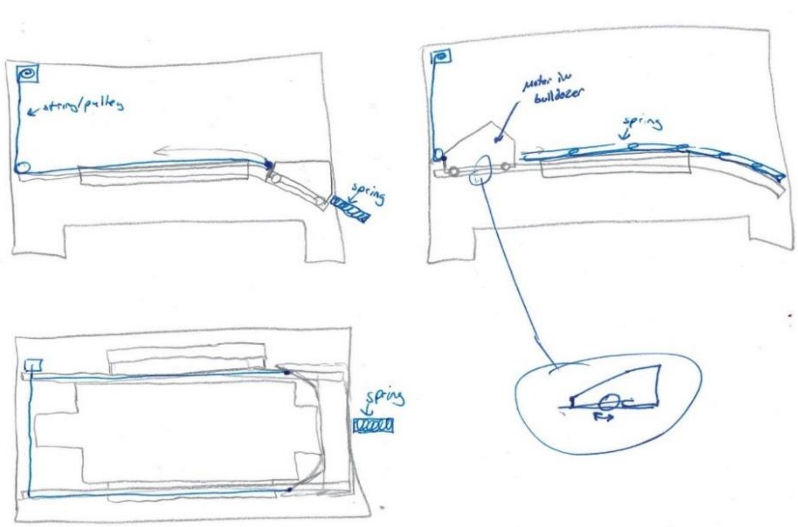


Figure 29: Concept 2-A bulldozer sweeper that runs along curved drawer sliders

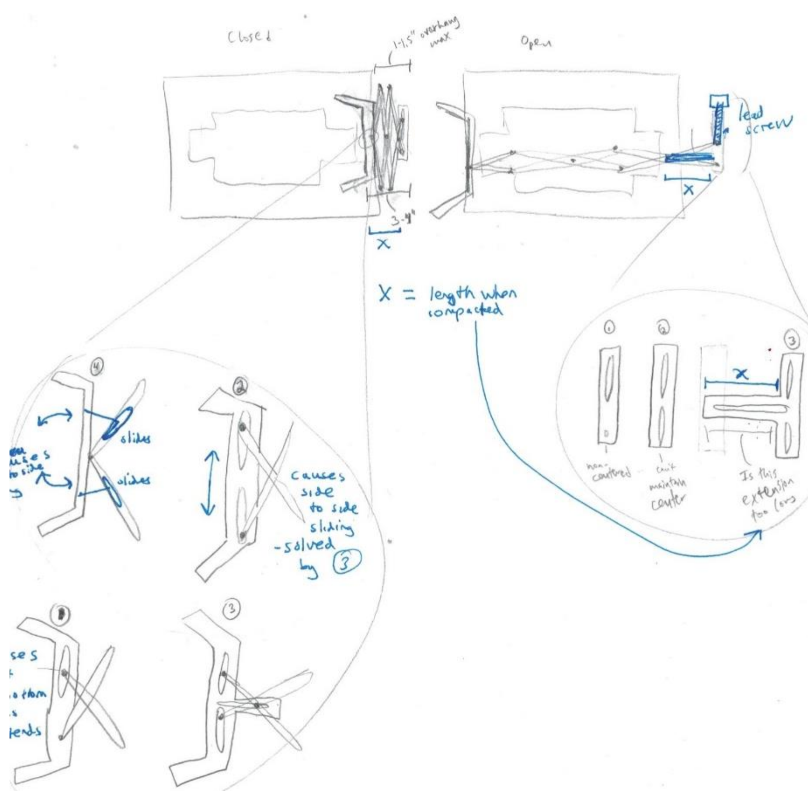


Figure 30: Concept 3-Siscssor lift mechanism moves sweeper forward/backward

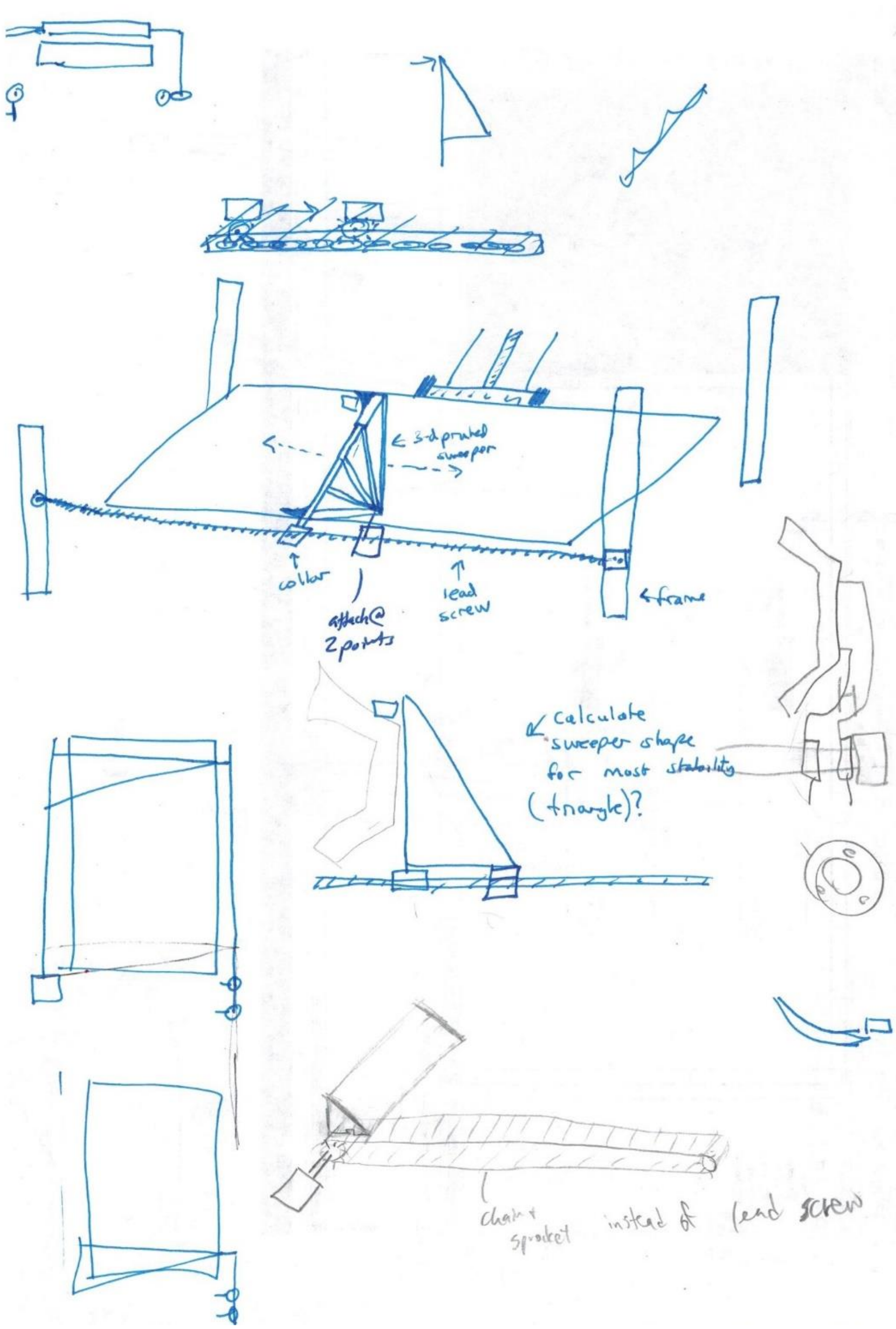


Figure 31: Concept 4-Sweeper mounted to a lead screw actuated by a motor

Some of these concepts include a scissor mechanism, a curved drawer slider, a scraper mounted to a torsion spring, and a sweeper mounted to a lead screw. Using a motor to power a lead screw attached to a 3D printed sweeper was selected because of its simplicity and apparent feasibility. With a sweeper starting position outside the perimeter of the build plate, the entire build plate can be used for printing, which effectively increases the build volume 50% from the original sweeper tested.

Sweeper Iterations

Multiple 3D printed versions of the threaded sweeper were tested until the most reliable version was identified. Figure 32 shows some of the sweeper iterations. All the sweepers were designed to require no support structures during printing so that the bottom of the sweeper could be completely flat. Tests have been performed with the final sweeper showing that it can reliably remove any part that is at least 0.1” tall, which is the minimum thickness for a printed part in the vending machine. The final sweeper design, shown on the bottom in Figure 33, incorporates a ramp on the front 1.25” of the build plate, to pry

Figure 32: Multiple 3D printed iterations of the threaded sweeper

large parts off of the build surface as needed. The majority of parts only contact the main face of the sweeper which provides a better transfer of force to taller parts.

Figure 33: Sweepers with ramps for prying up parts

The final all thread version of the sweeper is shown in Figure 34. The sweeper is attached to a secondary guide rod to keep the sweeper flat on the build plate. This mechanism solved multiple problems associated with the first sweeper, making it much

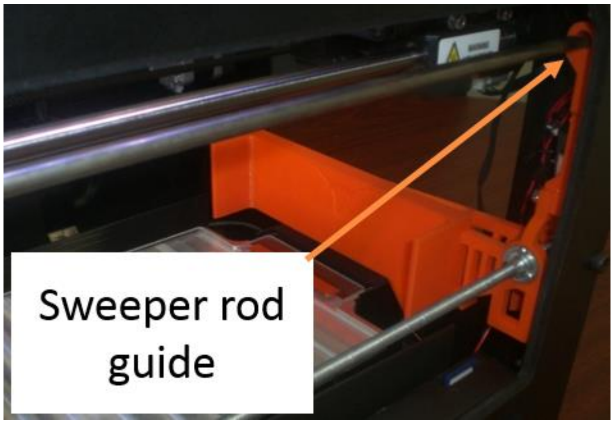


Figure 34: Final version of all thread sweeper

more reliable. The new sweeper routine requires 1 minute 20 seconds, less than half the time of the original one.

Sweeper powered by MakerBot MightyBoard

The MakerBot MightyBoard has the capability of running two extruders although the Replicator 2 printer that is used for this project only has one printer head extruder. Because of this, it was hypothesized that a motor could be connected to the extruder connection, powered by the 3D printer, and controlled via g-code. An extra Z-axis motor with built in lead screw was bought from MakerBot and a wire was modified to connect to the MightyBoard extruder B port. This test assembly can be seen in Figure 35. The way that an extruder is controlled in the g-code is completely different from how regular motors are controlled. Eventually the design team was successful in running the motor from the extruder B input, but even at the fastest g-code setting the motor ran the lead screw too slowly. It took the motor 15 minutes to sweep the entire length of the build plate, which is the maximum total length of part removal for the part removal system. The design team determined that the sweep cycle was so long because the power supply for the extruder B port is not sufficient to power the stepper motor.

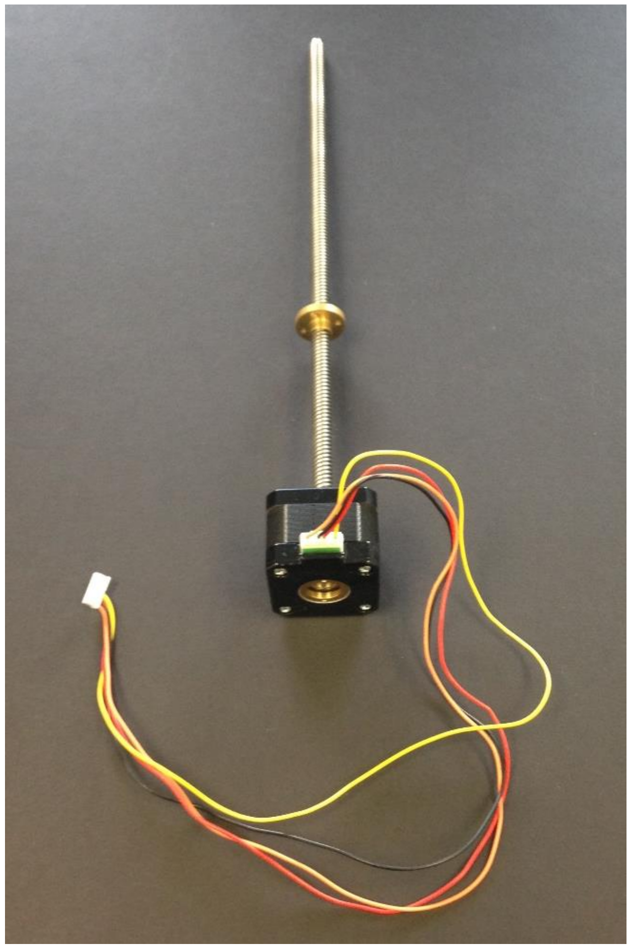


Figure 35: Lead screw with modified wire that connects to extruder B input

Externally Powered All Thread Sweeper

Instead of powering the sweeper via the MakerBot MightyBoard, an external laptop power source is used to power the motor via a circuit that turns the motor on/off and forward/backwards. This circuit also powers the fan for increasing the cooling rate of parts.

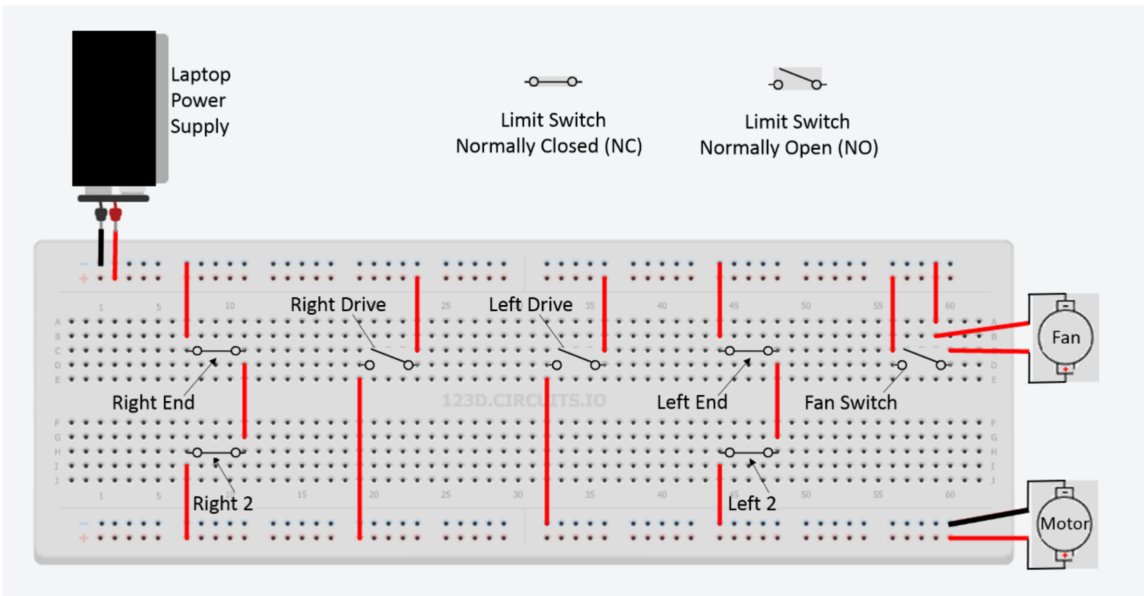


Figure 36: Circuit diagram designed to work without a microcontroller

The sweeper is activated by the printer head pushing switches on the top of the 3D printer. The circuit is set up with redundant switches so that all the logic of turning the motor on/off is dictated by the circuit design, eliminating the need for a microcontroller. The circuit design can be seen in Figure 36. This strategy reduces cost and increases the simplicity of the system so that other schools could replicate the system more easily. The circuit incorporates hard stop switches on each end to insure that the sweeper sweeps parts completely off of the build surface on one end and returns all the way to its neutral position on the other end, preventing it from interfering with the vertical motion of the build plate.

The motor is attached via a coupler to a lead screw that propels the 3D printed sweeper across the build plate.

Sweeper fixes

Sweeper guides were added to the build platform to prevent long parts from jamming when they are swept out of the 3D printer. These sweeper guides can be seen in Figure 37. Another problem is that some parts are still attached by a string to the extruder after printing. For smaller parts, this string can pull the parts up and over the sweeper during a sweep cycle. This problem can be seen in Figure 38. To fix this problem, the printer profiles heat the extruder after part cooling, which causes the string to become detached from the extruder nozzle when the parts are swept out of the 3D printer.

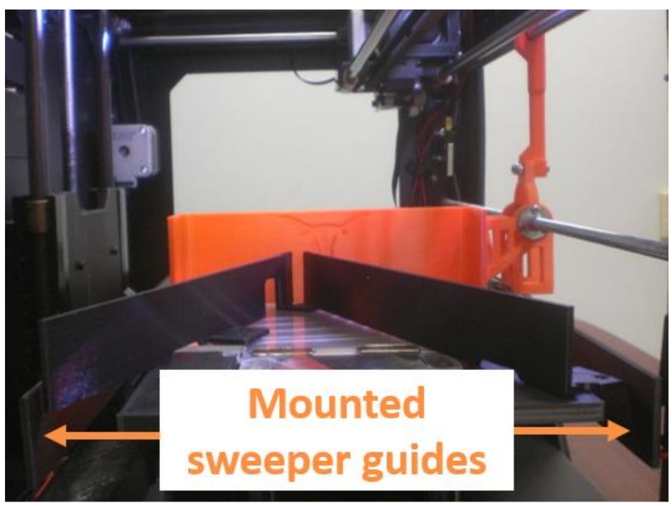


Figure 37: Sweeper guides being swept off the build plate. The mounted sweeper guides keep long parts from jamming as they exit the printer.

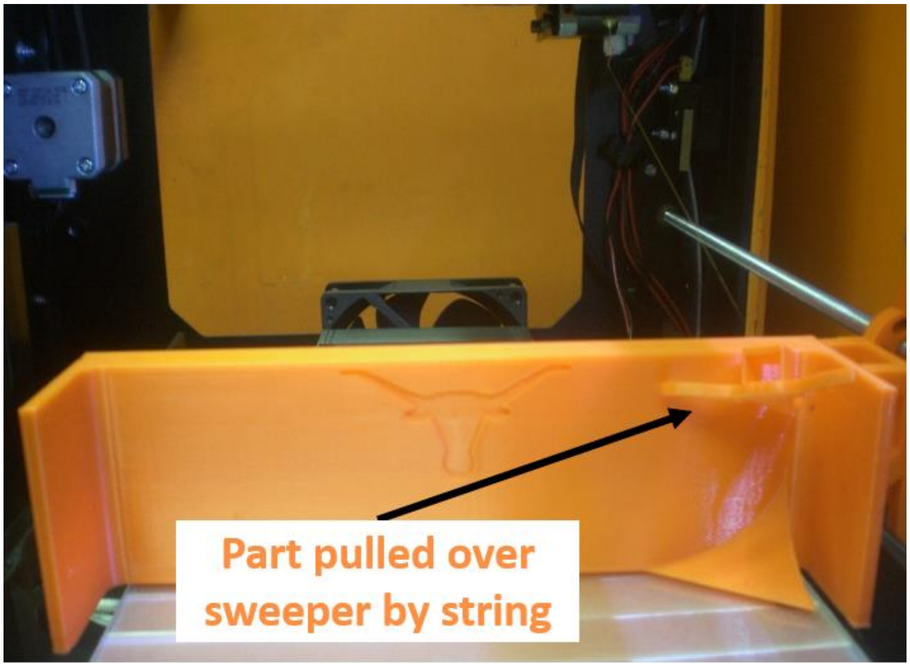


Figure 38: A small part attached to the printer head by a string of cooled plastic being pulled over the sweeper during a sweep cycle

3.2 FINAL DESIGN

The all thread sweeper worked well, but it could not sweep parts that required more than 5 pounds of removal force. The full power of the motor is not applied to the parts when they are swept because the sweeper is cantilevered and the brad tee nuts that connect the sweeper to the all thread are not perfectly aligned. Many partial sweepers were printed to improve the spacing between the two brad tee nuts, but still the brad tees were somewhat loose in the final design limiting the power imparted to parts through the sweeper. A picture of these partial sweepers can be seen in Figure 39.

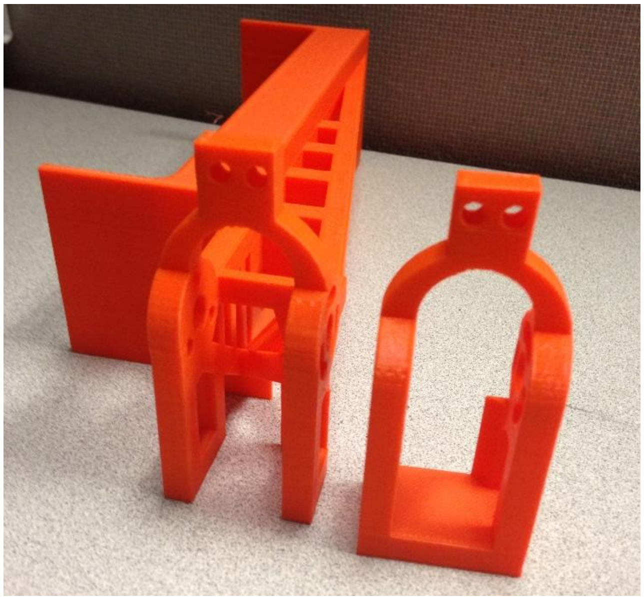


Figure 39: Partial sweeper next to full sweeper used to determine brad tee nut spacing

In order to apply more force to parts during sweeping a lead screw was ordered and the 3D printed sweeper was modified to attach to the 1” long lead screw nut. This fixed the spacing problem of the brad tee nuts increasing the maximum removal force to 8 pounds for the sweeper. The final sweeper has ramps on the front and the back 1.25”. This sweeper can be seen in Figure 40.

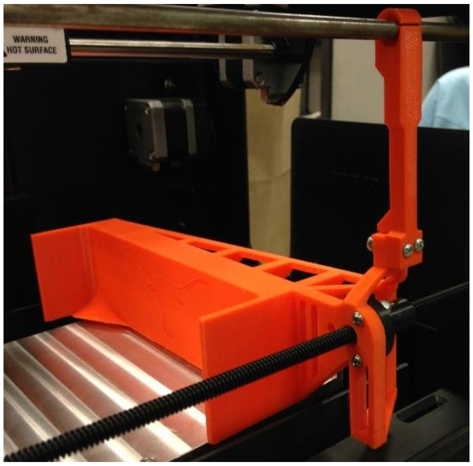


Figure 40: Final lead screw sweeper design

3.3 CLOSURE

This chapter discusses how a sweeper mechanism removes parts from the 3D printers after they are detached from the build plate. Many different sweeper designs were tested, ranging from sweepers mounted to the printer head to externally powered, motor driven, 3D printed sweepers. By using a sweeper that is driven by a motor along a lead screw, the sweeping cycle time was decreased, the build volume increased, the maximum part removal force increased, and the reliability of the automatic part removal system significantly increased relative to a sweeper mounted on the print head.

Chapter 4: Vending Machine Enclosure Design

The vending machine enclosure was designed to make the 3D printers secure, allow for easy part retrieval by users, and draw attention to the many uses of 3D printing. In this chapter, the vending machine security, accessibility, aesthetics, and thermal mitigation techniques are discussed in depth. In addition, the informative monitor next the Innovation Station, the open source enclosure designs, and the part retrieval system are discussed. The

Figure 41: CAD model of the Innovation Station

Figure 42: Innovation Station in the lobby of the Mechanical Engineering building

CAD model of the enclosure can be seen in Figure 41, alongside the actual vending machine in Figure 42.

4.1 INNOVATION STATION ENCLOSURE

4.1.1 Secure

As can be seen in the figures, the printers are fully enclosed. This serves the dual purpose of protecting the user from contact with the 3D printer nozzles, which reach temperatures of 230°C, and keeping the 3D printers safe from vandalism and theft. Locks and vandal proof bolts are used to maintain security. On the back of the vending machine are two sets of sliding doors that are locked via a push lock for each door. This lock and its mounting plate can be seen in Figure 43. There are two rotating cabinet locks on the side door that keep that access point secure. All of these locks open with keys.

Figure 43: Lock for the sliding back doors.

Two different types of vandal proof bolts are used for each bolted part of the Innovation Station enclosure. These bolts can be seen in Figure 44. This strategy forces the user to obtain both specialty screwdriver heads to be able to disassemble the machine.

A bike cable is threaded out of holes in the bottom of the machine and locked to a loop on the wall so that unauthorized persons cannot roll the Innovation Station away as a prank or out of malicious intent. To further prevent this from happening there is a security camera mounted near the Innovation Station. Pictures of the bike chain can be seen in Figures 45.

Figure 44: Two different types of vandal proof bolts used to secure the vending machine

Figure 45: Bike chain securing the vending machine to the wall

4.1.2 Accessibility

Sliding doors on the back and a hinged door on the right of the vending machine provide easy access to the entire machine for maintenance. Ease of access to the 3D printers is a priority because an adiministrator must access each machine every day in order to level the build plate, check that there is enough plastic filament for the day, and perform general maintence. All of these tasks can be performed from the side of the printer as long as there is access to the front LED panel. The side door in the open position can be seen in Figure 46. After the side door is opened, there is enough space behind the printers to angle them for full access to the side of the printer and the LED screen. The back sliding doors provide access to the computers that run the printers and the webcams and all the

Figure 46: Side door of the vending machine that allows all daily maintenance to be done

power cords. In addition the back doors provide access to the part retrieval bins and the webcams while the 3D printers are in their working positions. The Innovation Station has four locking wheels that allow the vending machine to be wheeled from the lobby to the lab when needed. The machine is also designed to fit in the elevator and pass through doorways without removing any parts.

4.1.3 Aesthetics

One of the main purposes of the Innovation Station is to inspire engineers and future engineers. In order to do this, it needs to catch the eye and create interest. The design team invited experts from the School of Architecture and College of Fine Arts to visit the lab and offer suggestions for the overall look of the vending machine. A sleek, modern design was deemed to most advantageous to the team's goals.

This design incorporates windows to hide some of the features that are not meant to be emphasized, while using transparent openings and lighting to draw the eye to the most important features. Some CAD models of different window designs can be seen in Figure 47. These windows are consistent with the shape of the MakerBot panels, which use short 45° sections to round off the corners. In addition, LED lights were used to highlight the part retrieval bins and the 3D printers. White LED lights were used for these sections of the vending machine while orange lights were used to highlight the retrieval bin handles and the Innovation Station sign. The main color used for the vending machine was black which helped to accentuate the two highlight colors of white and orange. Most of the 3D printed parts of the vending machine were printed in black plastic to follow this color scheme, which matches the original MakerBot color scheme as well.

Figure 47: CAD models of different window designs used to select the best look

Many different versions of the Innovation Station sign were modeled in CAD, as shown in Figure 48. Many different fonts were investigated, but one of the official fonts of The University of Texas was selected as the optimal font. An attempt was made to make the sign consistent with the overall look of the machine, so short 45° slants where used to

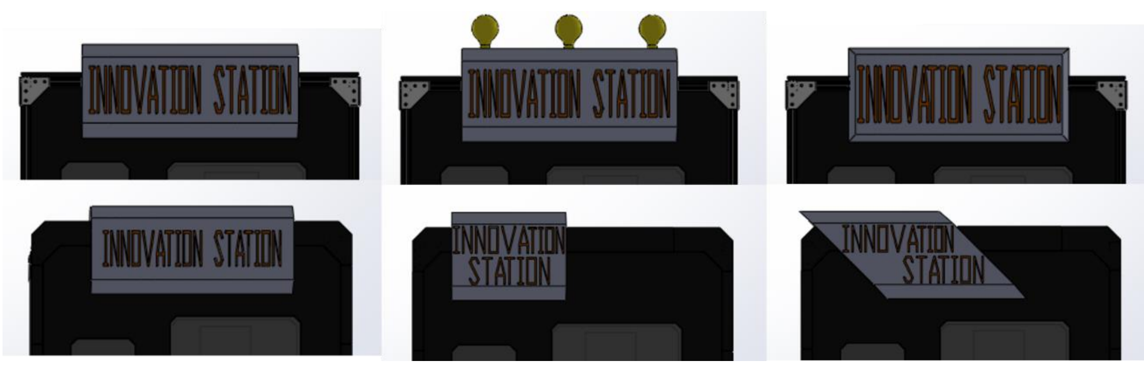


Figure 48: CAD models of different sign versions used to pick the best option

push the sign in front of the rest of the vending machine. A picture of the final sign with the 45° slants can be seen in Figure 49.

Figure 49: Final Innovation Station sign with 45° slants and backlit letters

The Innovation Station sign was fabricated with a selective laser sintering machine because the sign was too large to 3D print. Originally it was intended to show a unique feature of additive manufacturing—the use of thin, translucent walls. The sign was designed so that the words "Innovation Station" are etched into the inside of the sign in

Figure 50: One half of the Innovation Station sign being printed in a SLS machine

layers thin enough to glow when back-lit by LEDs. Because the sign is so large the build was laid out so that one half of the sign was flat and the other was vertical in the corner of the build. Figure 50 illustrates one half of the sign being formed. This part of the sign was created without any problems. The second part of the sign with the word "Innovation" was built in a vertical orientation, as shown in Figure 51. In that orientation, the SLS machine could not resolve the thin walls inside the letters. The SLS machine has higher resolution in the vertical axis because it has very fine control of the layer thickness. In the horizontal plane the resolution is constrained by the laser diameter which was larger than the thickness of the letters causing them not to sinter correctly. Figure 51 shows the part cake, where the second half of the sign is clearly visible. In order to fix this anomaly, the insides of the

Figure 51: Part cake with one half of the Innovation Station sign partially removed

letters in the “Station” part of the sign were cut out and translucent plastic was glued to the back of both signs to create the backlit LED effect shown in Figure 49.

The vending machine uses many 3D printed parts to demonstrate the possibilities afforded by 3D printing. The ramps, borders, and the drawer window frame and handle are some of the many parts featured in the vending machine that show the utility of 3D printing.

The purpose of the borders is to give the front of the Innovation Station a cleaner look by covering the 80/20 rods. In addition, adding borders provides another opportunity to highlight the uniqueness capabilities of 3D printing. Many different types of border designs were modeled and printed to determine the best fit. Figure 52 shows some of these test prints that were used in the decision making process. Eventually a hexagonal pattern was selected because it matched the honeycomb structure used in the retrieval bin design. One of the key design requirements for the borders was that they add to the sleek look of the vending machine without attracting too much attention. Accordingly, the borders were

Figure 52: Sample border designs used to select final border pattern

printed in the same color as the surrounding structure and a pattern was selected that was not excessively “busy” in nature. Because the honeycomb design is subtle a user cannot even see that there is a pattern on the border until they are within a few feet of the machine.

4.1.4 Thermal Mitigation

When housing electronics inside an enclosure, thermal mitigation is always a concern. The Innovation Station requires three computers and two 3D printers, all of which create a significant amount of heat. Excessive ambient temperature could cause the computers to overheat or the printers to malfunction. In order to reduce the internal temperature of the vending machine enclosure, two techniques were used: air flow through the use of holes to allow air to pass and forced convection by way of fans. Both of these techniques can be seen in Figure 53. Holes were drilled in a rectangular pattern in the shelf behind the 3D printers and in the top and bottom of the vending machine. These holes allow air to flow more freely throughout the entire enclosure instead of thermally isolating

Figure 53: Fans and air holes are used to move hot air out of the vending machine

each section. To increase the flow of hot air out of the Innovation Station, two 60 CFM fans are mounted to the top and bottom of the vending machine to blow air outwards. These fans are quiet enough not to disturb students studying nearby.

4.1.5 Monitor

A monitor is mounted next to the Innovation Station as can be seen in Figure 54. This monitor runs a slide show on a continuous loop. At the bottom of each page of the slide show is a link to the website where students can upload their parts to be printed. The slide show includes instructions on how to use the Innovation Station, example 3D printed parts that have been printed by the Innovation Station 3D printers, and links to help resources in the event of a printer malfunction. Using a slide show to present this

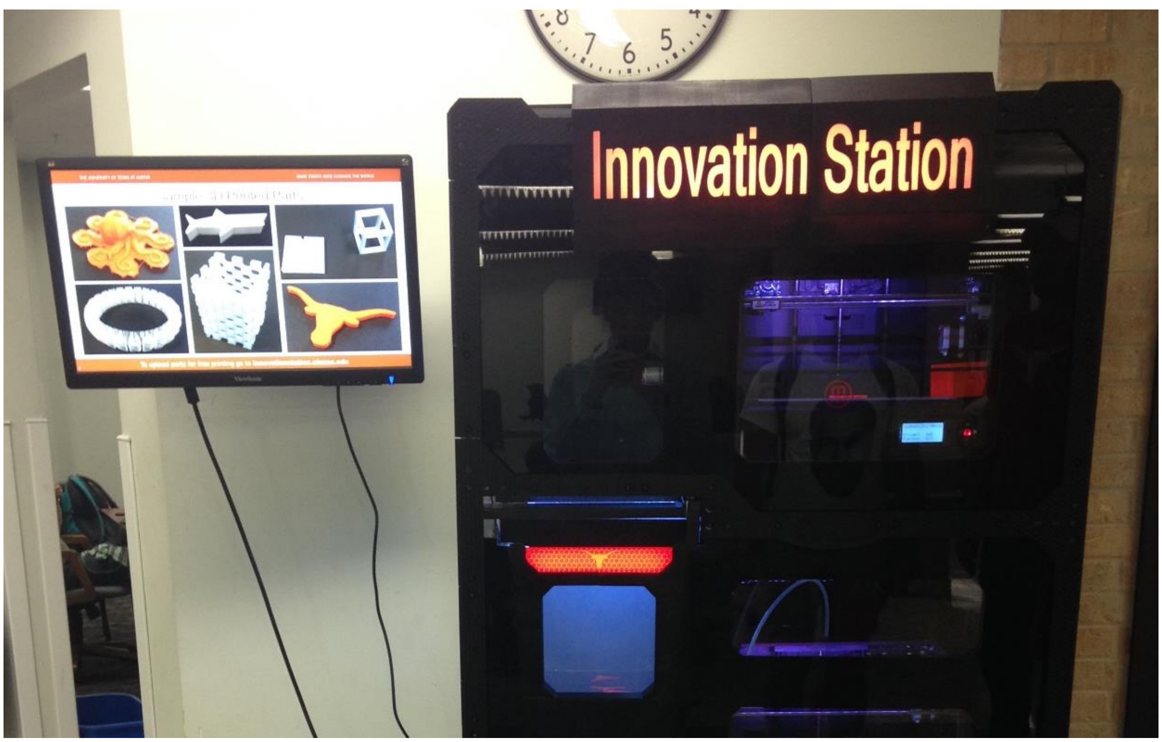


Figure 54: The monitor located next to the Innovation Station.

information gives Innovation Station administrators flexibility in what is displayed and the content can be easily updated. For example, in the future the monitor could be used to announce 3D printing design challenges and other events.

4.1.6 Simplified Enclosure Versions

The plans for the Innovation Station enclosure and the upgrades to the MakerBot Replicator 2 3D printer will be open source so that other universities can replicate the station. Plans for simplified, low-cost versions of the vending machine will also be available for download from the Innovation Station website. The CAD models of these simplified enclosures can be seen in Figures 55 and 56. The design team hopes that other universities and even high schools will create their own 3D printing vending machines, using this design as a starting point.

The full Bill of Materials for all the versions as well as instructions for how to assemble the vending machine and upgrade a Replicator 2 to automatically remove parts will all be downloadable as well. The Bill of Materials is located in Appendix B. Exploded views of the enclosures in addition to part drawings are included in Appendix C while a guide to upgrading a Replicator 2 3D printer to automatically remove parts is in Appendix D.

A simplified, one printer or two printer vending machine is expected to cost approximately $1,900 or $2,400, respectively, while the cost to upgrade to a vending machine exactly like the Innovation Station will be $3,100. Additional costs would include the purchase price of the MakerBot Replicator 2s themselves, plus approximately $490 per printer to add the automatic part removal system.

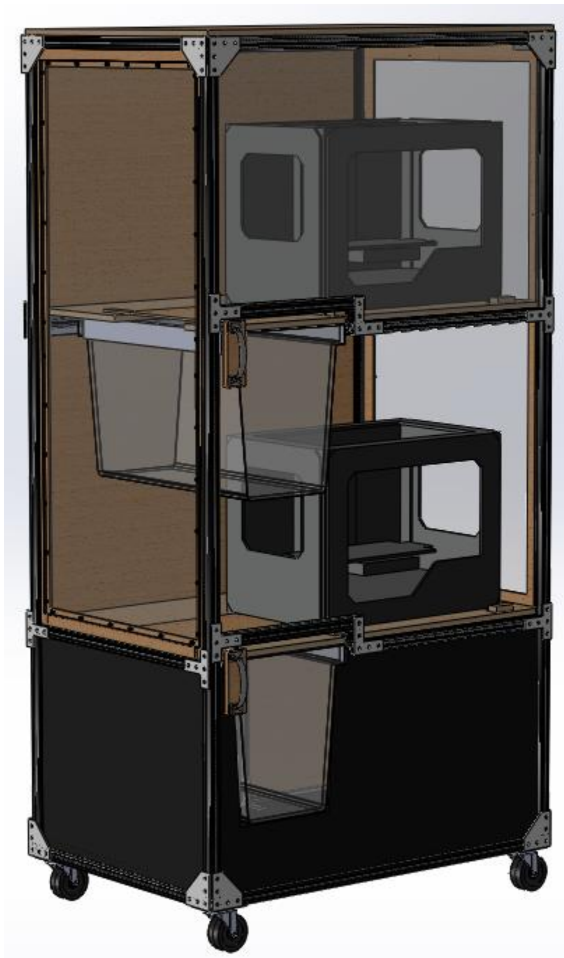


Figure 55: CAD model of the simple, 2 printer vending machine

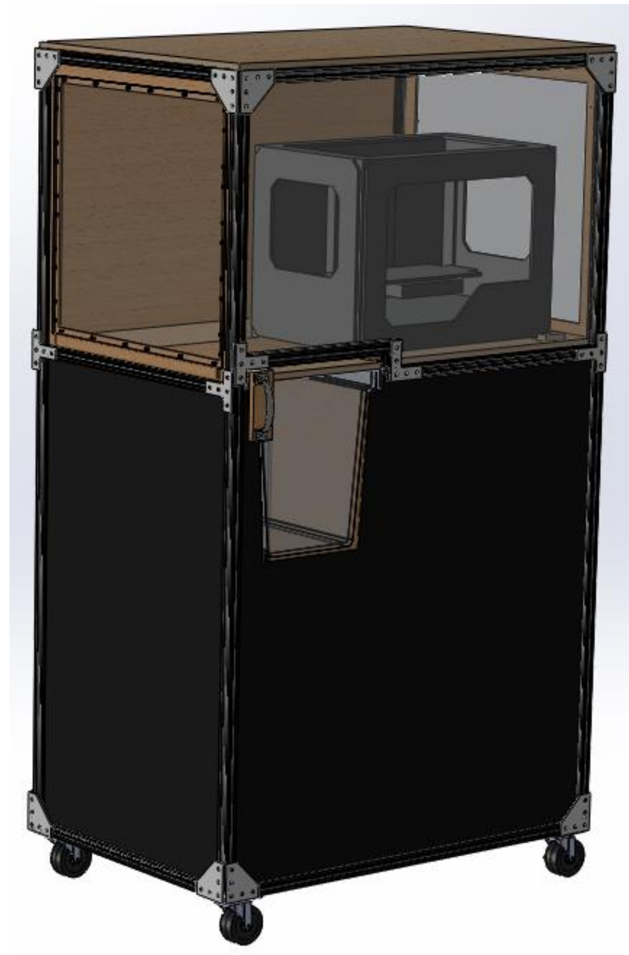


Figure 56: CAD model of the simple, 1 printer vending machine

4.2 PART RETRIEVAL

After parts are swept from the build platform, they land in a retrieval bin where users can access them. It was important to design the part retrieval bin as part of the automatic part removal system so that it functions seamlessly. The primary requirement for the retrieval bin was to give users access to their parts without allowing them to interact with the 3D printer directly for safety and vandalism reasons. Another requirement was that the bin be able to hold multiple days' worth of parts, so that even if students did not retrieve their parts immediately, there would still be room for additional parts. The retrieval bin also needed to be large enough to accommodate the maximum size part that could be printed on the 3D printers. The system also needed to be easy to use and avoid damaging the parts.

Low Resolution Prototypes

Many concepts for the part retrieval bin were considered. To determine the feasibility of these designs low resolution prototypes where created. Low resolution prototypes are simple prototypes usually made out of materials that are easily accessible in which only the key functions of a design are created. These types of inexpensive prototypes are very useful in quickly filtering out designs that will not work, by giving the designer a

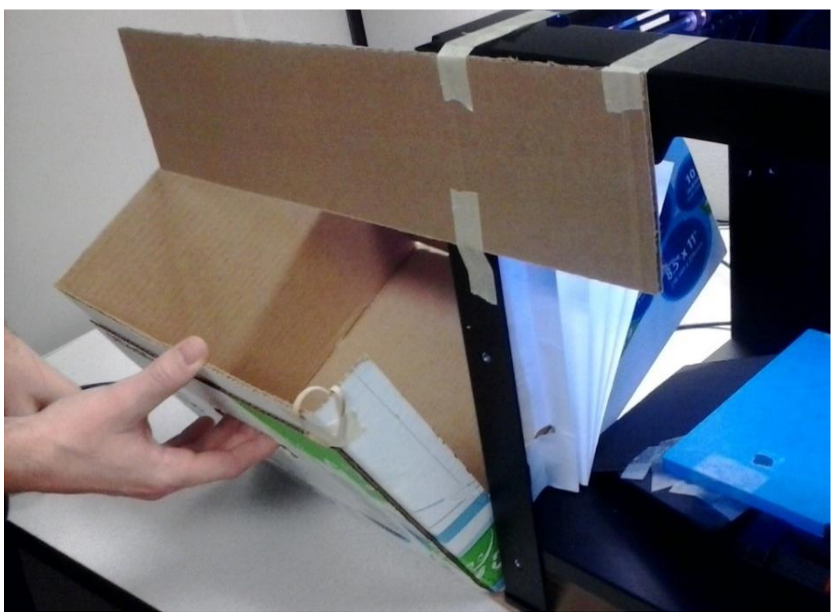


Figure 57: Concept 1-Low resolution prototype of a bin that pivots on its corner and has a fan-like cover that prevents access to printer

Figure 58: Concept 2-Low resolution prototype of bin that prevents access to printer by built-in walls

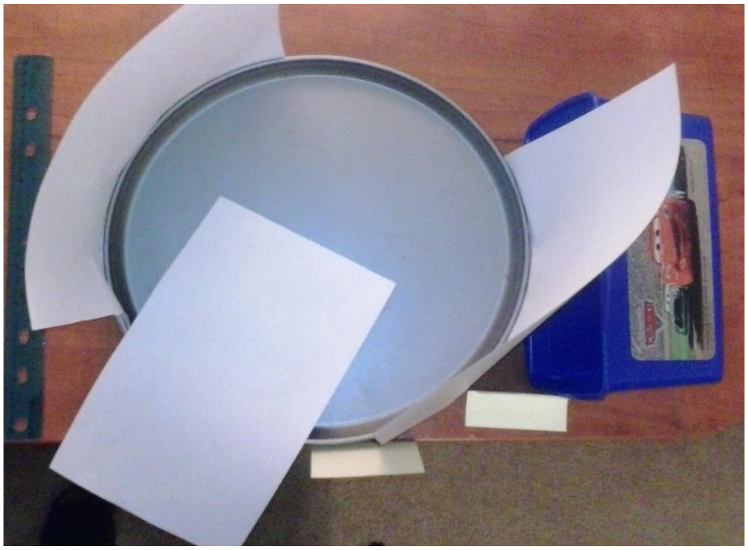


Figure 59: Concept 3-Low resolution prototype of a turn table retrieval bin (Blue bin represents location of 3D printer)

physical representation of their idea. These prototypes were particularly useful in determining user access to the 3D printers through the retrieval bin. Figures 57-59 show some examples of low resolution prototypes of retrieval bins. Concept 1 pivots on its lower corner and uses a fan to cover up the hole to eliminate user access to the 3D printer. This design is very compact, but the problem with this design is that the fan must actuate in the opposite direction of the motion of the drawer, and it does not cover up the entry hole quickly enough to completely prevent access. Concept 2 uses distance to prevent access, but it has a box that extends past the front of the vending machine which is undesirable. Concept 3 is a turntable that uses walls to prevent access.

The turn table design was pursued further because of the desire to have an aesthetically pleasing retrieval method. By turning the turn table counter clockwise the user can access parts without accessing the 3D printer. Figure 60 shows the prototype of this turn table with a low resolution maximum-size part in it for testing. Challenges with this concept included the fact that it was hard to manufacture and difficult to operate. The

Figure 60: Turn table prototype with max size part in it

turn table required the user to turn it 270° to prevent user access, which was not very user friendly, and it could be prone to jamming or parts falling out of the bin.

4.3.2 Final Design

The final design uses a sliding drawer style retrieval bin that is very familiar to users. It is a commercial storage bin that slides on aluminum U channels. For users to open the parts bin they must slide the drawer cover all the way to the left as can be seen in Figures 61 and 62. This two-step process allows parts to fall into the retrieval bin but prevents the user from accessing the printers themselves. 3D printed ramps surround the hole that leads to the bin, insuring that parts land in the drawer. Even if the drawer cover

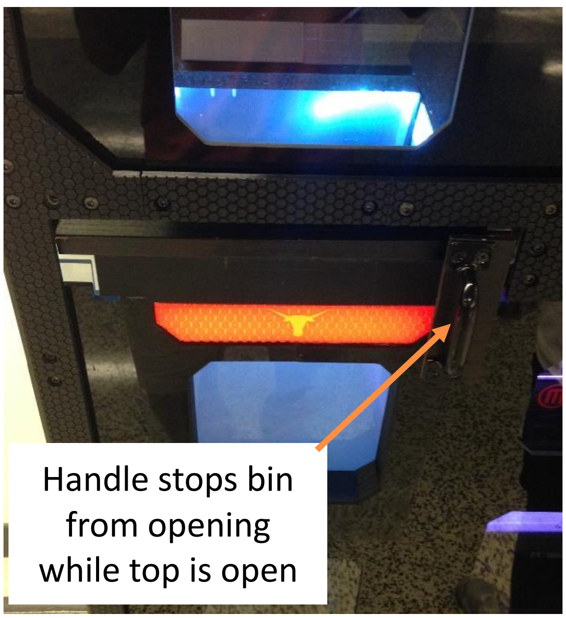


Figure 61: Vending bin open on the top to receive parts. In this position the bin is blocked by the handle and cannot open.

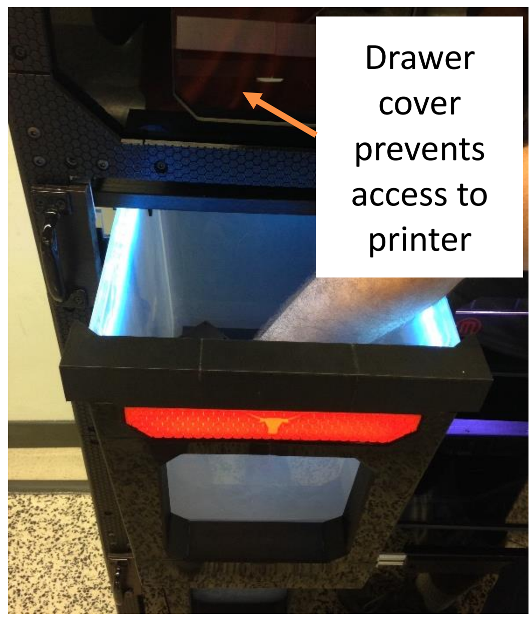


Figure 62: Vending bin closed on the top to prevent vandalism and user injury while the drawer is open

is not replaced to its original open position, parts that are swept out of the printers are constrained within the ramps, and the drawer cover can later be opened to let the parts fall into the bin without jamming.

The handle used for the slider was the commercial handle that can be seen in Figure 61 and 62. In some of the final testing with lead users one of the users pulled the handle completely off. The wood backing to this handle was very thin in order to clear the 3D printed borders and was made of particle board making it very weak. The wood yielded when the handle was pulled out instead of slid sideways. In order to prevent this from happening again, a new handle was designed and 3D printed. This handle can be seen in

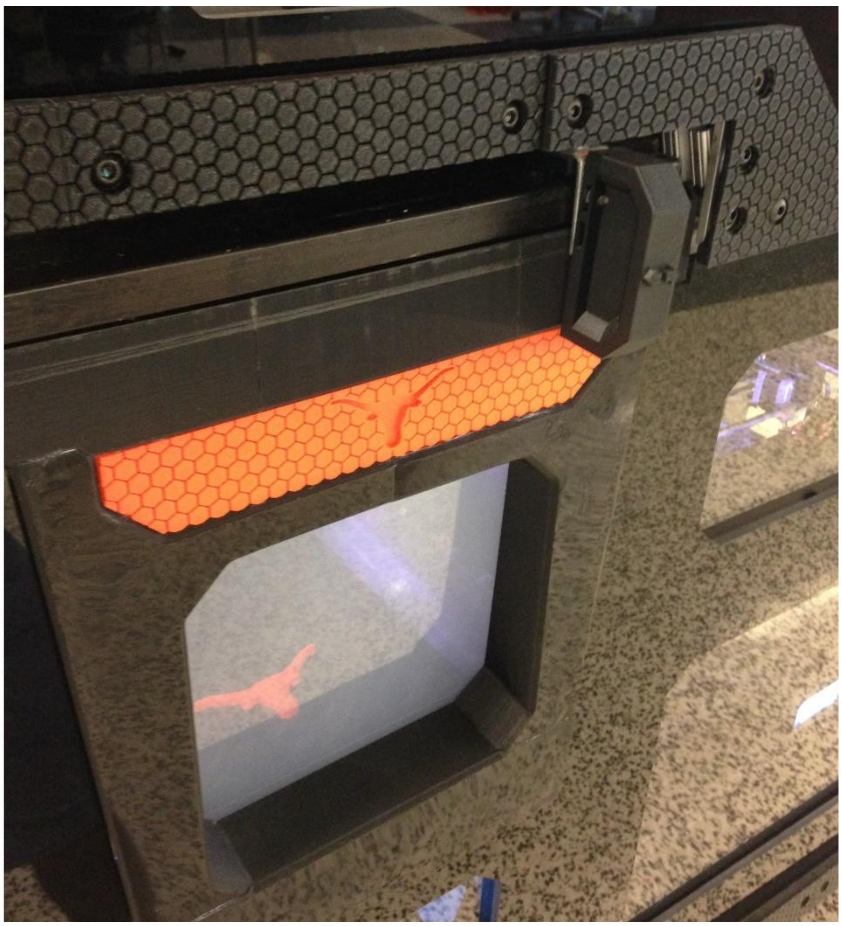


Figure 63: 3D printed handle for drawer slider

Figure 63. This handle eliminates the need for the particle board mount and also includes arrows indicating the direction of travel. The original style handle is generally used for pulling. To prevent the natural inclination to pull the handle, the final handle does not have a hole all the way through it like the original handle, making it more natural to slide it than pull it.

The part bins are designed to be large enough for a 10.5” x 5.5” x 4.75” part, which is the maximum part size that can be printed. They also have the capacity to hold a week’s worth of parts in case parts are not retrieved by the users immediately.

Figure 64: Six black 3D printed pieces were made to create a window for the part retrieval bin and a mounting place for the LED backlit longhorn logo

So that the front of the part retrieval bin matches the overall look of the vending machine, 6 parts are 3D printed and glued together to form a window. To assemble the window, the top three parts clip onto the top of the bin, the bottom piece is bolted to the bottom of the bin and the side pieces are glued to hold the entire fixture together. These features can be seen in Figure 64. A foam pad is adhered to the bottom of the retrieval bin to cover up the bolts and to lessen the impact of parts falling into the bin. The middle two 3D printed pieces form a handle for users to pull out the bin.

As part of the aesthetics of the drawer, LED lights run along the top of the bin illuminating the inside of the bin as well as a front panel. Multiple designs for this front panel were modeled and small, sample pieces were printed in order to determine which designs worked best. Figure 65 shows some of these test prints. Full front panels were printed in two different styles before the one on the left of Figure 66 was chosen. This front panel is mounted within the frame created by the black 3D printed pieces and glued into place as shown in Figure 64.

Figure 65: Sample drawer handle LED backlit longhorn logos

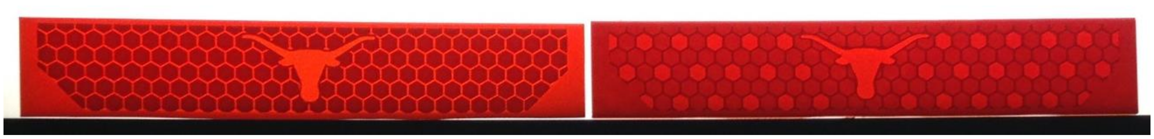


Figure 66: Full drawer handle LED backlit longhorn logos

4.4 CLOSURE

This chapter discusses the effort to make the vending machine enclosure safe, secure, and aesthetically pleasing. Many different techniques were used to maintain the security of the Innovation Station. Locks, vandal proof bolts, and a security camera were all implemented to reduce the opportunity for vandalism or theft. A specially designed retrieval bin allows users to retrieve their parts without accessing the printers themselves. The Innovation Station has a sleek, modern look that incorporates as many functional 3D printed parts as possible in order to inspire the use of 3D printing.

Chapter 5: Online Resources for the Innovation Station

Students access the 3D printers via a web portal by logging on with their student IDs. This website is located at https://innovationstation.utexas.edu/. At this website students can submit their parts, access the software and tutorials for preparing their parts for printing, and review a designer's guide with tips for designing their parts for 3D printing. Figure 67 shows the front page of the Innovation Station in its final version.

Figure 67: Front page of the Innovation Station website

5.1 Part Submission

As shown in Figures 68 and 69, students submit two files associated with their part. The .STL file is submitted and uploaded to the online database so that administrators can review it as needed. The .THING file is used by station administrators to review the user's proposed build orientation, check that parts fit within the dimensional constraints of the

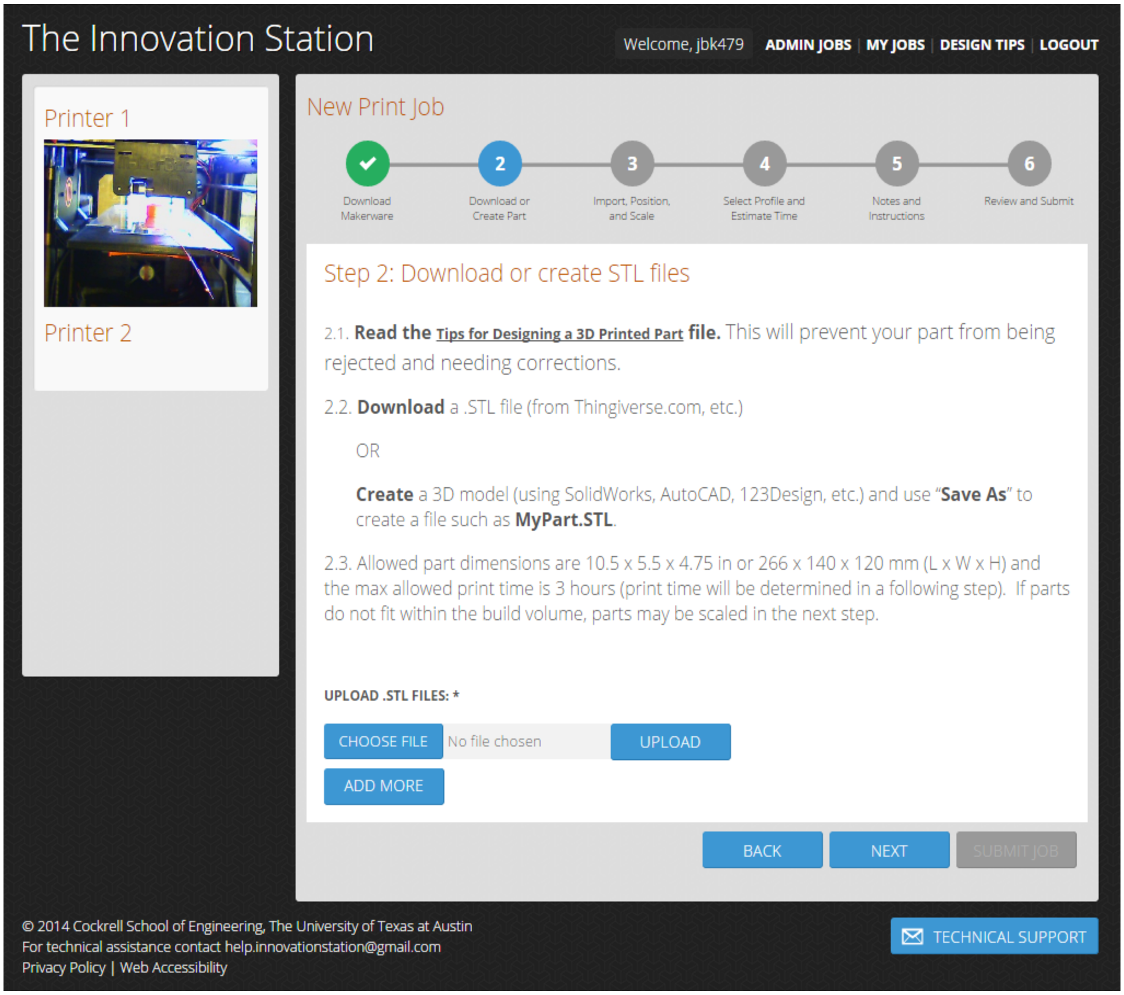


Figure 68: Part submission page

printers, and make suggestions for corrections as needed. It is generated by MakerWare software, which is freely available to students from MakerBot. At the time of the build, the .THING file is sliced by MakerWare software, which also creates the process plan, and the files are transferred directly to the station. Special modifications to the final files operate the heated build plate and the part removal system. Users also upload an estimate of the print time, which is provided by MakerWare software, and choose whether their part needs supports and/or rafts. This is shown in Figure 70. Figure 71 shows how users have the option of what part color they want by selecting the associated printer. In addition,

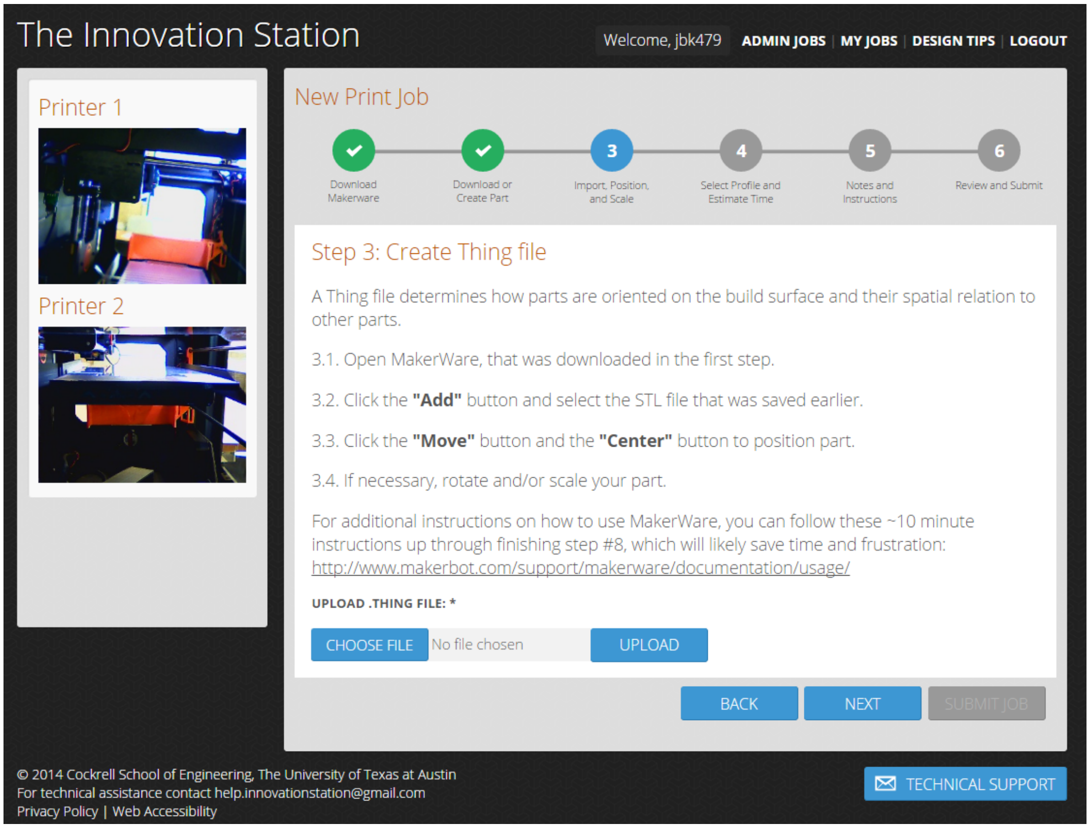


Figure 69: .Thing file submission

there is a place for students to give special instructions to the administrators to inform them that their part is for a class project, etc. The submission pages walk users through the files and the additional instructions they need to upload in a step-by-step manner that is easily followed by first time users.

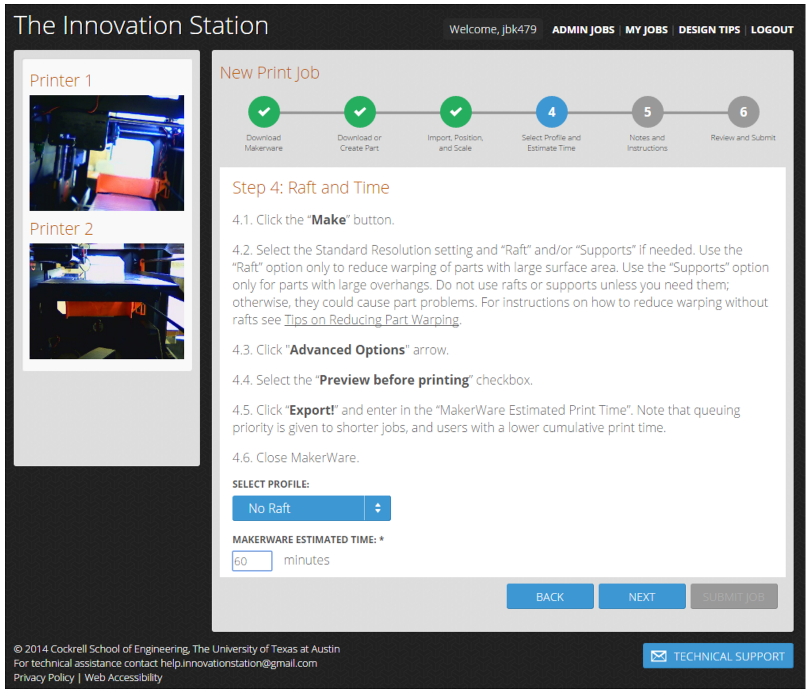


Figure 70: Profile selection and part build time

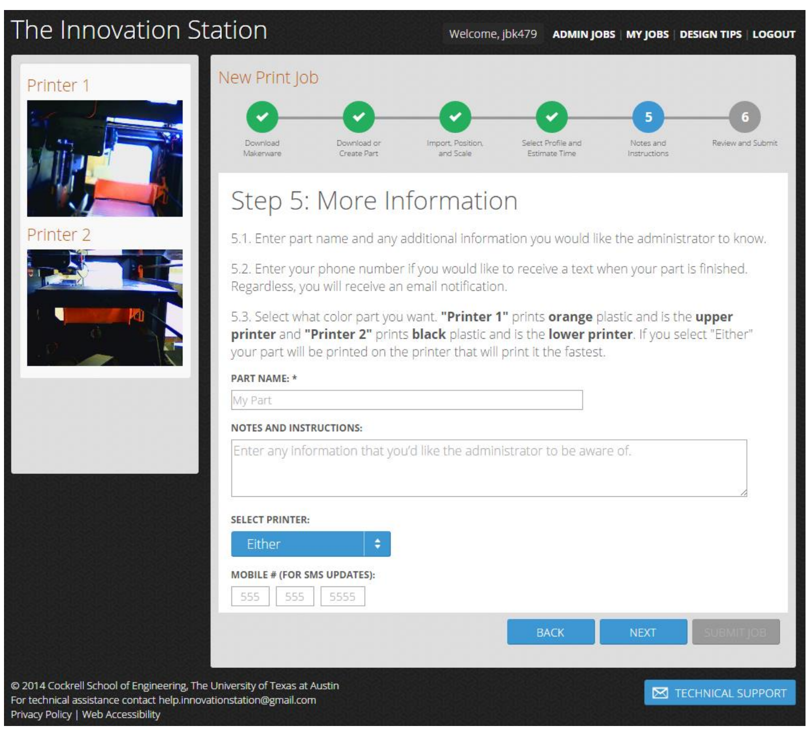


Figure 71: Part name, special instructions for administrators,

5.2 Administrating the Queue

As shown in Figure 72, station administrators can log in to the web portal and view a list of submitted parts and their associated files. Before sending print jobs to the printers each morning, the administrator checks submitted parts for appropriateness, proper build

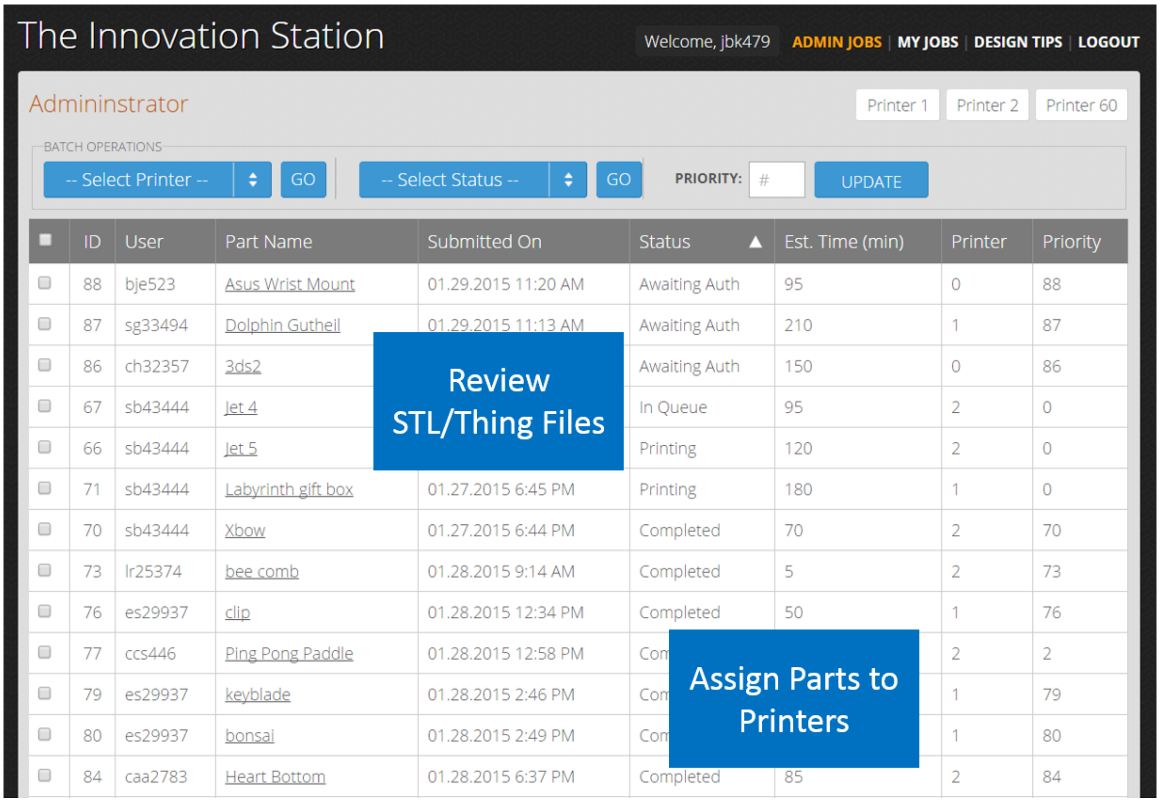


Figure 72: Queuing page as seen by the administrators

orientation, and build time. Certain types of parts do not print well. For example, parts with really small features can cause clogging problems. Administrators allow these parts to be printed once, but if they cause the printers to cancel, they are cancelled and the user is told why their part was not able to print. Parts with unsupported overhangs and/or bridges in addition to parts that have insufficient contact area between the part and the build platform were also parts that sometimes cause problems while printing. These problems can usually be fixed by changing the part orientation or adding supports. When the parts are approved, they are routed into the queue to print automatically in the order in which they are queued. The queue is governed by when the part was submitted, how long the parts take to print, how many parts the student has already printed, whether the part is for a course or personal use, and the filament color chosen.

When the student's part begins to print, they receive a text and/or email alert that the part is printing. Then, the student can view the printing process online via a webcam or go to the lobby of the Mechanical Engineering building to watch their part print in

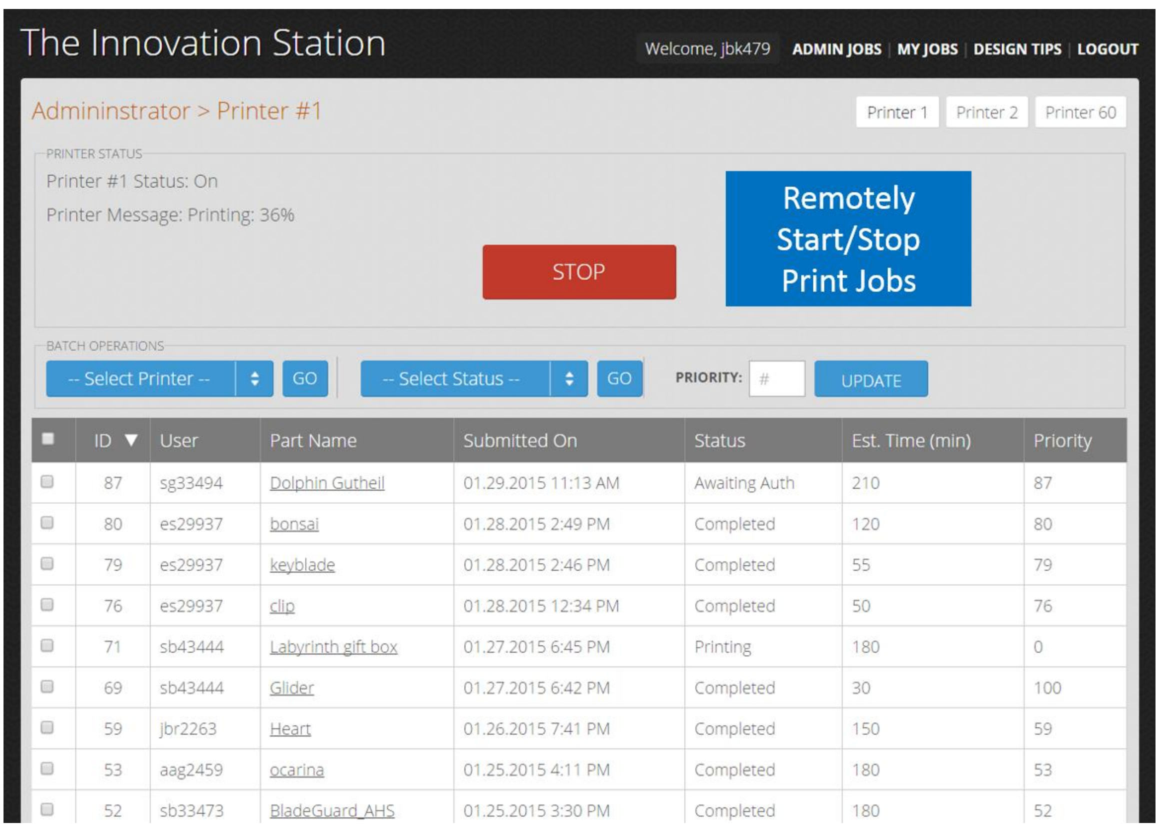


Figure 73: Printer 1 queue with ability to remotely start/stop print jobs

person. The administrator can monitor the webcam throughout the day and remotely stop the queue if any failures are detected as can be seen in 73.

5.3 INSTRUCTING USERS IN DESIGNING PARTS FOR 3D PRINTING

Designing parts for 3D printing is a very different from designing parts for other manufacturing processes and requires some extra instruction for many students. For this purpose, a designer's guide for 3D printing was created and posted on the Innovation Station website. The guide explains how 3D printing works, how to reduce part build time, how to orient and position parts on the build plate, how to post-process parts after printing, and how to reduce part warping. In addition, these guides include information on the tolerances, minimum feature sizes, minimum angle of overhangs, maximum length of overhangs, and maximum length for bridging across a void for a Replicator 2 3D printer. As an example of the type of information provided in the designer's guide, the design team

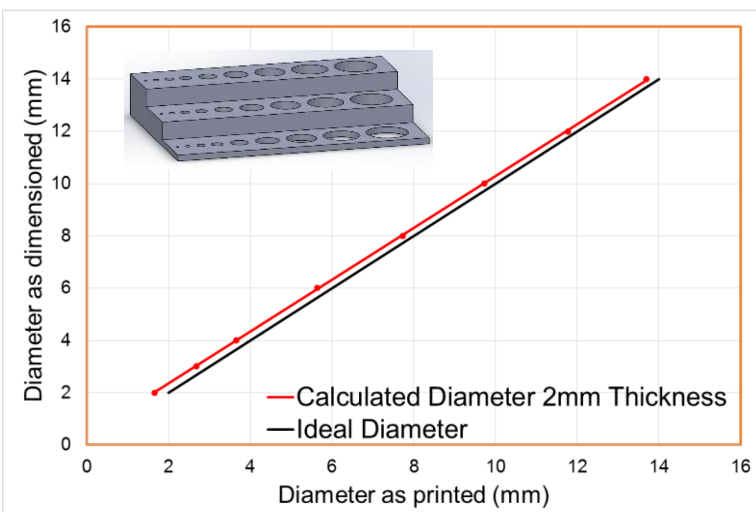


Figure 74: Graph of adjusted diameters needed for vertical through holes

conducted experiments on 3D printed parts with holes to compare the printed diameter of the hole to the original hole dimension in the CAD file. Because of build patterns and the thermal and viscous properties of fused filament plastic, 3D printed parts tend to expand into holes that are printed. This means that if the user wants a ¼" hole they must have a larger dimensioned hole in their CAD model so that the 3D printed hole is actually ¼". As shown in Figure 74, the experiments indicate a linear relationship between the intended and as-printed diameter of the hole. The full designer's guide is in Appendix F.

5.4 CLOSURE

Having an online portal to submit parts is one of the key innovations of this vending machine. It has streamlined the process of printing by allowing users to submit parts from anywhere without having to wait in long lines to use the machine. It also allows users to watch their parts print remotely and informs them when their parts are printing. In addition the online portal gives administrators more control over what is printed and allows for continuous printing and remote stopping of print jobs. The web portal also allows administrators to monitor the usage of the vending machine. The web portal guides users through the entire process of designing parts for printing, creating and submitting the appropriate files, and cleaning parts after printing. The website also supports an online community of makers by making available for download instructions on how to create your own 3D printing vending machine.

Chapter 6: Conclusion

6.1 Summary of work

The Innovation Station is accessible to all UT students and faculty—anyone with a UT Austin electronic ID. It contains two MakerBot Replicator 2 3D printers that have been modified so that they can automatically remove parts after they have been printed. This automatic part removal system uses optimized heating and cooling cycles to reliably detach all printed parts. Then, these parts are swept into a part retrieval bin by an externally powered motor connected to a lead screw and sweeper. Users access their parts via the retrieval bin, which is designed to prevent direct access to the 3D printers and potential vandalism and to protect users from the 230°C extruder head. Instructions for creating and uploading parts are available online, and anyone who wishes to learn 3D CAD modeling can make use of the machine.

6.1.1 Innovations in the Innovation Station

The Innovation Station at UT Austin is an upgrade over previous 3D printing vending machines in various ways. First, UT students upload their parts via an online portal that streamlines the user experience, allowing users to receive design assistance, and administrators to manage the queue easily. In contrast, users of other vending machines must physically queue and upload their parts at the machine itself, sometimes waiting hours in the hallways for the machine to become available. Second, the Innovation Station utilizes a customized automatic part removal system that reliably removes parts from the 3D printer while maintaining a large build volume. Finally, the Innovation Station is constructed with commercially available parts, with construction and assembly instructions to be made available to other educators online via the web portal, so that other schools can replicate the machine.

6.2 USAGE STATISTICS

Many people from all over The University of Texas at Austin used the Innovation Station in its first semester of use. In total 1,206 unique users logged into the Innovation Station with a student ID, which is possible only by UT students, staff, or faculty. The numbers of people who viewed the website could be a lot higher. Staff members and students from at least seven different colleges within the university submitted parts to the vending machine.

Table 3: Usage Statistics for the Innovation Station in its first and last full months of use during the fall semester of 2014

	September	**November**
% Engineering	60%	57%
% Non-Engineering	40%	43%
Of Engineering, % ME	49%	35%
Of Non-Engineering, % College of Natural Sciences	47%	40%
Of Non-Engineering, % College of Liberal Arts	15%	12%
Of Non- Engineering, % College of Business	12%	9%
Of Non- Engineering, % College of Communications	9%	5%
Of Non- Engineering, % Other Colleges	17%	35%

In September 2014, the first month of operation, 186 unique users submitted parts to the Innovation Station for printing. In November, the last month of operation for the fall semester of 2014, 100 unique users submitted parts to the vending machine. As can be seen in Table 3, more engineering students use the Innovation Station than non-engineering students; nevertheless, nearly half of the users were non-engineering students. The table also shows a slight increase of usage by non-engineering students from 40% of the overall usage to 43% of the overall usage over the course of the semester. Of the engineering users, most were mechanical engineers in September, but there was a 14% increase of usage by non-mechanical engineering students by the month of November which shows increasing interest by other engineering students during the semester. Of the non-engineering users the highest percentage were from the College of Natural Sciences followed by the College of Liberal Arts, the McCombs School of Business, and the Moody College of Communications for both months.

Comparing these statistics with the usage of a vending machine at another university shows interesting results. As mentioned previously, Christopher Williams and a team of graduate students from Virginia Tech designed and created the first 3D printing vending machine in 2013 entitled DreamVendor [9]. The following data is taken from the Solid Freeform Fabrication Symposium paper discussing the DreamVendor [9]. It includes initial usage data taken from a survey over the first five months of use of the DreamVendor. As can be seen in Table 4, 92% of the DreamVendor users were engineering students while 59% of the Innovation Station users were engineering students. Far more non-engineering students used the Innovation Station in its first semester of use than the DreamVendor. This could be because of the mass publicity that the Innovation Station received in addition to the ease of uploading parts via the web portal. Of the engineering student users, 71% of the DreamVendor users were mechanical engineering students while 42% of the Innovation Station users were mechanical engineering students. This substantial difference partially explains why significantly more parts were created by the users for the DreamVendor than the users of the Innovation Station. 72% of the DreamVendor users designed the parts that they printed while only 34% of the Innovation Station users designed the parts that they printed. Another factor that likely contributed to this difference is the current popularity of websites like Thingiverse.com from which anyone can download already created .STL files. These .STL files can then directly be 3D printed, eliminating the need for CAD experience to 3D print parts. Thingiverse.com has grown in popularity significantly since the DreamVendor was launched and has many more parts available for downloading, which has allowed many non-engineering students to 3D print parts in the Innovation Station. The percentage of parts printed for class projects or for research purposes was very similar.

Table 4: Usage Comparison between the Innovation Station and the DreamVendor 3D printing vending machines

	Innovation Station	**DreamVendor**
% Engineering	59%	92%
% Non-Engineering	42%	8%
Of Engineering, % ME	42%	71%
Part Downloaded	63%	25%
Part Designed by User	37%	72%
Class Project/Research	18%	16%

During the fall semester of 2014, 824 parts were submitted to the Innovation Station, of which 382 or roughly 46% were printed. The parts that were not printed were reviewed by an administrator and returned to the users with comments on how to fix their parts. Many of these parts were resubmitted and printed successfully. Parts were cancelled for several reasons. Sometimes, the parts exceeded the maximum build time of 180 minutes. In other cases, the parts were not buildable due to excessively small feature sizes, improper orientations on the build plate, lack of support structures for overhangs, and other geometric features that are difficult for the printers to resolve.

Most of the parts printed on the Innovation Station were downloaded from online for personal use, but many parts were personalized or created by users. 63% of the parts printed were downloaded from online sources, primarily from Thingiverse.com or Yobi 3D. Of the parts designed by users it was deemed that 52% were created for either a class project or for research.

The top 10 most popular printed parts are listed as follows with the number of prints indicated in parentheses: Pokémon characters (20), phone cases/accessories (17), longhorns (16), chess pieces (14), microcontroller accessories (9), flexible elephants (8), keychains (7), headphone holders (6), bunnies (5), and companion cubes (4). Some of these parts can be seen in Figure 75. Many of these parts were “trendy” in that soon after one was printed many other users printed the exact same part after seeing it being printed. These trendy parts included the Pokémon characters, longhorns, flexible elephant, bunny, and the companion cube from the video game Portal. The chess pieces were for 3-4 chess sets but took 14 prints to print all the pieces in two colors. Six out of the nine microcontroller accessories were Raspberry Pi cases making them the most common microcontroller accessory.

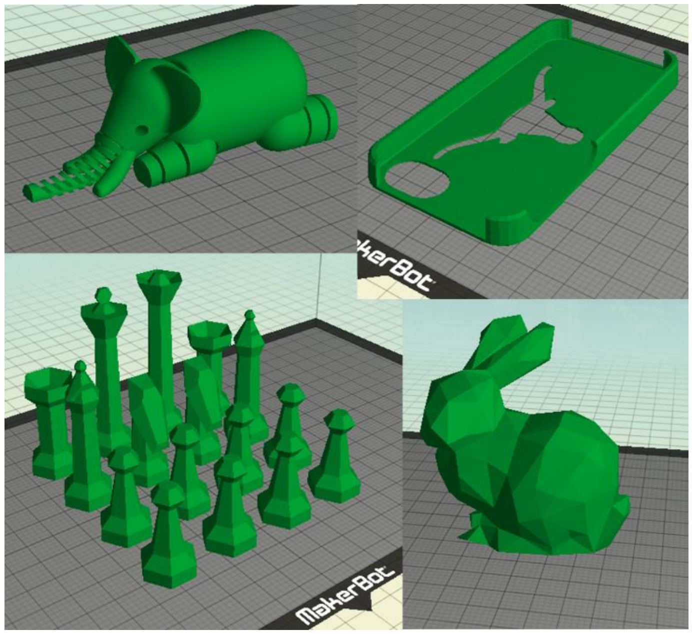


Figure 75: The flexible elephant, a longhorn phone case, a chess set, and the bunny: four of the most popular types of parts printed on the Innovation Station

6.3 FUTURE WORK

Currently some parametric CAD models are being created that will be available for downloading from the website so that those with limited knowledge of CAD systems can print personalized parts. These parts could be useful for K12 outreach activities or for encouraging non-engineering students to experiment with the station. The web portal is in the process of being upgraded to include the ability to download these parametric parts and to download the open source design of the vending machine along with the instructions for constructing it. Design competitions focusing on using the vending machine to create unique parts will be held to inspire future engineers as well as involve non-engineering students in additive manufacturing.

The success of the Innovation Station could someday lead to 3D printing vending machines in hardware stores such as Home Depot or Lowes. Before this could happen increased automation and reliability would be required. Several operational challenges were encountered with the Innovation Station over its first few months of operation. The nozzle frequently clogged, leading to air-printing. The constant printing of complex designs is much more strenuous on the nozzle than standard use and often caused the clogging. Because the Innovation Station has a maximum part build time of 180 minutes, many submitted designs were scaled down versions of other designs. This scaling often led to designs becoming too small and finely detailed to be 3D print-able. This issue in particular was usually, but not always, caught by the screening process during the queueing of parts.

Some other limitations of the station include insufficient ventilation, long cooling times, and part theft. Because of time constraints, the 3D printers were not tested sufficiently while operating inside the Innovation Station enclosure to ascertain how the change in temperature of the environment affected the part removal. In the current configuration, the air temperature increases in the enclosure by 4-5°C when both 3D printers are printing, which has increased the part removal force. Increasing the ventilation, by adding more fans and ventilation holes, should fix this problem. In the current design, forced convection by two fans is used to decrease the temperature of the build plate. To reduce the part removal force sufficiently, this takes 7-12 minutes depending on the part. To increase the rate of cooling, and thereby decrease cooling time, chilled air or liquid cooling could be introduced. This would be more easily achieved by designing a custom 3D printer to seamlessly incorporate this cooling system. There have been some instances of part theft from the Innovation Station. The addition of a security camera and signs have reduced this, but it is still occurring. To eliminate this problem, key pads could be installed requiring users to enter a code they would receive by text or email once their part was finished printing. Lastly, to make this system completely automated a feedback system would need to be added. By integrating sensors into the system, design failures, such as the next part in the queue starting when the sweeper is still on the build plate, could be detected and prevented. The existing cameras could be used, along with image recognition, to detect if a part or the sweeper are on the build plate at the wrong time. Making these improvements, along with further testing, might be enough to bring this technology to a store near you.

6.4 CLOSURE

The Innovation Station is successfully meeting its goals of allowing students at The University of Texas at Austin to fabricate almost any part they can imagine, automatically, in a public university space. In its first semester of operation, more than 800 parts were submitted to the online portal, of which almost 400 were printed. Approximately 75 parts were submitted and 35 parts were printed per week for its first semester of use. If these numbers continue, roughly 2,500 parts will be submitted and 1,150 parts will be printed in the Innovation Station's first year of operation. It is exciting to see that these parts are not only being submitted by engineering students, but also by many students outside the Cockrell School of Engineering, indicating that awareness of 3D printing as a useful technology has increased across campus. These statistics combined with the design team's observations show that the Innovation Station has helped increase student excitement levels about additive manufacturing and making things in general. By using the Innovation Station, students are gaining knowledge of 3D computer-aided design and engineering as well as experience in innovation and design-for-manufacturing by using the vending machine. More importantly, students are learning to think like designers—to formulate and solve open-ended problems and synthesize a real-world product and its manufacturing process. The architects of the Innovation Station believe that this project is beginning to cultivate a new generation of entrepreneurs.

Appendix A: Contextual Needs Assessment

Context Factor	Question Prompts	Response Notes
Task application	What specific purpose(s) will print system be used for? How will the print system be used?	Printing 3D parts for class projects, personal use, research, gifts, and experimentation with 3D printing. Users will submit print jobs online and retrieve parts at some point after they have been ejected from the system.
Task function	What major function(s) should the print system provide?	Intuitive, fast, visible, consistent … see system Hardware and Software working documents for detailed list of functions.
Task quality	What quality of the primary function is needed?	The print quality should not be noticeably degraded from MakerBot Rep2 medium to low-quality settings. The system should crash (hardware &/or software) as little as possible, ideally < 1/month (300 hours run time.)
Task process	What is the current usage process? How will print system change the current usage process?	Users currently submit class or research related SLS jobs with a 1 week turn-around. Parts for a variety of purposes might be submitted online to a service bureau such as Shapeways.
Task frequency	How often will print system be used?	Projection is continuous usage during available hours with jobs ranging from 15min to 6 hours (Between 50 to 2 jobs per 12 hour day, per machine)

Task duration	How long will print system be used each time?	Projection is continuous usage during available hours with jobs ranging from 15min to 6 hours.
Task quantity	How much quantity of the print system's output is needed? At what rate should the print system perform?	Unknown. This may be determined by installing one machine with system modularity such that 1 to 3 more may easily be added.
Task ruggedness	How roughly will print system be handled/treated?	Very little abuse by users is expected beyond heavy fingerprints, possibly attempting to thwart the isolation system to retrieve a jammed part, and possibly kicking or shaking by a disgruntled user ("tilt".) The maintenance team is expected to be careful and reasonably competent.
Transportation type & amount	How often, how far, and in what way will print system be transported?	System transportation is not expected after installation, however individual printers need to be easily swapped in and out for repairs, heavy maintenance, or replacement. Note: need to estimate MTBF for various required maintenance items.
Operator position	What physical position will the user be in (standing, sitting, hands occupied)?	Most users will be: (1) standing watching the printer, (2) at a remote location watching via webcam, or (3) nearby sitting with a laptop to submit the part and watching the machine. Note: a small table to place a laptop table may

		be advantageous for users submitting jobs or maintenance members wanting to hook a laptop to a printer.
Cleaning	How and where might the print system be cleaned?	Routine cleaning of the printers will occur in-place without transportation. Strands of plastic and dust may accumulate.
Surroundings	Where and in what type of surroundings will print system be used? What in the surroundings might influence what the print system must be like?	In the ETC lobby, possibly near the front entrance. ETC occupants will be passing by and small crowds may form at times. The print system should be compatible with the ETC lobby look and feel and conducive to accommodating as many onlookers as possible. Ideally the printer will be <u>visible through an exterior window</u>.
Surroundings (sound)	How noisy are print system surroundings? How much noise from the print system is acceptable?	The lobby ranges from very quiet to very noisy, and the <u>printer should either be located away from quiet study areas, or sound shielded</u> (note printer observers may make additional noise.)
Weather/ climate	What weather/climate will print system be exposed to?	The lobby climate should be stable with normal office temperature and humidity. <u>In the event of building AC failure</u> the machine may overheat. Certain portions of the system such as the power supply and controller board should not be over heated. The Rep2 is rated for 60-90F.

Environment ruggedness	What objects and substances will print system interact with? Will print system be exposed to any unusual substances or conditions?	The isolation system should <u>insure that objects and tools may not be dropped or inserted into the printer encasement.</u> The chance of liquid spills is possible, but fairly low.
Space (when in use)	How much space is available for using print system?	Space is adequate for a housing a handful of printers and a reasonably sized encasement system.
Space (storage)	How and where will print system be stored? How much space is available for storing print system?	The system will be "stored" the same place it is used. <u>An area underneath the active print bay for standby printers</u> may be advantageous.
Aesthetics of surroundings	What do the print system surroundings look like? How should the print system interact w/ the surrounding aesthetics?	The print system should be compatible with the engineering lobby aesthetics. The system will likely become a centerpiece for gathering to watch and converse. Posting information nearby of interest to "makers" and displaying interesting past projects makes sense.
Maintenance & parts cost & availability	What is the cost & availability of maintenance & parts?	Replacement parts are expensive and may have long lead times. <u>Keeping a stock of spare parts</u> may be advantageous.

		Maintenance labor may range from student volunteers to a paid printer maintainer.
Energy availability & cost	What is the cost & availability of possible energy sources (human, battery, gas, electric, biomass, etc.)?	Grid electricity is readily available. Human energy is available when a user claims their part, but not necessarily when the part starts, finishes, and is ejected.
User	Who will use the print system? (Choose it? Buy it?) What user characteristics affect what the print system must be like?	Users: UT faculty, staff, and primarily students. Choosers: 3DVend design team with input from stakeholders. Buyers: UT internal funding. At other institutions the choosers and buyers are likely to be engineering or architecture departments. Students expect a clear, intuitive, robust interface.
User skills & education	How skilled/experienced is the user with the task? What is the user's education level?	Users range from moderate to zero experience with 3D printing. Advanced users are possible as well, but are more likely to access other 3D printing equipment allowing more personal control or quality. Virtually all users are expected to have completed a high school education, and the majority (though not necessarily all) will have a technical orientation.
Physical ability	Does the user have any physical conditions that may cause difficulty	Part retrieval should be ergonomic enough that most of the population can open the parts bin and retrieve parts, and <u>accessible to wheelchair users</u>. Print bed viewing -

	performing the task? (strength, control, range-of-motion, vision).	display via webcam is a plus. Users with computer interface difficulties will likely already have high-contrast screen settings or screen readers in place on their devices.
User tolerance for complexity	What is the most complex print system the user is comfortable using? Must this print system be less complex? How long is user willing to spend learning the print system?	Many users will only be familiar with 2D paper printers, sending email attachments, and uploading files to websites. Using this system should ideally be as intuitive and easy as uploading pictures to facebook. Users will need 10-30 minutes initially installing the software and learning to print a part. <u>Installation of software on lab machines</u> might reduce first usage to 5 minutes. Perhaps the web portal should include <u>"click to print" parts</u> not requiring the user to install 3D printing software.
Relevant customs and practices	Are there any cultural practices or expectations related to this print system?	Parts which are considered inappropriate for public display (e.g. obscene or dangerous) should not be printing since they will be on public display during printing. <u>3D printing has been perhaps over-sold in the popular culture</u> as what will "put stores out of business" because everything can be printed. Users should be clearly informed early in the process of the limitation of this particular 3D printer, and perhaps <u>briefly educated on primary types and costs of 3D printing/Additive Manufacturing</u>.

Cost expectations: (purchase)	About how much is the buyer willing to pay to purchase this print system?	Approximately twice the cost of the 3D printer is a ballpark estimate: $2,200 printer + $2,200 system/printer = $4,500 per printer in the system.$1,000 per printer is a good design target.
Cost expectations: (operation)	How much is the user willing to pay/work monthly to **<u>operate</u>** this print system?	Unknown RE payment. Users are likely willing to spend the 5-10 minutes needed to layout and upload a part.
Cost expectations: (maintenance)	How much is the user willing to pay/work monthly to **<u>maintain</u>** this print system?	Unknown, but a 30min/day maintenance interval is reasonable for a system of 4 machines.
Time expectations: setup & operation	About how much time is the user willing to spend to setup this print system? To operate this print system? How valuable is saving time?	As mentioned in the c3 learning time tolerance above, users will need 10-30 minutes initially installing the software and learning to print a part. Installation of software on lab machines might reduce first usage to 5-10 minutes. Perhaps the web portal should <u>include "click to print" parts</u> not requiring the user to install 3D printing software. User time is not a "cost" to the project, but is inherently valuable and inconveniencing users could lead to reduced usage. On the other hand, having to wait a bit could lead to more careful planning.

Safety expectations	What print system safety concerns does the user have? What safety features is the user expecting? What dangers must be avoided? What is the most dangerous print system familiar to the user? Must this one be less dangerous?	This system should pose no hazards to the user (no more than a 2D printer.) Moderate airflow in the area (already present) is helpful to dissipate possible melted plastic gases. Only authorized maintenance personal should be allowed access to the heated bed (60C) and hot nozzle (230C). A warning sticker "Caution HOT! Heats to 230C / 446F." should be used.
Durability expectations	How long does the user expect the print system to last?	The system should last several years, and with maintenance hopefully the 3D Printers will as well.
Purchase context	Where and how might the print system be purchased? How would the buying decision be made (research, referral, impulse)?	Other academic institutions (6-12 and higher education) will likely see the design showcased at conferences and decide to buy one (if a kit is available) or make one, most likely to be maintained through an existing IT computer lab structure, or possibly through a drafting lab structure (the same individual responsible for maintaining a plotter, for example.) Individuals or institutions simply wanting the automation capability may be interested in open source documentation and/or a kit including only the heated build plate, print head sweep code, and system of pushing a queue of files to the printer.

Appendix B: Vending Machine Bill of Materials

Printer Upgrade:

Description	Dimensions	Amount	Part number	Company	Qty. for one printer	Price	Qty. for two printers	Price		Company	Website
Fan				Amazon	1	$8.95	2	$17.90		Jameco	http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_2099286_-1
Bread board				Amazon	1	$5.95	2	$11.90		BC Technological Solutions	http://www.bctechnologicalsolutions.com/
1pcs DR 4mmx6.35mm D20L25 CNC Stepper Motor Flexible Coupling				Amazon	1	$9.99	2	$19.98		Amazon (fan)	http://www.amazon.com/gp/product/B0054SD8KM/ref=oh_details_o01_s00_i00?ie=UTF8&psc=1
25mm DC 12V 40-50mA 1000RPM Torque Gear Box Motor				Amazon	1	$12.00	2	$24.00		Amazon (collars)	http://www.amazon.com/gp/product/B00A43PRME/ref=oh_aui_detailpage_o08_s00?ie=UTF8&psc=1
Sweeper Power Supply				Amazon	1	$9.38	2	$18.76		Amazon (bread board)	http://www.amazon.com/gp/product/B005GYAIES/ref=ox_sc_act_title_4?ie=UTF8&psc=1&smid=A1LHQ5G6ONPXVT
HBP w/ glass plate (no handles)				BC Technological Solutions	1	$175	2	$350		Amazon (motors)	http://www.amazon.com/gp/product/B005HNHJAO/ref=oh_aui_detailpage_o05_s00?ie=UTF8&psc=1
Power supply for HBP				Jameco	1	$75	2	$150		Amazon (Sweeper power supply)	http://www.amazon.com/gp/product/B00B0SZO0M/ref=oh_details_o05_s00_i00?ie=UTF8&psc=1
# 4-40 bolts and nuts	3/4" Long	bag of 14		Lowe's	1	1.5	2	3		Haydon Kerk	http://www.haydonkerk.com/LinearActuatorProducts/LeadScrewsAndNuts/Nuts/BFWSeriesNuts/tabid/254/Default.aspx
# 4-40 bolts and nuts	1 1/4" Long	bag of 14		Lowe's	1	1.5	2	3		Amazon (motor crimps)	http://www.amazon.com/gp/product/B00G9JOJ8U/ref=oh_aui_detailpage_o05_s00?ie=UTF8&psc=1
Super Glue				Lowe's	1	5	1	5			
#6-32 bolts	1/2" Long	Pack of 100		Lowe's	1	3.5	1	3.5			
Small L brackets	2 holes			Lowe's	2	4	4	8			
Hardened Precision Steel Shaft	5/8" Dia, 3" Long		6061K434	McMaster	2	$8.30	4	$16.60			
Ultra-high-pull Neodymium Disc Magnet	5/8" Dia, 1/8" Thick, 10.8 Pull Lbs, Nickel Plated		5862K86	McMaster	2	$13.20	4	$26.40			
Miniature Snap-Acting Switch	Rigid Lever, 15 Amps, Quick Disconnect		7779K63	McMaster	7	$20.51	14	$41.02			
Set Screw Shaft Collar	For 1/4" Diameter	Black-oxide Steel	9414T6	McMaster	3	$2.76	6	$5.52			
Sae 841 Bronze Flanged-sleeve Bearing	For 1/4" Shaft Diameter, 3/8" Od, 1/4" Length		6338K411	McMaster	2	$1.54	4	$3.08			
Insulated Barrel Quick-Disconnect Terminal (crimps for switches)	Standard Female, 22-18 Awg, .187"w X .02" Thk Tab	Pack of 10	7060K18	McMaster	2	$7.28	4	$14.56			
Bolts for mounting motor 18-8 Stainless Steel Button-Head Socket Cap Screw	M3 Size, 6 mm Length, .5 mm Pitch	Pack of 100	92095A179	McMaster	1	5.06	1	5.06			
2.75 6-32 bolts (for fan)		box of 50	91772A165	McMaster	1	6.66	1	6.66			
Small crimps for motor	3.1mm Wide Female Spade Crimp Terminal Connectors	Pack of 100		Amazon	1	5.43	1	5.43			
Low carbon steel rod		3 ft length	8920K115	McMaster	1	2.46	2	4.47			
Wrap-around Sleeving, Braided	3/4" Id, 3' Long		1459T14	McMaster	1	5.24	2	10.48			
Znc-pltd Grade 2 Stl Nylon-insert Hex Locknut	6-32 Thread Size, 5/16" Width, 11/64" Height	1 pack of 100	90631A007	McMaster	1	2.67	1	2.67			
Uv-resistant Cable Tie Holder, Adhesive Backed,four Way	.19"maximum Tie Width	1 pack of 50	7582K11	McMaster	1	8.53	1	8.53			
Standard Nylon Cable Tie	8"length,2-1/8"bundle Dia,18#tensile Strg,uv Black	1 pack of 100	7130K32	McMaster	1	5.62	1	5.62			
Solid Wire, 300v Ac, 22 Gauge	Black	50 ft	8251T2	McMaster	1	5.91	2	10.74			
Solid Wire, 300v Ac, 22 Gauge	Red	50 ft	8251T3	McMaster	1	5.91	2	10.74			
Znc-pltd Grade 2 Stl Nylon-insert Hex Locknut	4-40 Thread Size, 1/4" Width, 9/64" Height	1 pack of 100	90631A005	McMaster	1	2.55	1	2.55			
Glue gun and glue				Walmart	1	6.45	1	6.45			
Lead screw and nut	20" Long	BFW SERIES: FLANGE MOUNT (Round)	BFWFKR-025-0059-BY20	Haydon Kerk	1	59.56	2	119.12			
				Total for printer upgrade	=	$487.41	=	$902.84			

Innovation Station Enclosure:

ITEM NO.	PART	DESCRIPTION	DIMENSIONS	PART NUMBER	COMPANY	QTY.	Price		Company	Website
1	Front Bottom_inset	1/4" Black Acrylic	39.7" x 24"		ePlastics	1	$0.00		Grainger	http://www.grainger.com/category/80-20/ecatalog/N-1z0zhnpZbjzZbjy?_=1395260029729&perPage=32&requestedPage=4
2	Side Bottom Door_inset	1/4" Black Acrylic	24" x 22.65"		ePlastics	2	$0.00		ePlastics	http://www.eplastics.com/Plastic?search=ACRYCLR0.250
3	Front Acrylic	1/4" Clear Acrylic	39.7" x 24.375"		ePlastics	1	$0.00		Global Industrial	https://www.globalindustrial.com/p/storage/struts-and-framing/8020/4136-4-hole-inside-gusset-corner-bracket-2w
4	Left Side Acrylic_new	1/4" Clear Acrylic	44.75" x 20.65"		ePlastics	2	$0.00		Pricefalls	http://www.pricefalls.com/product/Compx-National-C8043-C415A-14A-Sliding-Door-Lock-Nickel-Key-C415A/4633626
5	Front Acrylic Top	1/4" Clear Acrylic	39.7" x 22.3"		ePlastics	1	$575.40		Best Buy	http://www.bestbuy.com/site/pavilion-slimline-desktop-4gb-memory-500gb-hard-drive/3199387.p?id=1219088677005&skuId=3199387&st=pcmcat143400050013_categoryid$abcat0501000&cp=1&lp=9
6	8020-2317-Caster Wheel Assembly	4" Dia Caster Wheel			Global Industrial	4	$105.20		Tamperproof Screw Co.	http://tamperproof.com/categories/tri-wing.html
7	80-20_39 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	5	$150.60			
8	80-20_24 Inches_insetv3	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
9	80-20_1 Inch	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
10	80-20_14.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
11	80-20_22 Inches_inset	1x1 80/20 rod	Part #: 1010-97		Global Industrial	6	$0.00			
12	80-20_23.875 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	1	$0.00			
13	80-20_25.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
14	80-20_72 Inches	1x1 80/20 rod	Part #: 1010-72		Global Industrial	4	$84.40			
15	4 hole L bracket			Part #: 4115	Global Industrial	8	$33.60			
16	Sliding Door Handle_8020-2887			Part #: 2062	Global Industrial	4	$18.76			
17	Lower Sliding Door Track		39 In Long sections	Part #: 2221	Global Industrial	1	$29.20			
18	Upper Sliding Door Track		39 In Long sections	Part #: 2211	Global Industrial	1	$29.20			
19	2 hole L bracket			Part #: 4119	Global Industrial	20	$60.20			
20	T-Joining Plate_8020			Part #: 4140	Global Industrial	8	$60.80			
21	corner bracket			Part #: 4151	Global Industrial	12	$78.96			
22	Joining plate for drawer cover			Part #: 4150	Global Industrial	8	$45.60			
23	Slide-In T-nuts		1/4-20 Black Zinc	Part #: 3382	Global Industrial	200	$42.00			
24	Button head socket		1/4-20 Black Zinc	Part #: 3061	Global Industrial	200	$46.00			
25	Shipping				Global Industrial		$100.00			
26	Sliding Door Locks	Push Lock	Master Key		Pricefalls/Drill Spot, LLC.	2	$47.30			
27	Bottom shelf_inset	1/2" Thick Wood	39.75" x 22.65"		Lowe's	1	$119.00			
28	Printer shelves_24.0 In	1/2" Thick Wood	39.75" x 23.275"		Lowe's	2	$0.00			
29	Top_24 In_v3	1/2" Thick Wood	41" x 24"		Lowe's	1	$0.00			
30	Drawer cover	1/4" Thick Wood	24" x 16.375"		Lowe's	2	$0.00			
31	Side Wood Panel	1/4" Thick Wood	46.75" x 22.65"		Lowe's	2	$0.00			
32	Window Support	1/4" Thick Wood	19.65" x .65"		Lowe's	2	$0.00			
33	Sliding Door	.2" Thick Wood	47.71" x 20.5"		Lowe's	2	$0.00			
34	Sliding Door Top	.2" Thick Wood	21.625" x 20.5"		Lowe's	2	$0.00			
35	Clear Vending Bin				Lowe's	2	$0.00			
36	Highly Corrosion-resistant 6063 Aluminum, U-channel	1/8" Thick Aluminum	1-3/4" Base, 3/4" Legs, 20" Long	9001K66	McMaster	1	$32.58			
37	Vandal proof Bolts	Tri-Wing, Pan Head, Machine Screw	100 3/4", 10-32 bolts		Tamperproof Screw Co.	1	$28.83			
38	Vandal proof Bolt Driver	W5 Tri-Wing Driver			Tamperproof Screw Co.	1	$8.00			
39	Multipurpose 6061 Aluminum, Rectangular Bar	1/8" x 2", 1/2' Long	for sliding lock mount	8975K582	McMaster	1	1.59			
40	webcams	HDE USB Webcam with LED Lights			Amazon	2	18.88			
41	usb extenders				Amazon	2	11.58			
42	L bracket for drawer cover handle	4 holes			Lowe's	2	4			
43	Computer	HP - Geek Squad Certified Refurbished Desktop - AMD E-Series	4GB Memory - 500GB Hard Drive		Best Buy	2	625.98			
44	power strip				Amazon	2	27.34			
45	ether net cord				Best Buy	2	13.98			
46	10-32 nuts		100 pack	90480A195	McMaster	1	$1.71			
					Total for enclosure only	=	$2,398.98			
					Cost of 2 printers with upgrades	=	4902.84			
					Total cost of vending machine	=	$7,301.82			
					Total cost of vending machine (w/o printers)	=	$3,301.82			

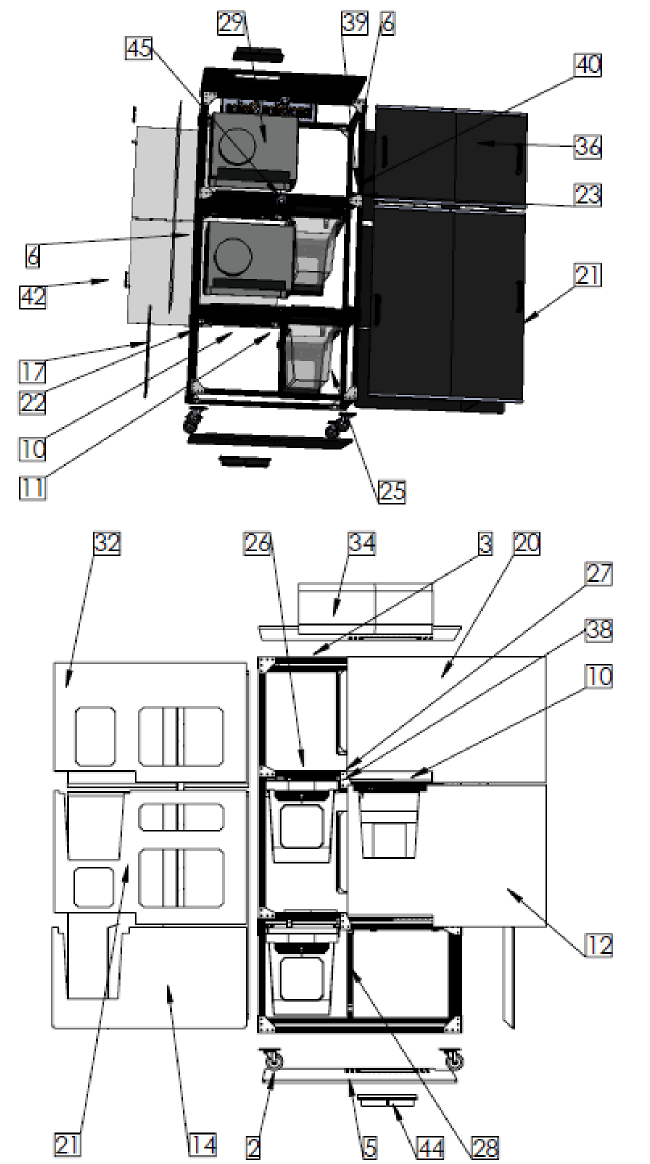
Simple, 2 Printer Enclosure:

ITEM NO.	PART	DESCRIPTION	DIMENSIONS	PART NUMBER	COMPANY	QTY.	Price		Company	Website
1	Front Bottom_inset	1/4" Black Acrylic	39.7" x 24"		ePlastics	1	$0.00		Grainger	http://www.grainger.com/category/80-20/ecatalog/N-1z0zhnpZbjzZbjy?_=1395260029729&perPage=32&requestedPage=4
2	Side Bottom Door_inset	1/4" Black Acrylic	24" x 22.65"		ePlastics	2	$0.00		ePlastics	http://www.eplastics.com/Plastic?search=ACRYCLR0.250
3	Front Acrylic	1/4" Clear Acrylic	39.7" x 24.375"		ePlastics	1	$0.00		Global Industrial	https://www.globalindustrial.com/p/storage/struts-and-framing/8020/4136-4-hole-inside-gusset-corner-bracket-2w
4	Left Side Acrylic_new	1/4" Clear Acrylic	44.75" x 20.65"		ePlastics	2	$0.00		Pricefalls	http://www.pricefalls.com/product/Compx-National-C8043-C415A-14A-Sliding-Door-Lock-Nickel-Key-C415A/4633626
5	Front Acrylic Top	1/4" Clear Acrylic	39.7" x 22.3"		ePlastics	1	$575.40		Best Buy	http://www.bestbuy.com/site/pavilion-slimline-desktop-4gb-memory-500gb-hard-drive/3199387.p?id=1219088677005&skuId=3199387&st=pcmcat143400050013_categoryid$abcat0501000&cp=1&lp=9
6	8020-2317-Caster Wheel Assembly	4" Dia Caster Wheel			Global Industrial	4	$105.20		Tamperproof Screw Co.	http://tamperproof.com/categories/tri-wing.html
7	80-20_39 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	5	$150.60			
8	80-20_24 Inches_insetv3	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
9	80-20_1 Inch	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
10	80-20_14.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
11	80-20_22 Inches_inset	1x1 80/20 rod	Part #: 1010-97		Global Industrial	6	$0.00			
12	80-20_23.875 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	1	$0.00			
13	80-20_25.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
14	80-20_72 Inches	1x1 80/20 rod	Part #: 1010-72		Global Industrial	4	$84.40			
15	4 hole L bracket			Part #: 4115	Global Industrial	8	$33.60			
16	Sliding Door Handle_8020-2887			Part #: 2062	Global Industrial	4	$18.76			
17	Lower Sliding Door Track		39 In Long sections	Part #: 2221	Global Industrial	1	$29.20			
18	Upper Sliding Door Track		39 In Long sections	Part #: 2211	Global Industrial	1	$29.20			
19	2 hole L bracket			Part #: 4119	Global Industrial	20	$60.20			
20	T-Joining Plate_8020			Part #: 4140	Global Industrial	8	$60.80			
21	corner bracket			Part #: 4151	Global Industrial	12	$78.96			
22	Joining plate for drawer cover			Part #: 4150	Global Industrial	8	$45.60			
23	Slide-In T-nuts		1/4-20 Black Zinc	Part #: 3382	Global Industrial	200	$42.00			
24	Button head socket		1/4-20 Black Zinc	Part #: 3061	Global Industrial	200	$46.00			
25	Shipping				Global Industrial		$100.00			
26	Sliding Door Locks	Push Lock	Master Key		Pricefalls/Drill Spot, LLC.	2	$47.30			
27	Bottom shelf_inset	1/2" Thick Wood	39.75" x 22.65"		Lowe's	1	$119.00			
28	Printer shelves_24.0 In	1/2" Thick Wood	39.75" x 23.275"		Lowe's	2	$0.00			
29	Top_24 In_v3	1/2" Thick Wood	41" x 24"		Lowe's	1	$0.00			
30	Drawer cover	1/4" Thick Wood	24" x 16.375"		Lowe's	2	$0.00			
31	Side Wood Panel	1/4" Thick Wood	46.75" x 22.65"		Lowe's	2	$0.00			
32	Window Support	1/4" Thick Wood	19.65" x .65"		Lowe's	2	$0.00			
33	Sliding Door	.2" Thick Wood	47.71" x 20.5"		Lowe's	2	$0.00			
34	Sliding Door Top	.2" Thick Wood	21.625" x 20.5"		Lowe's	2	$0.00			
35	Clear Vending Bin				Lowe's	2	$0.00			
36	Highly Corrosion-resistant 6063 Aluminum, U-channel	1/8" Thick Aluminum	1-3/4" Base, 3/4" Legs, 20" Long	9001K66	McMaster	1	$32.58			
37	Vandal proof Bolts	Tri-Wing, Pan Head, Machine Screw	100 3/4", 10-32 bolts		Tamperproof Screw Co.	1	$28.83			
38	Vandal proof Bolt Driver	W5 Tri-Wing Driver			Tamperproof Screw Co.	1	$8.00			
39	Multipurpose 6061 Aluminum, Rectangular Bar	1/8" x 2", 1/2' Long	for sliding lock mount	8975K582	McMaster	1	1.59			
40	webcams	HDE USB Webcam with LED Lights			Amazon	2	18.88			
41	usb extenders				Amazon	2	11.58			
42	L bracket for drawer cover handle	4 holes			Lowe's	2	4			
43	Computer	HP - Geek Squad Certified Refurbished Desktop - AMD E-Series	4GB Memory - 500GB Hard Drive		Best Buy	2	625.98			
44	power strip				Amazon	2	27.34			
45	ether net cord				Best Buy	2	13.98			
46	10-32 nuts		100 pack	90480A195	McMaster	1	$1.71			
					Total for enclosure only	=	$2,398.98			

Simple, 1 Printer Enclosure:

ITEM NO.	PART	DESCRIPTION	DIMENSIONS	PART NUMBER	COMPANY	QTY.	Price		Company	Website
1	Front Bottom_inset	1/4" Black Acrylic	39.7" x 24"		ePlastics	1	$0.00		Grainger	http://www.grainger.com/category/80-20/ecatalog/N-1z0zhnpZbjzZbjy?_=1395260029729&perPage=32&requestedPage=4
2	Side Bottom Door_inset	1/4" Black Acrylic	24" x 22.65"		ePlastics	2	$0.00		ePlastics	http://www.eplastics.com/Plastic?search=ACRYCLR0.250
3	Front Acrylic	1/4" Clear Acrylic	39.7" x 24.375"		ePlastics	1	$0.00		Global Industrial	https://www.globalindustrial.com/p/storage/struts-and-framing/8020/4136-4-hole-inside-gusset-corner-bracket-2w
4	Left Side Acrylic_new	1/4" Clear Acrylic	44.75" x 20.65"		ePlastics	2	$0.00		Pricefalls	http://www.pricefalls.com/product/Compx-National-C8043-C415A-14A-Sliding-Door-Lock-Nickel-Key-C415A/4633626
5	Front Acrylic Top	1/4" Clear Acrylic	39.7" x 22.3"		ePlastics	1	$575.40		Best Buy	http://www.bestbuy.com/site/pavilion-slimline-desktop-4gb-memory-500gb-hard-drive/3199387.p?id=1219088677005&skuId=3199387&st=pcmcat143400050013_categoryid$abcat0501000&cp=1&lp=9
6	8020-2317-Caster Wheel Assembly	4" Dia Caster Wheel			Global Industrial	4	$105.20		Tamperproof Screw Co.	http://tamperproof.com/categories/tri-wing.html
7	80-20_59.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	4	$146.60			
8	80-20_24 Inches_insetv3	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
9	80-20_1 Inch	1x1 80/20 rod	Part #: 1010-97		Global Industrial	1	$0.00			
10	80-20_14.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	1	$0.00			
11	80-20_22 Inches_inset	1x1 80/20 rod	Part #: 1010-97		Global Industrial	4	$0.00			
12	80-20_36.725 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	1	$0.00			
13	80-20_34 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	2	$0.00			
14	80-20_21.5 Inches	1x1 80/20 rod	Part #: 1010-97		Global Industrial	1	$0.00			
15	4 hole L bracket	Part #: 4115			Global Industrial	6	$25.20			
16	Sliding Door Handle_8020-2887	Part #: 2062			Global Industrial	2	$9.38			
17	Lower Sliding Door Track	Part #: 2221	39 In Long sections		Global Industrial	1	$29.20			
18	Upper Sliding Door Track	Part #: 2211	39 In Long sections		Global Industrial	1	$29.20			
19	2 hole L bracket	Part #: 4119			Global Industrial	20	$60.20			
20	T-Joining Plate_8020	Part #: 4140			Global Industrial	5	$38.00			
21	corner bracket	Part #: 4151			Global Industrial	12	$78.96			
22	Joining plate for drawer cover	Part #: 4150			Global Industrial	6	$34.20			
23	Slide-In T-nuts	Part #: 3382	1/4-20 Black Zinc		Global Industrial	200	$42.00			
24	Button head socket	Part #: 3061	1/4-20 Black Zinc		Global Industrial	200	$46.00			
25	Shipping				Global Industrial		$100.00			
26	Sliding Door Locks	Push Lock	Master Key		Pricefalls/Drill Spot, LLC.	1	$23.65			
27	Bottom shelf_inset	1/2" Thick Wood	39.75" x 22.65"		Lowe's	1	$119.00			
28	Printer shelves_24.0 In	1/2" Thick Wood	39.75" x 23.275"		Lowe's	1	$0.00			
29	Top_24 In_v3	1/2" Thick Wood	41" x 24"		Lowe's	1	$0.00			
30	Drawer cover	1/4" Thick Wood	24" x 16.375"		Lowe's	1	$0.00			
31	Side Wood Panel	1/4" Thick Wood			Lowe's	2	$0.00			
32	Window Support	1/4" Thick Wood	19.65" x .65"		Lowe's	1	$0.00			
33	Sliding Door	.2" Thick Wood	47.71" x 20.5"		Lowe's	2	$0.00			
34	Clear Vending Bin				Lowe's	1	$0.00			
35	Highly Corrosion-resistant 6063 Aluminum, U-channel	1/8" Thick Aluminum	1-3/4" Base, 3/4" Legs, 20" Long	9001K66	McMaster	1	$20.20			
36	Vandal proof Bolts	Tri-Wing, Pan Head, Machine Screw	100 3/4", 10-32 bolts		Tamperproof Screw Co.	1	$28.83			
37	Vandal proof Bolt Driver	W5 Tri-Wing Driver			Tamperproof Screw Co.	1	$8.00			
38	Multipurpose 6061 Aluminum, Rectangular Bar	1/8" x 2", 1/2' Long	for sliding lock mount	8975K582	McMaster	1	1.59			
39	Webcams	HDE USB Webcam with LED Lights			Amazon	1	9.44			
40	USB extenders				Amazon	1	5.79			
41	L bracket for drawer cover handle	4 holes			Lowe's	2	2			
42	Computer	HP - Geek Squad Certified Refurbished Desktop - AMD E-Series	4GB Memory - 500GB Hard Drive		Best Buy	1	312.99			
43	Power strip				Amazon	1	13.67			
44	Ether net cord				Best Buy	1	6.99			
45	10-32 nuts		100 pack	90480A195	McMaster	1	$1.71			
					Total for enclosure only	=	$1,871.69			

Appendix C: Vending Machine CAD Model Exploded Views



ITEM NO.	PART NUMBER	QTY.
2	8020-2317-Caster Wheel Assembly	4
3	80-20_34 inches	5
4	80-20_24 inches_insetv3	2
5	Bottom shelf_inset	1
6	80-20_66 inches	4
7	Printer shelves_IS	2
8	80-20_22 inches_inset	6
9	C-channel	4
10	80-20_21.5 inches	2
11	2 hole L bracket	9
12	Front Acrylic	1
13	Top_IS	1
14	Front Bottom_inset_2P	1
15	Right Side Acrylic_2P	1
16	Drawer cover_IS	2
17	Side Bottom Door_inset_2P	2
18	Side Wood Panel_IS	2
19	Window Support_black	2
20	Front Acrylic Top	1
21	Sliding Bottom Door Assembly_IS_v2	1
22	1 hole L bracket	14
23	Tepee Joining Plate_8020	8
24	corner bracket	12
25	Vending Bin_Lowes	2
26	80-20_14.5inches	2
27	80-20_1 inch	2
28	Bottom shelf support_2P	1
	80-20_17.875 inches	1
29	MakerBot_Rep2	2
31	Front Middle windows	1
32	Front Top windows	1
33	Drawer Assm	2
34	Sign V4 JK_hollow_Innovation_v3	1
35	Sign V4 JK_hollow v3_Station	1
36	Sliding Top Door Assembly_IS	1
37	Handle v2	2
38	Tepee_Half_Joining Plate_8020	8
39	Door clasp 1 v2	2
40	Door clasp 2 v2	2
41	Left Side Acrylic_2P	1
42	Hinge_1798A250	2
43	Side Door Lock	2
44	Enclosure Cooling Fans	2
45	Push Lock Assembly	2
46	Ramp Assem	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

SolidWorks Student Edition.
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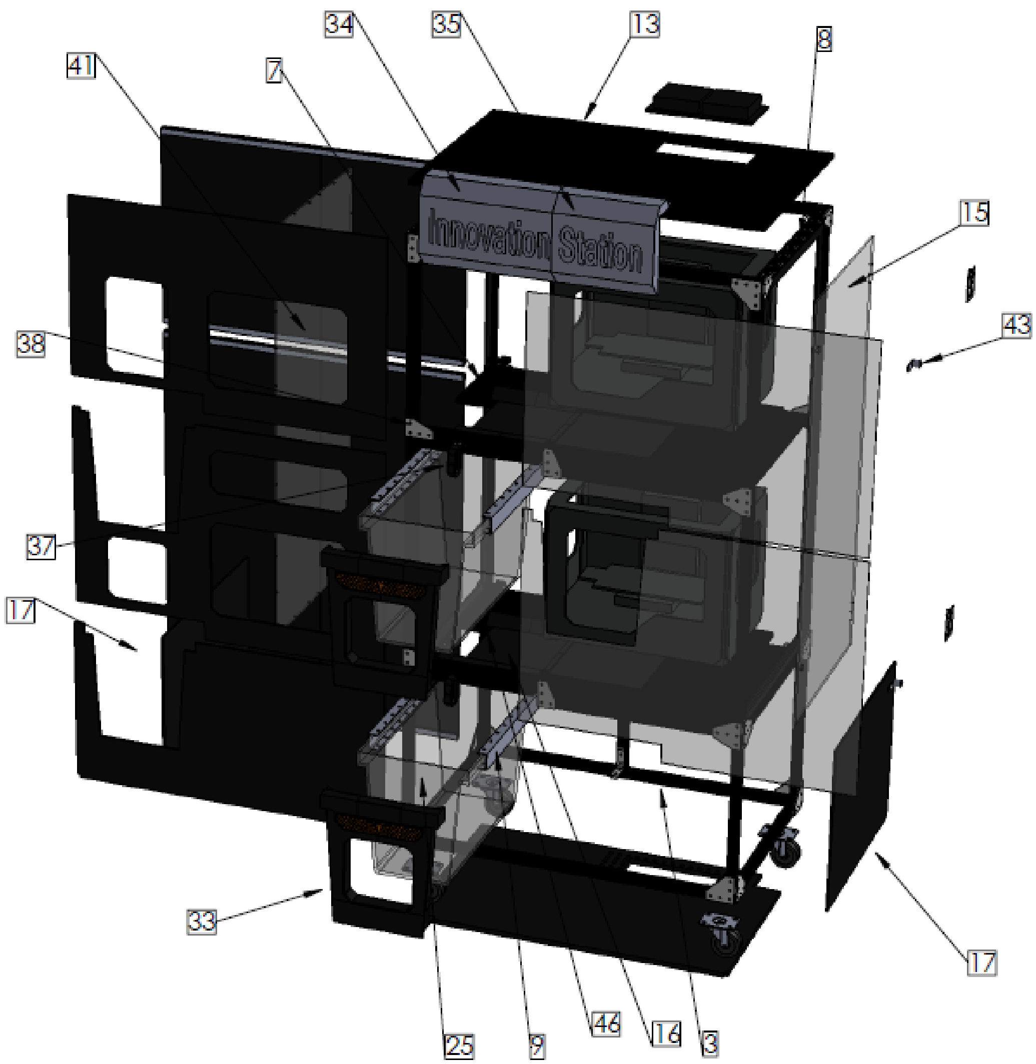
DWG NO.
Innovation Station_EXP

A4

WEIGHT:

SCALE:1:50

SHEET 1 OF 2



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MATERIAL:

WEIGHT:

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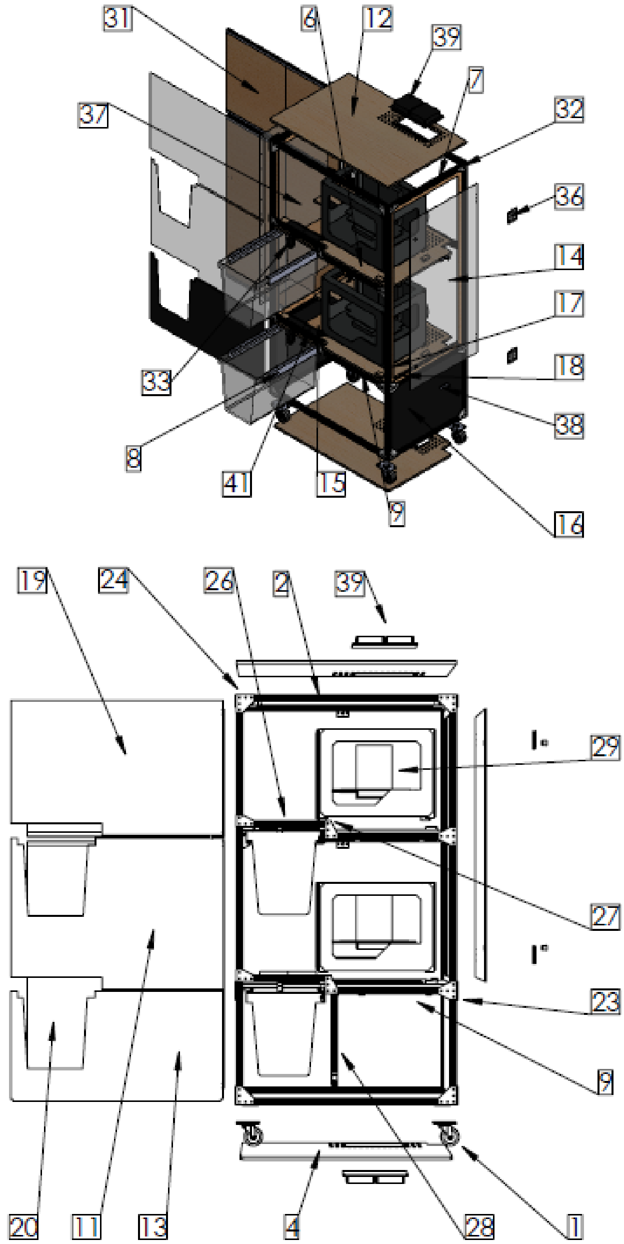
DWG NO.
Innovation Station_EXP

A4

SCALE:1:50

SHEET 2 OF 2



ITEM NO.	PART NUMBER	QTY.
1	8020-2317-Caster Wheel Assembly	4
2	80-20_34 Inches	6
3	80-20_24 Inches_insetv3	2
4	Bottom shelf_inset	1
5	80-20_66 Inches	4
6	Printer shelves_24.0 In	2
7	80-20_22 Inches_inset	6
8	C-channel	4
9	80-20_21.5 Inches	2
10	2 hole L bracket	9
11	Front Acrylic	1
12	Top_24 In_v3	1
13	Front Bottom_inset_2P	1
14	Right Side Acrylic_2P	1
15	Drawer cover	2
16	Side Bottom Door_inset_2P	2
17	Side Wood Panel_2P	2
18	Window Support_wood	2
19	Front Acrylic Top	1
20	Sliding Bottom Door Assembly_2P	1
	2221 X 48	1
	Sliding Door_2P_plain	2
	Back Door Bottom_wood_2P	1
	Sliding Door Handle_8020-2887	1
	2211 X 48	1
22	1 hole L bracket	14
23	Tepee Joining Plate_8020	8
24	corner bracket	12
25	Vending Bin_Lowes	2
26	80-20_14.5Inches	2
27	80-20_1 Inch	2
28	Bottom shelf support_2P	1
	80-20_17.875 Inches	1
	2 hole L bracket	3
29	MakerBot_Rep2	2
31	Sliding Top Door Assembly_plain	1
	2221 X 48	1
	2211 X 48	1
	Sliding Back Door Top_wood	3
	Sliding Door Handle_8020-2887	3
32	Tepee_Half_Joining Plate_8020	8
33	Handle v2	2
34	Door clasp 1 v2	2
35	Door clasp 2 v2	2
36	Hinge_1798A250	2
37	Left Side Acrylic_2P	1
38	Side Door Lock	2
39	Enclosure Cooling Fans	2
40	Push Lock Assembly	2
41	Ramp Assem	2

UNLESS OTHERWISE SPECIFIED:
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MATERIAL:

TITLE:

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2P Vending Machine_EXP

A4

WEIGHT:

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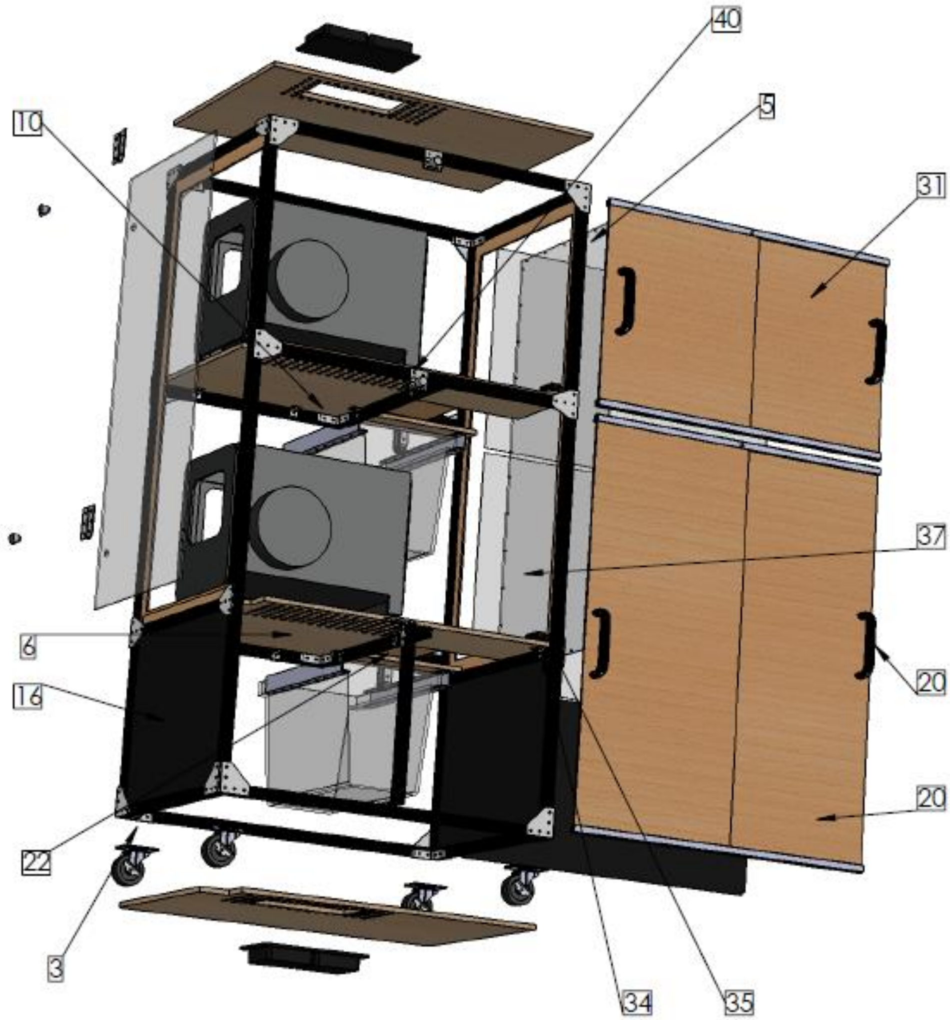
SHEET 1 OF 2



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2P Vending Machine_EXP

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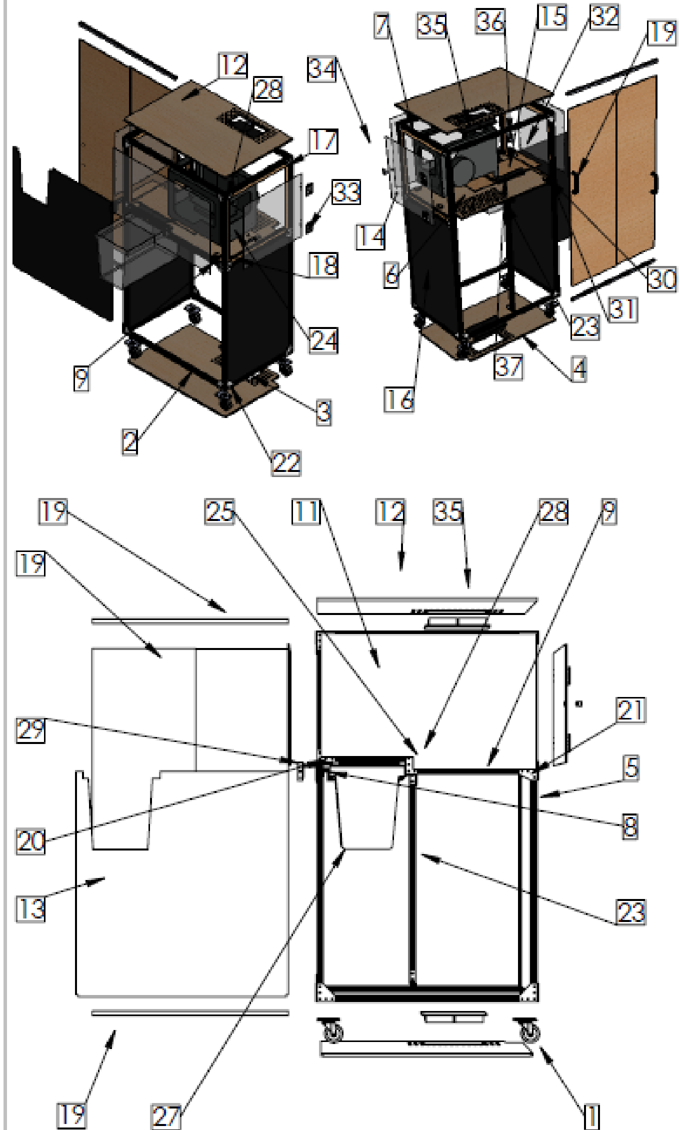
SCALE:1:50

SHEET 2 OF 2



ITEM NO.	PART NUMBER	QTY.
1	8020-2317-Caster Wheel Assembly	4
2	80-20_34 Inches	4
3	80-20_24 Inches_insetv3	2
4	Bottom shelf_inset	1
5	80-20_59.5 Inches	4
6	Printer shelves_24.0 In	1
7	80-20_22 Inches_inset	5
8	C-channel	2
9	80-20_21.5 Inches	1
10	2 hole L bracket	3
11	Front Acrylic	1
12	Top_24 In_v3	1
13	Front Bottom_inset_1P	1
14	Right Side Acrylic_1P	1
15	Drawer cover	1
16	Side Bottom Door_inset_1P	2
17	Side Wood Panel_1P	2
18	Window Support_wood	2
19	Sliding Bottom Door Assembly_1P	1
	2221 X 48	1
	Sliding Door_1P	2
	Sliding Back Door Bottom_wood_1P	1
	Sliding Door Handle_8020-2887	1
	2211 X 48	1
20	1 hole L bracket	3
21	Tepee Joining Plate_8020	5
22	corner bracket	12
23	Bottom shelf support_1P	1
	80-20_36.725 Inches	1
	2 hole L bracket	3
24	MakerBot_Rep2	1
25	80-20_1 Inch	1
26	80-20_14.5Inches	1
27	Vending Bin_Lowes	1
28	Tepee_Half_Joining Plate_8020	6
29	Handle v2	1
30	Door clasp 1 v2	1
31	Door clasp 2 v2	1
32	Left Side Acrylic_1P	1
33	Hinge_1798A250	2
34	Side Door Lock	1
35	Enclosure Cooling Fans	2
36	Push Lock Assembly	1
	Sliding Lock Mount	1
	Sliding Door Push Lock	1
37	Ramp Assem	1

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DWG NO.

1P Vending Machine_EXP

A4

WEIGHT:

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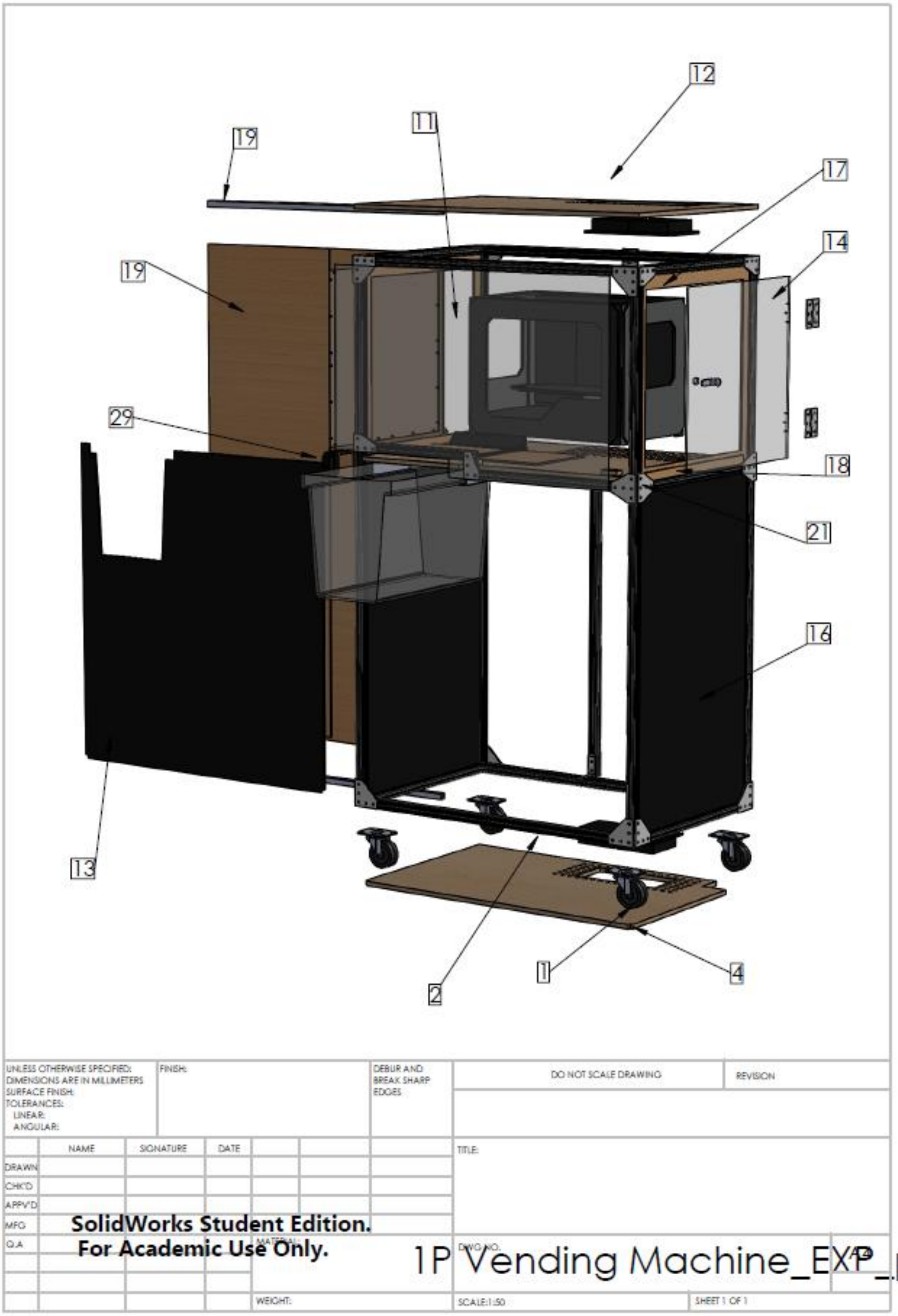
SHEET 1 OF 1



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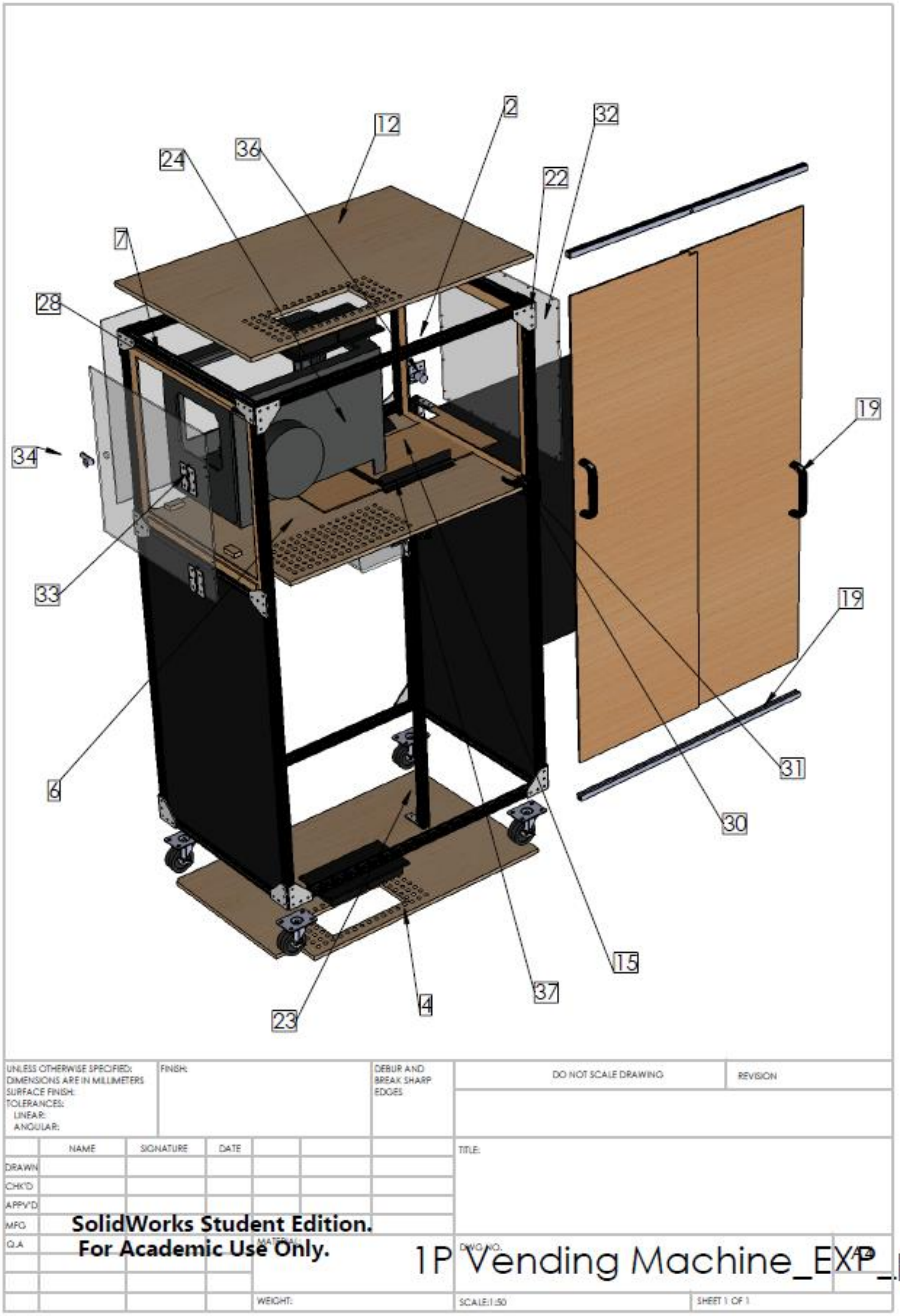
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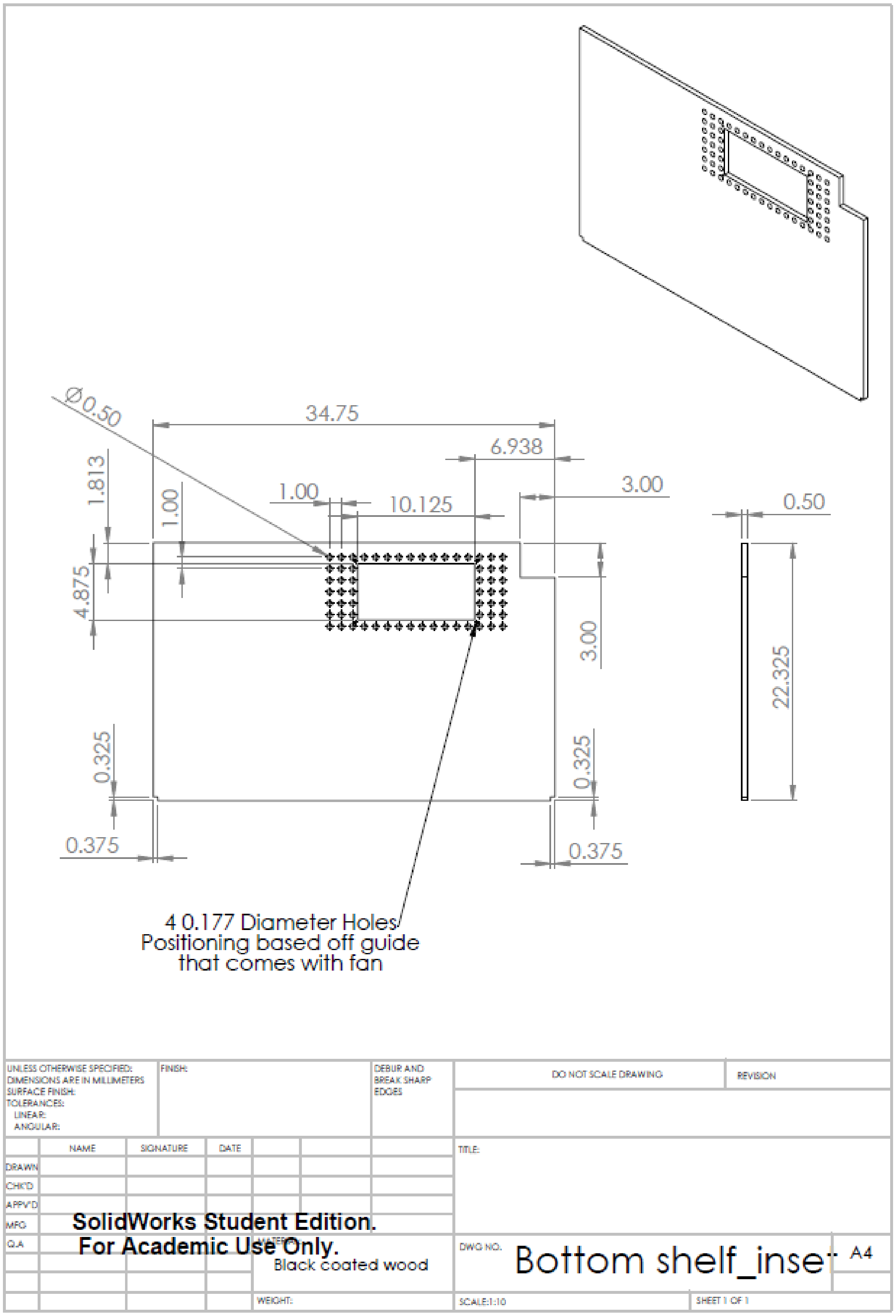

Ø0.50
34.75
6.938
1.813
1.00
1.00
10.125
3.00
0.50
4.875
3.00
22.325
0.325
0.325
0.375
0.375
4 0.177 Diameter Holes
Positioning based off guide
that comes with fan
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MATERIAL:
Black coated wood
DWG NO.
Bottom shelf_inse
A4
WEIGHT:
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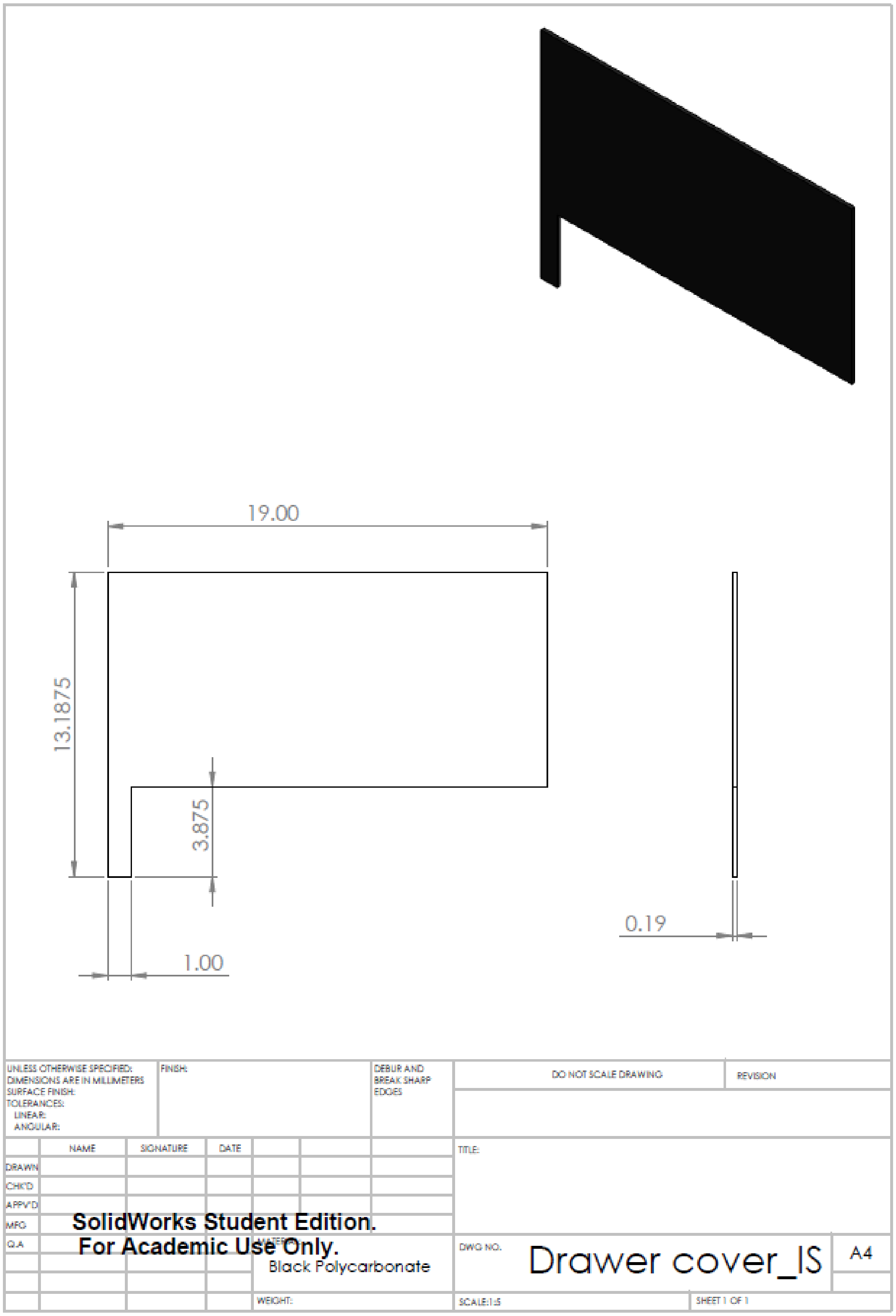
SHEET 1 OF 1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13.1875
3.875
1.00
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APPV'D
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TITLE:
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MATERIAL:
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DWG NO.
Drawer cover_IS
A4
WEIGHT:
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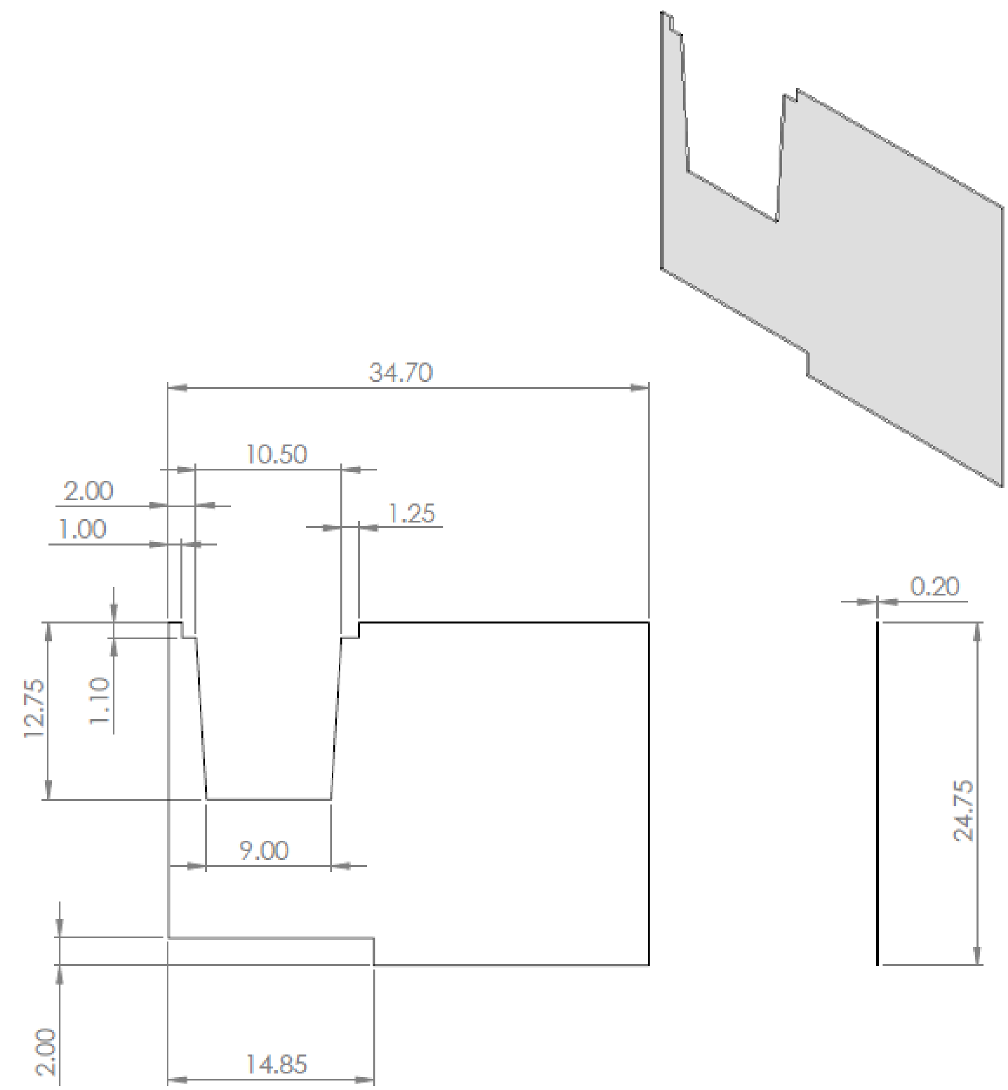
SHEET 1 OF 1



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REVISION

	NAME	SIGNATURE	DATE
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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Clear Acrylic

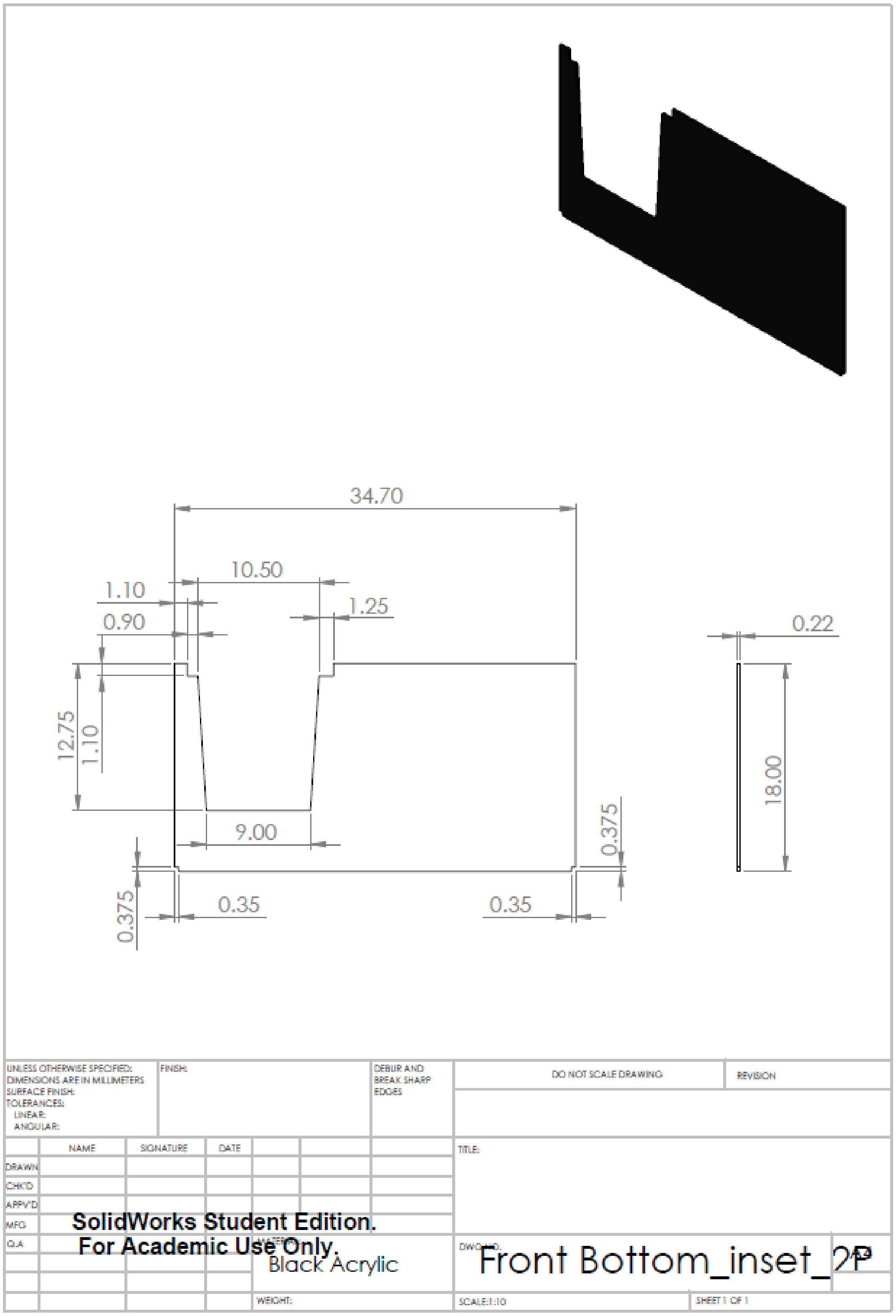
DWG NO.
Front Acrylic

A4

WEIGHT:

SCALE:1:10

SHEET 1 OF 1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10.50
1.10
0.90
1.25
12.75
1.10
9.00
0.375
0.35
0.35
0.375
0.22
18.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
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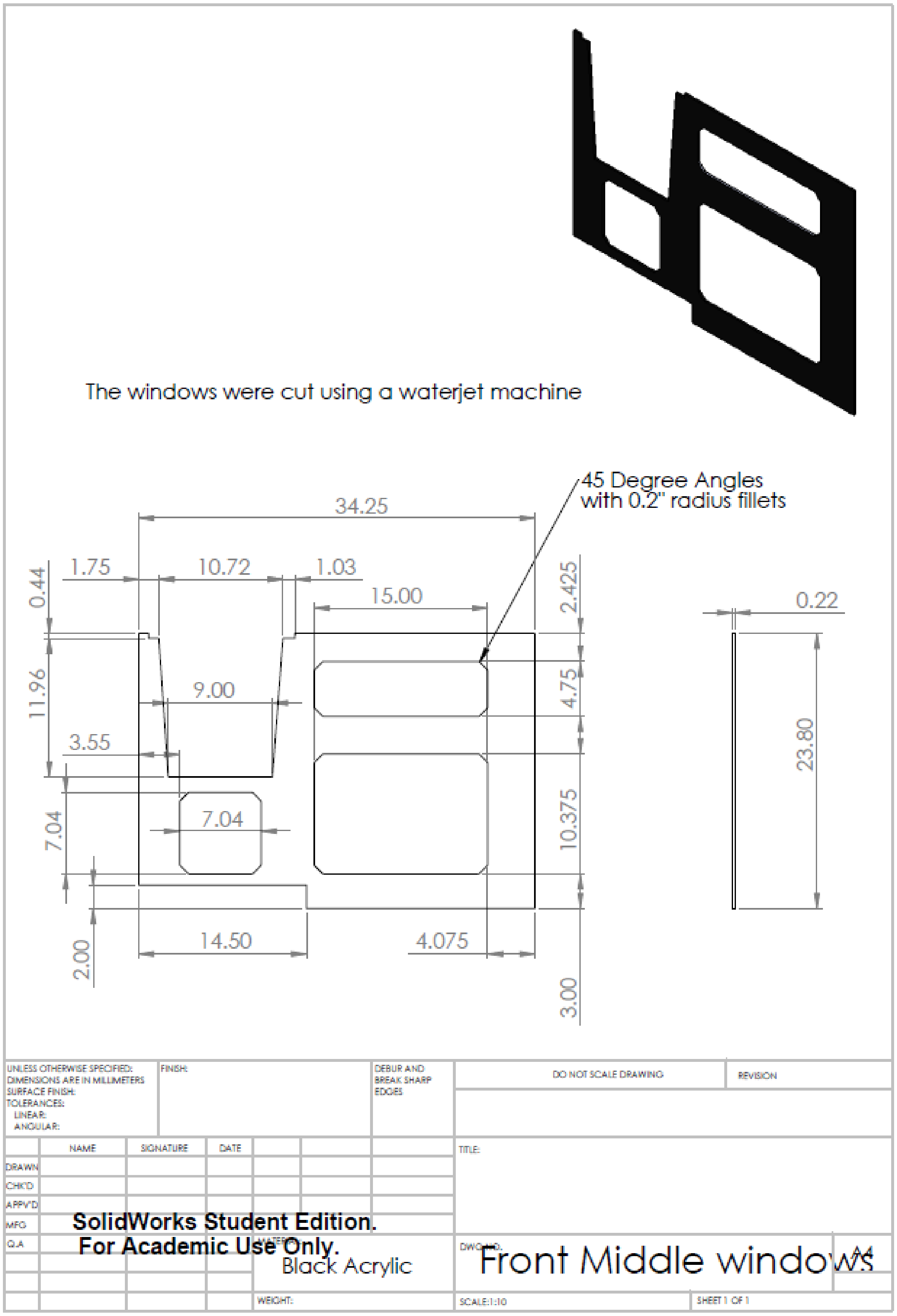
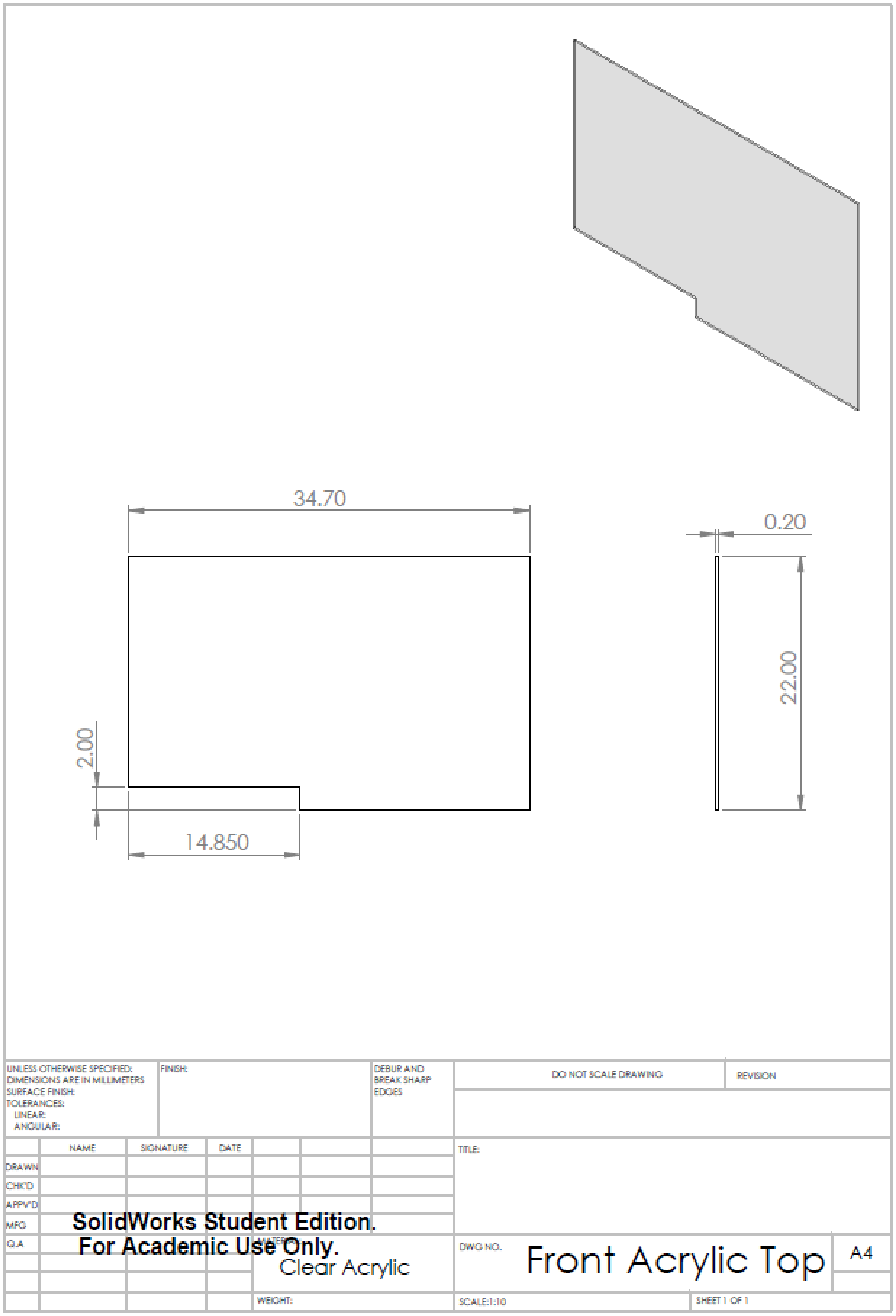
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
SolidWorks Student Edition.
For Academic Use Only.
MATERIAL:
Black Acrylic
DWG NO.
Front Bottom_inset_2P
A4
WEIGHT:
SCALE:1:10
SHEET 1 OF 1



The windows were cut using a waterjet machine
45 Degree Angles
with 0.2" radius fillets
34.25
1.75
10.72
1.03
15.00
0.44
2.425
0.22
11.96
9.00
4.75
3.55
23.80
7.04
7.04
10.375
2.00
14.50
4.075
3.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
SolidWorks Student Edition.
For Academic Use Only.
MATERIAL:
Black Acrylic
DWG NO.
Front Middle windows
A4
WEIGHT:
SCALE:1:10
SHEET 1 OF 1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22.00
2.00
14.850
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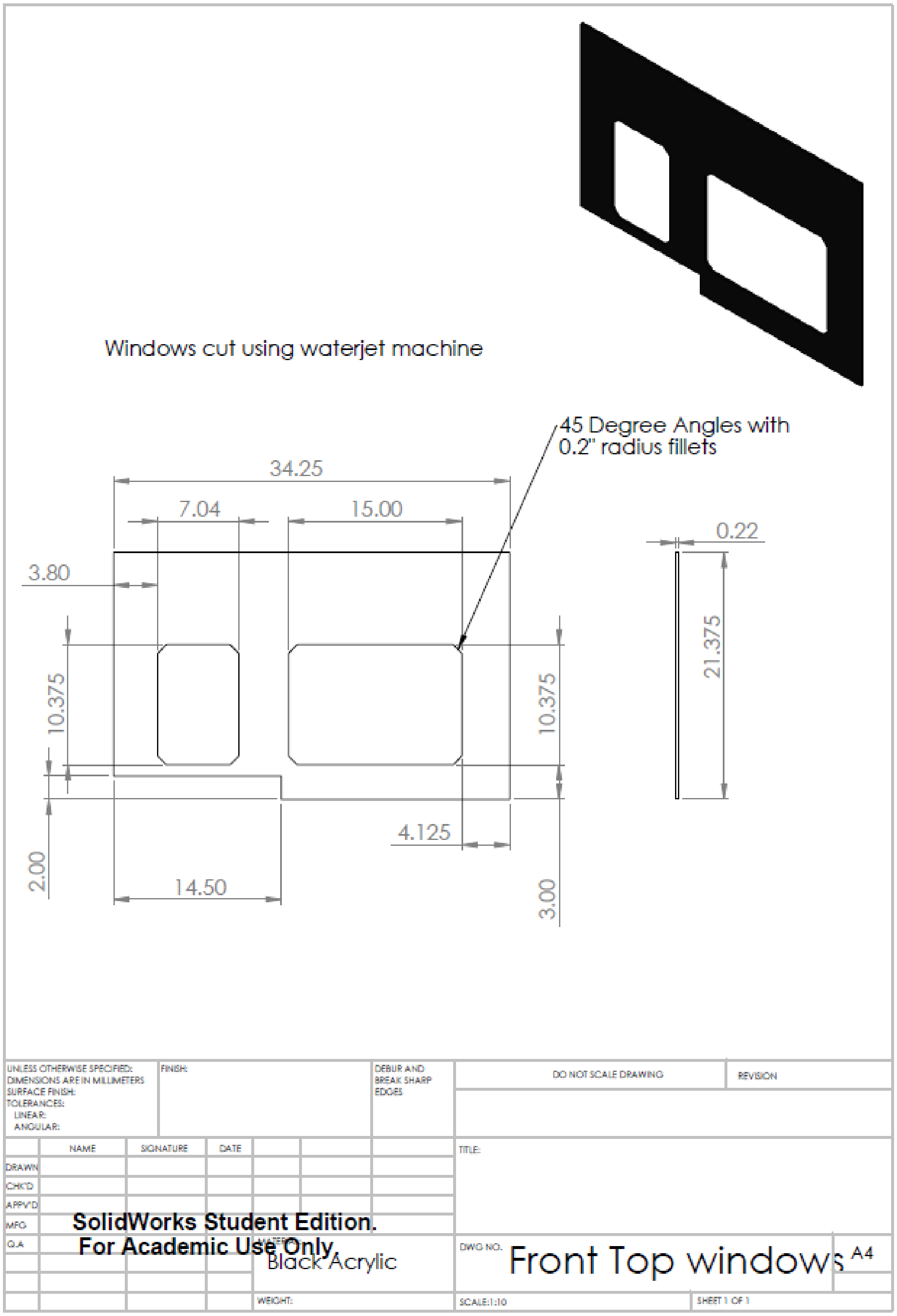
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
SolidWorks Student Edition.
For Academic Use Only.
MATERIAL:
Clear Acrylic
DWG NO.
Front Acrylic Top
A4
WEIGHT:
SCALE:1:10
SHEET 1 OF 1


Windows cut using waterjet machine
45 Degree Angles with
0.2" radius fillets
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7.04
15.00
3.80
10.375
10.375
0.22
21.375
4.125
2.00
14.50
3.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
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CHK'D
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MFG
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TITLE:
SolidWorks Student Edition.
For Academic Use Only.
MATERIAL:
Black Acrylic
DWG NO.
Front Top windows
A4
WEIGHT:
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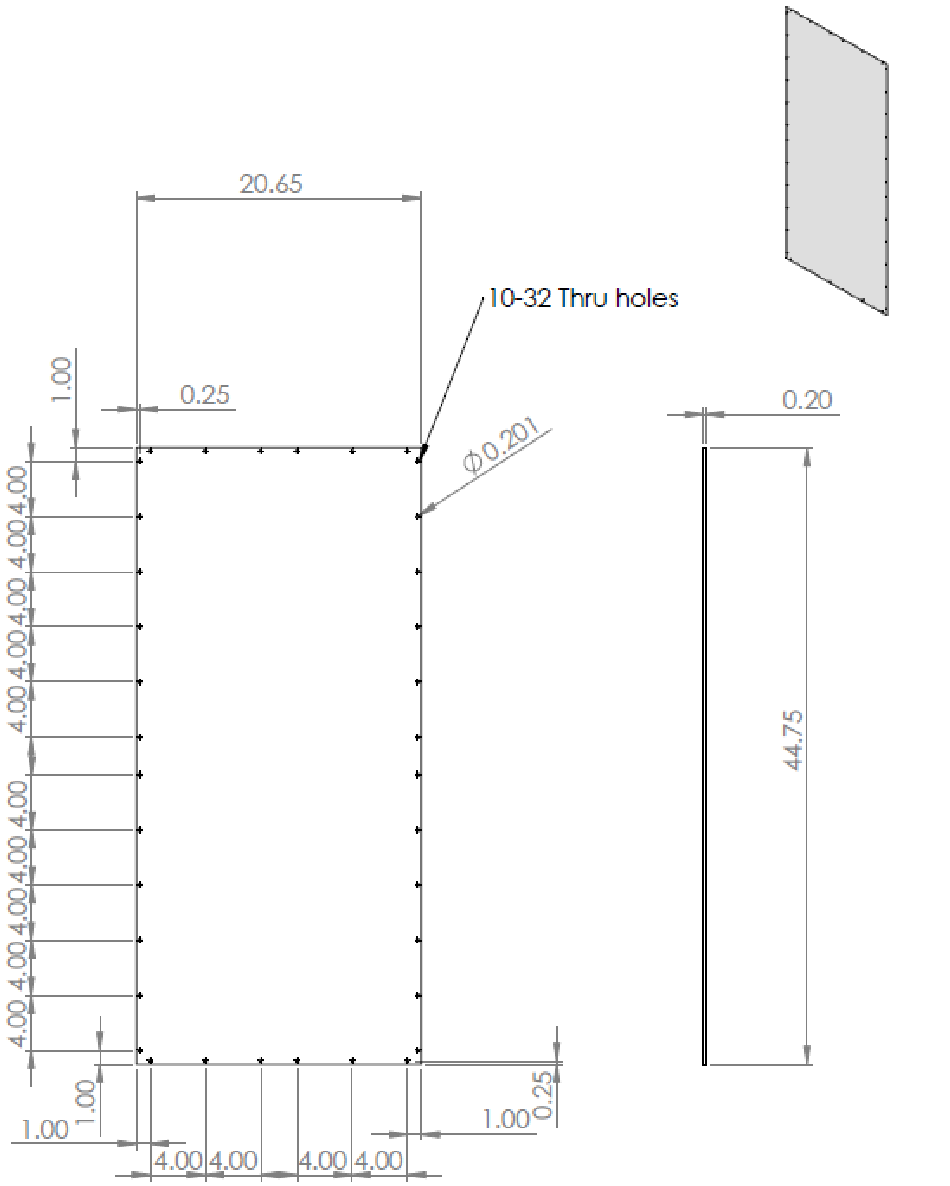
SHEET 1 OF 1



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DEBUR AND BREAK SHARP EDGES

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TITLE:

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DWG NO. Left Side Acrylic_2

A4

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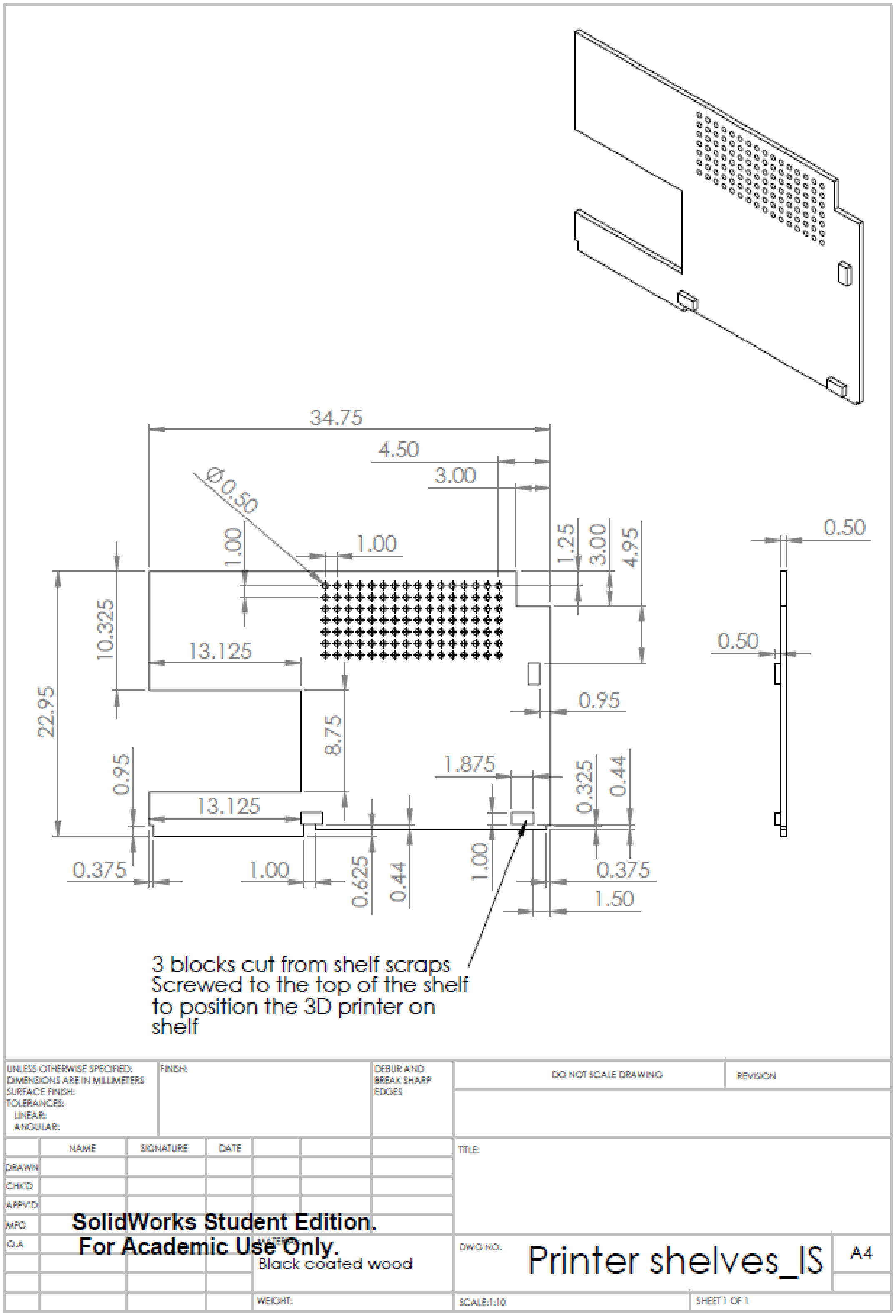
SHEET 1 OF 1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Screwed to the top of the shelf
to position the 3D printer on
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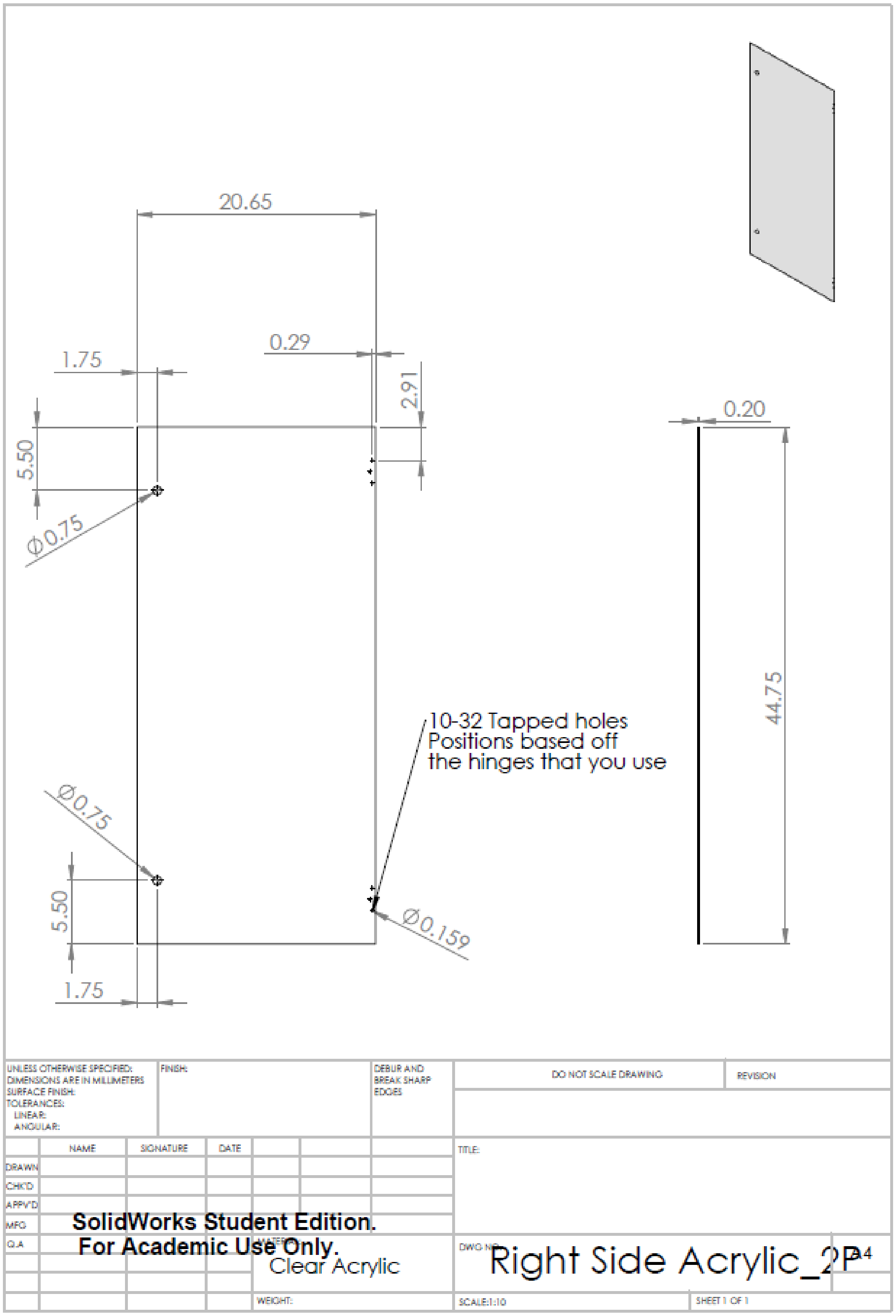
SHEET 1 OF 1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10-32 Tapped holes
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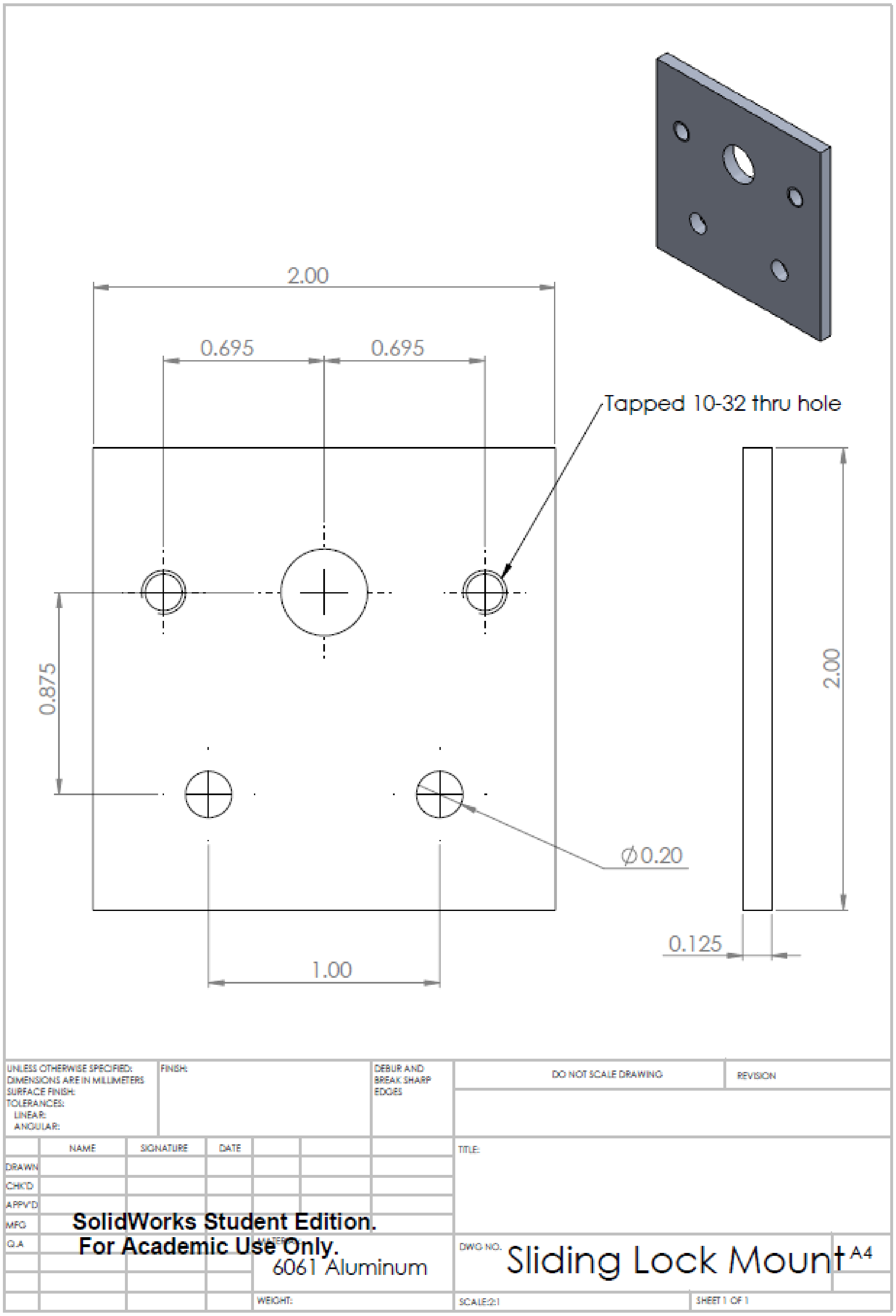
SHEET 1 OF 1



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MATERIAL:
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Sliding Lock Mount
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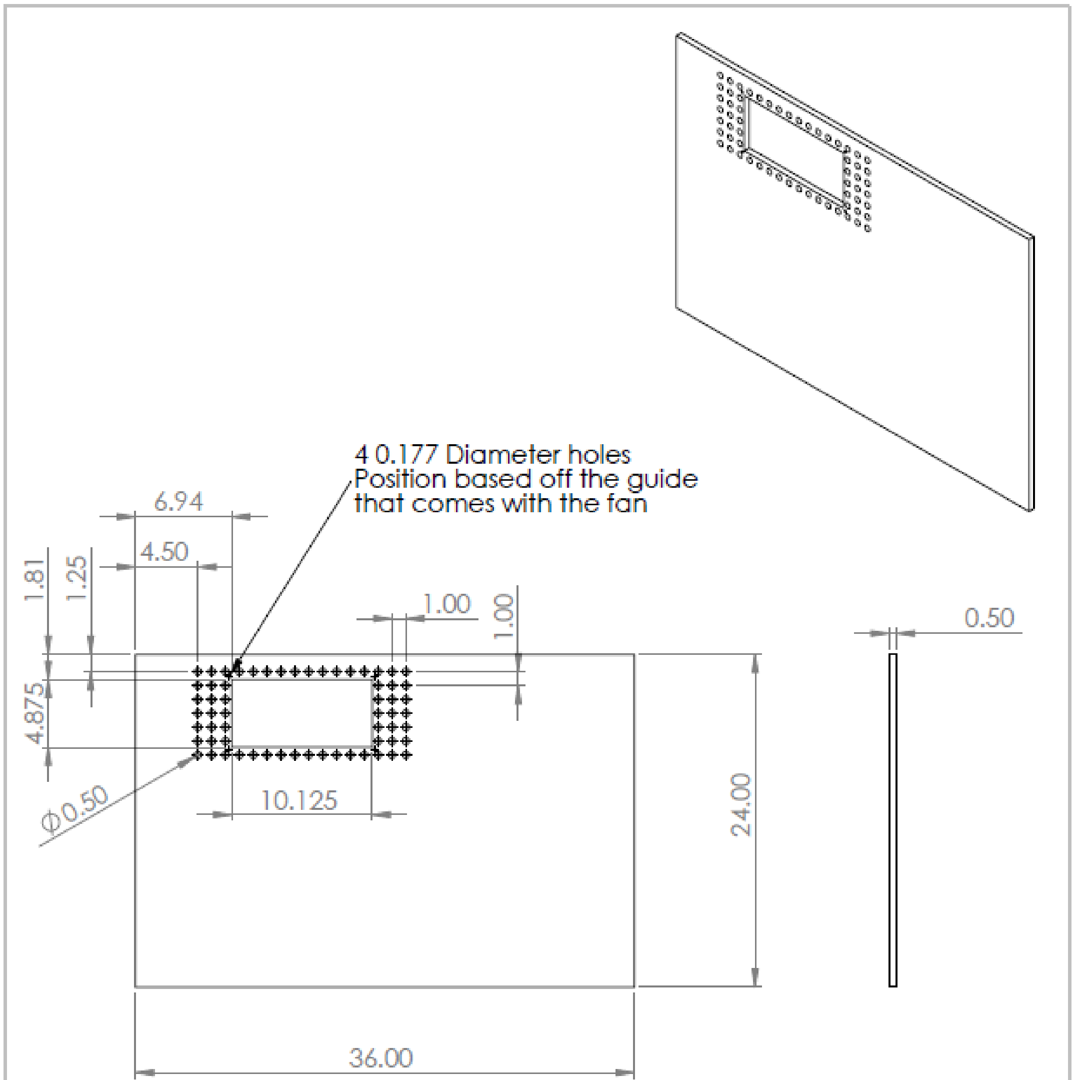

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MATERIAL:
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SHEET 1 OF 1

Appendix D: Diagram of Automatic Part Removal System Upgrade

By following the steps listed in this document, a person can minimize printer downtime by upgrading their MakerBot Replicator 2 3D printer to include an automatic part removal system. Additional software needs to be downloaded, as detailed later in this document, so that the automatic part removal system functions well. This automatic part removal system is designed to automatically remove parts printed in PLA plastic. Other materials may be printed using the printer in the modified form, but the parameters in the profiles are optimized for PLA plastic and should be changed for ABS or other materials.

1. Print all the parts that need to be 3D printed. Below are a list of the .THING files that need to be printed. They can be found at this website https://innovationstation.utexas.edu/open-source-files The recommended color for all parts is black. The sweeper and the sweeper guide rod look good when printed in another color of the user's choice.

    - Build plate extension LONG v2
    - Glass holder L side_shafts
    - Glass holder R side with legs and holes v4
    - Limit switch trigger v5
    - Motor mount 3
    - Sweeper rod guide v2
    - Sweeper v26

    Optional parts include:

    - Back sweeper guides
    - Sweeper guides F

- Bread Board Cover v2

The sweeper guides are important to print if you will be using the upgraded printer in a 3D printing vending machine because they help to assure that the parts are swept completely out of the printer before the next part is printed. The bread board cover is purely for aesthetics.

2. Buy all the parts from the Bill of Materials included in this download under the "Printer Upgrade" tab. The Bill of Materials includes websites for vendors, but does not necessarily list the least expensive vendors. A few parts are listed as optional and are not essential to the functioning of the automatic part removal system, but are useful if the printer will be used in a 3D printing vending machine.
3. Essential to the automatic part removal system is the use of a heated build plate bought from http://www.bctechnologicalsolutions.com/ The heated build plate comes with a glass plate and a heated aluminum plate that interlock. When ordering the heated build plate, make sure that you tell the vendor to send the glass without the 3D printed handles. If you forget, you can use a heat gun to remove the handles leaving you with a glass plate as shown in Figure D.1. Follow the instructions of the vendor to install the heated build plate.

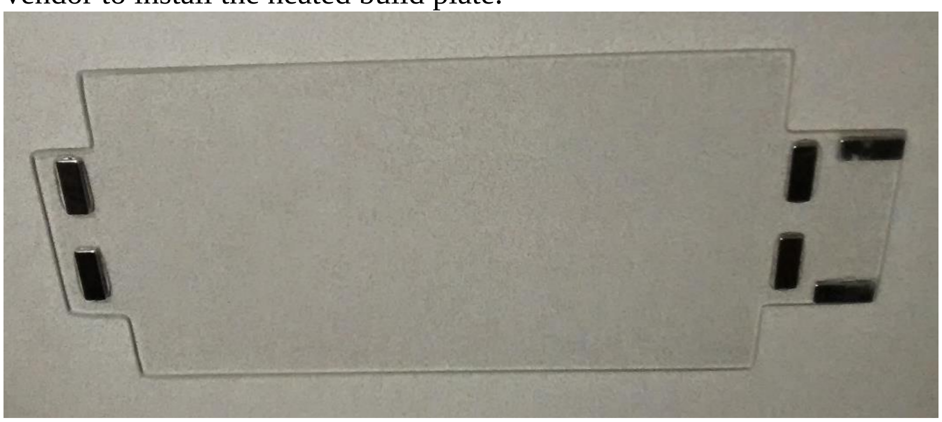


Figure D.1: Glass plate without handles

4. Now the parts you printed can be incorporated into the 3D printer. Unscrew the 2 phillips head screws on the left side of the printer head and then reattach them after adding the "Limit switch trigger v5" part. This can be seen in Figure D.2.

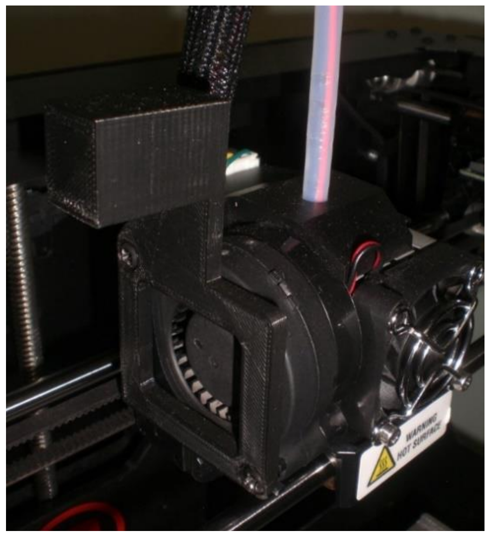


Figure D.2: Limit switch trigger part attached to the printer head

5. Next, bolt the "glass holder R side with legs and holes" to the fan using the 6-32 x 2.75 inch bolts as pictured in Figure D.3. The right glass holder is fixed to the base of the MakerBot 3D printer by cylindrical magnets.

Figure D.3: Fan mounted to the back of the right glass holder

6. If the upgraded printer will be used as part of a 3D printing vending machine it is highly recommended that the back and front sweeper guides are installed to keep parts from falling off the sides of the build plate during sweeping that can cause the 3D printer to jam. Figures D.4 & D.5 show the positions where the holes should

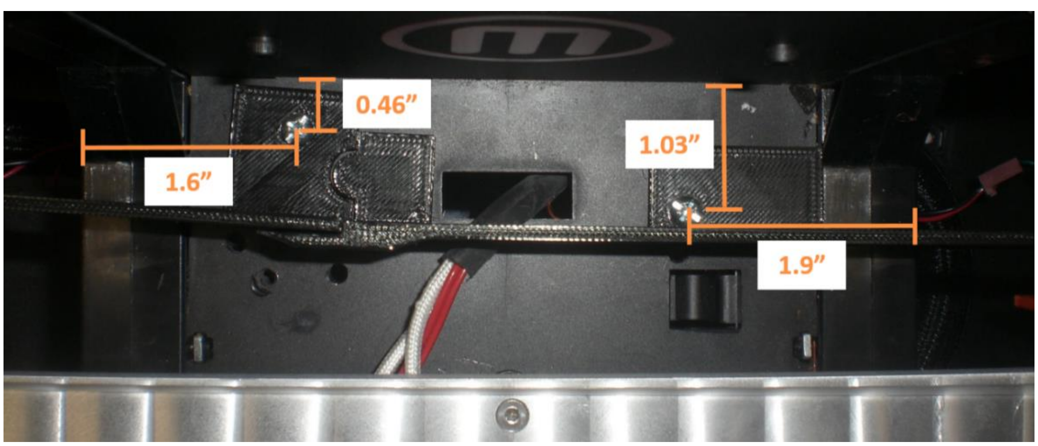


Figure D.4: Back sweeper guide hole placement dimensions

Figure D.5: Front sweeper guide hole placement dimensions

be drilled to mount the sweeper guides. The holes are all 0.15” in diameter. The bolts used to mount them are the 6-32 x ½ inch bolts and it is suggested that lock nuts are used to secure them. Before the sweeper guides are mounted they should be super glued to each other (the right back guide should be glued to the left back guide and the right front guide should be glued to the left front guide).

7. Next, the front, middle holes on both of the sides need to be drilled out. Figure D.6 shows the location of the hole that needs to be drilled by a 3/8” drill bit. Before drilling make sure that the wires are out of the way inside the printer as can be seen in Figure D.7. Once both holes are drilled, push the brass bushings into each hole. This might require a rubber mallet.

Figure D.6: Location of hole to be drilled with a 3/8" drill bit

Figure D.7: Move the wires aside before drilling the holes

8. Next, drill 2 holes for the motor mount. Before you do so, make sure that you take off the left side panel. You can keep it off until otherwise noted. They are 0.15” diameter holes with their positions marked as shown in Figure D.8. Attach the motor to the motor mount first using the M3 bolts and then use the 4-40 x ¾” bolts to mount the motor mount to the 3D printer with lock nuts.

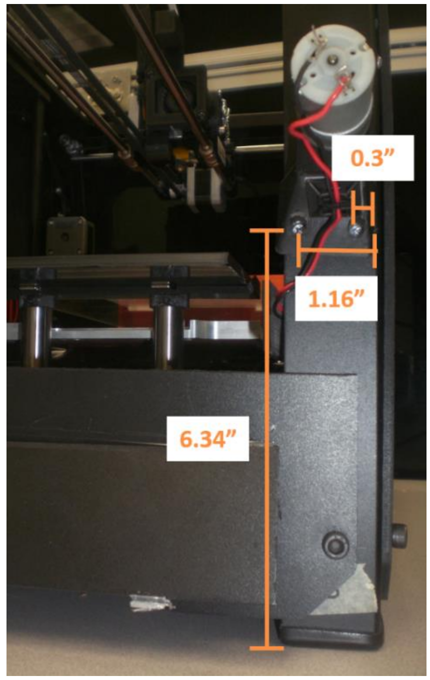


Figure D.8: Positions of motor mount holes

9. Next, mount the flexible motor coupling to the motor shaft by tightening the set screws. This set up can be seen in Figure D.9.

Figure D.9: Flexible motor coupling attached to the motor

10. Next, mount the 3D printed sweeper to the lead screw nut with 4-40 x ¾" bolts and lock nuts as seen in Figure D.10.

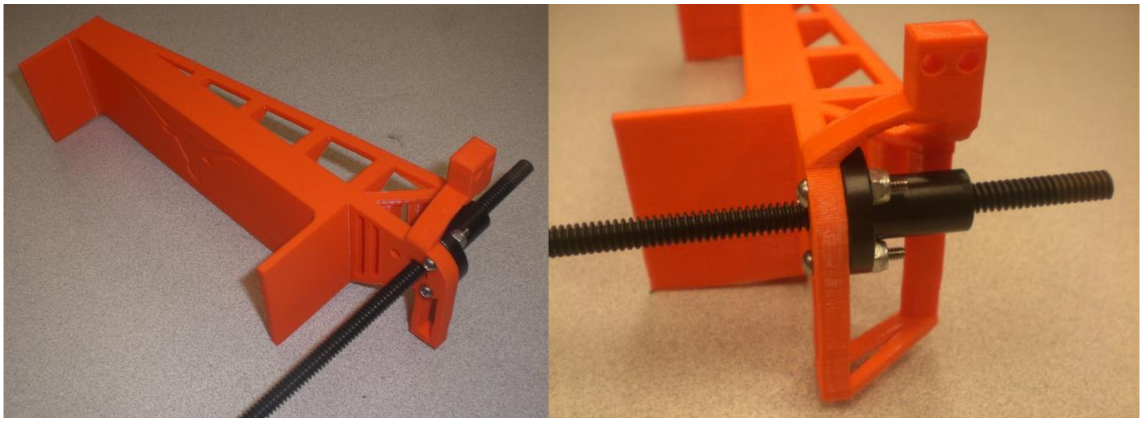


Figure D.10: Sweeper mounted to the lead screw nut

11. Now install the lead screw with the sweeper attached into the bushings. As the lead screw is placed within the 3D printer you might have to adjust how close it is to the right end of the lead screw. Once the lead screw is in position in the bushings, push the lead screw as far as it will go into the motor coupling and then tighten the set

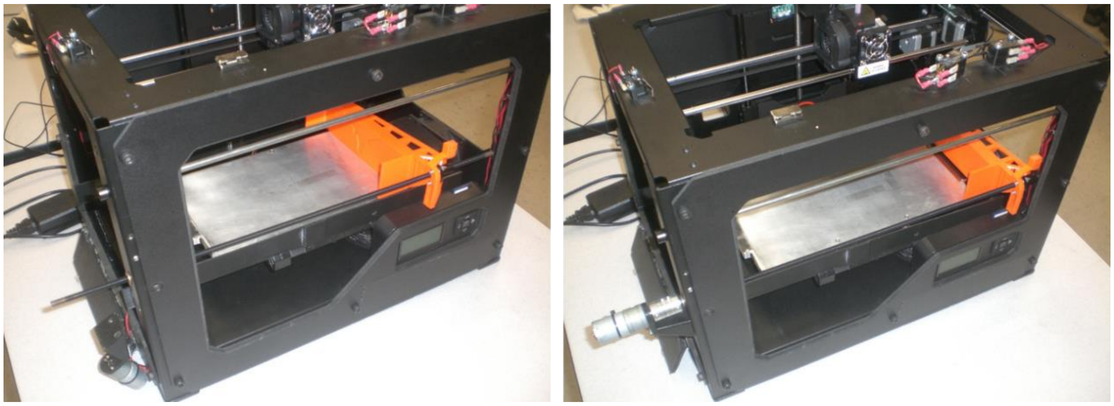


Figure D.11: Left picture shows the lead screw installed into the bushings. Right picture shows the lead screw in final position, fastened to motor coupling.

screw in the motor coupling to fix the coupling to the lead screw. This installation can be seen in Figure D.11.

12. Next the holes for mounting the limit switches need to be drilled. Figure D.12 shows the placement of the six holes on top of the MakerBot 3D printer. 4-40 x

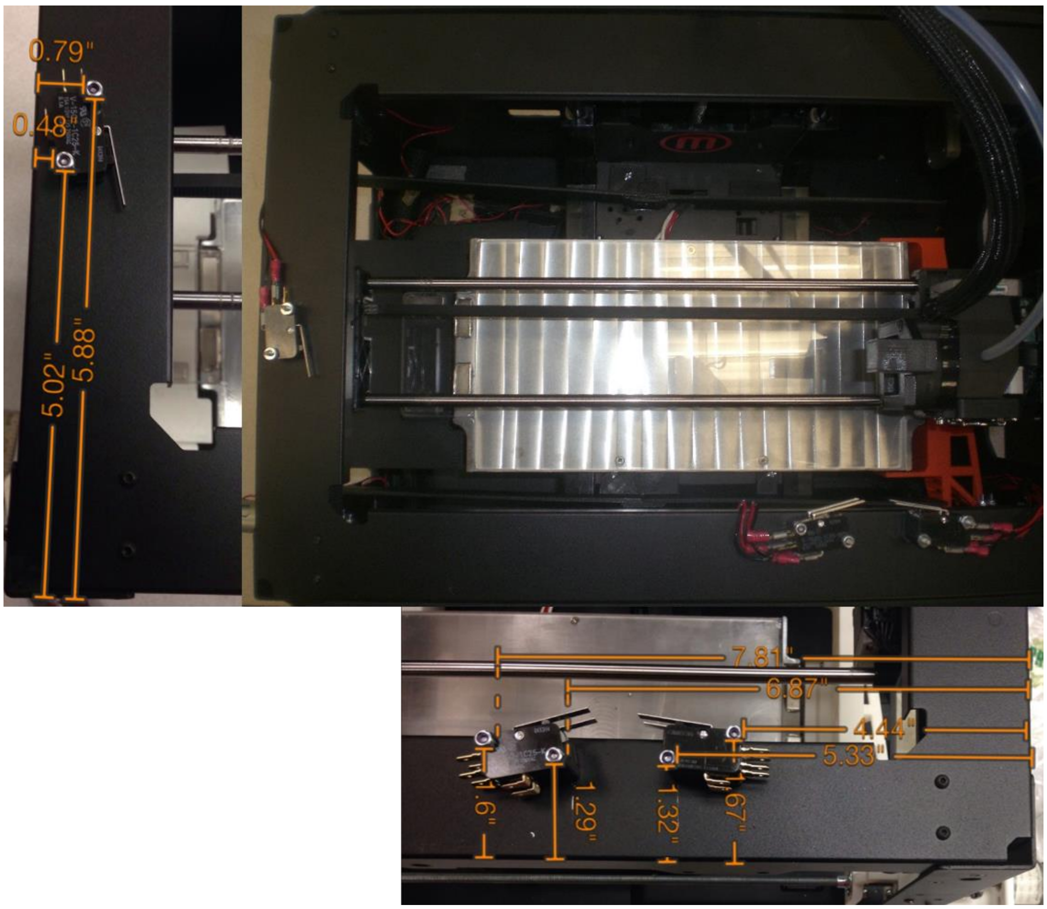


Figure D.12: The top right picture shows the 3D printer as seen from the top and the locations of limit switches. The 2 adjoining pictures specify the placement of the holes. All dimensions are to the center of the holes.

1.25” bolts and lock nuts are used to secure the stacks of two limit switches while 4-40 x ¾” bolts and lock nuts are used to secure the limit switch on the left side. There are also 2 limit switches mounted inside the 3D printer frame to constrain the position of the sweeper. A front view of the 3D printer with the placement of the holes that need to be drilled can be seen in Figure D.13. Make sure you take the front panel off the 3D printer before drilling the holes. A spacer is placed between the limit switch and the inside wall of the 3D printer as can be seen in Figure D.14.

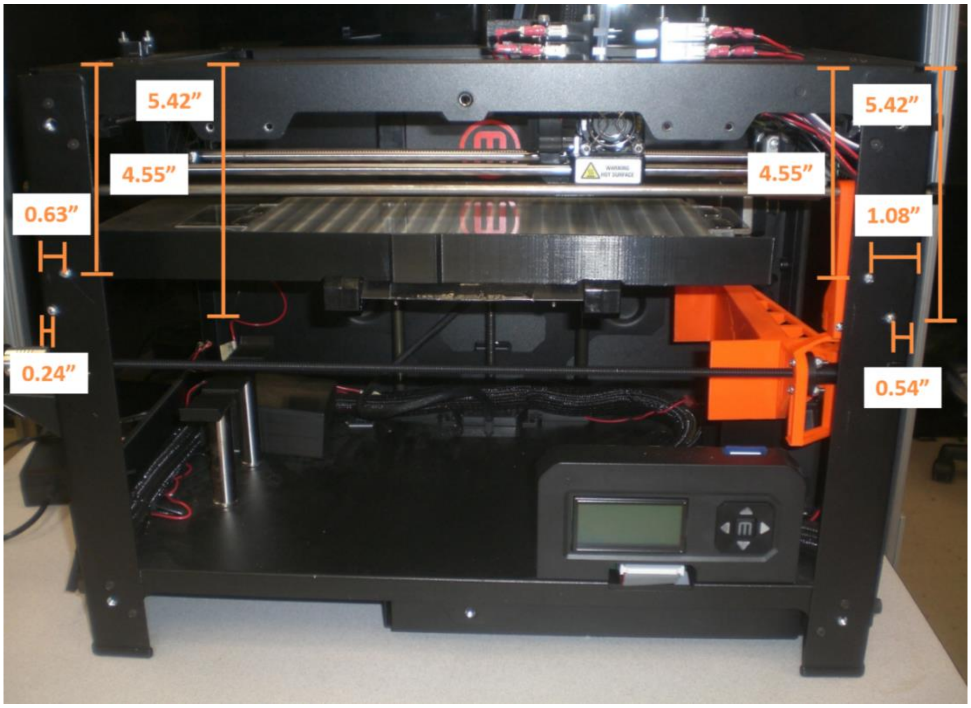


Figure D.13: Positions of the front 4 limit switch holes

Figure D.14: Limit switch and spacer mounted to the inside of the 3D printer

4-40 x 1.25” bolts and lock nuts are used to secure these limit switches. Once the limit switches are in place you can reattach the front panel over the top of the limit switch screws which will effectively hide them from view.

13. Next, measure and cut the wires to length. The lengths can be seen in Table D.1. Once the wires are cut, strip the ends of the wires. Then, add the crimps to the one end of the wires that will attach to the limit switches. Figure D.15 shows how the wires should look once the crimps are attached to the wires and it also shows the crimped wires attached to the limit switches. Wait until step 15 to attach the crimps to the limit switches.

Table D.3: Lengths of wires and cable sleeves for automatic part removal system

Name	**Length (inches)**
Right 2	44 (in both colors)
Right Drive	44 (in both colors)
Left 2	43 (in both colors)
Left Drive	43 (in both colors)
Right End	33 (in both colors)
Motor	15 (in both colors)
Fan	15 (in both colors)
Left End	22 (in both colors)
Fan Switch	21 (in both colors)
Jumpers x 12	1.5 (all red)
Cable Sleeve 1	24
Cable Sleeve 2	12

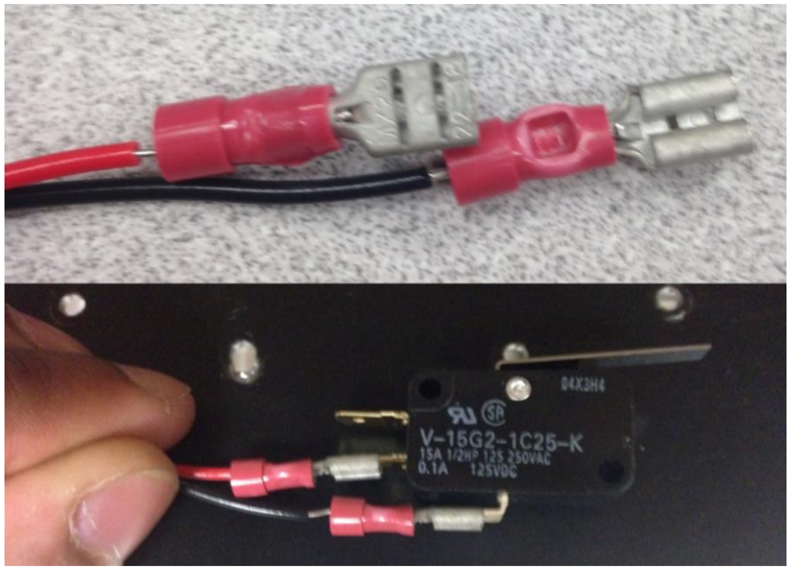


Figure D.15: Crimps attached to wires and secured to a limit switch

14. The laptop power supply that you bought now needs to be modified so that it can be used to power the sweeper motor. Cut off the end of the wire so that it looks like the left picture in Figure D.16. Then twist the ends to the wires that were cut for the power supply as can be seen in the right picture of Figure D.16.

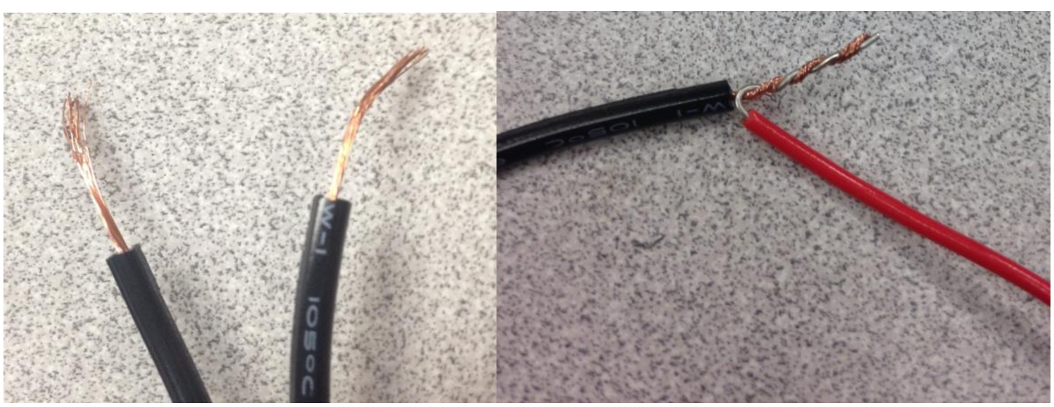


Figure D.16: Modified power supply wires attached to precut wires that will be inserted into the bread board

15. Now it is time to wire up the bread board circuit to run the motor and fan and connect all the limit switches. Figure D.17 illustrates the bread board with all the jumpers installed.

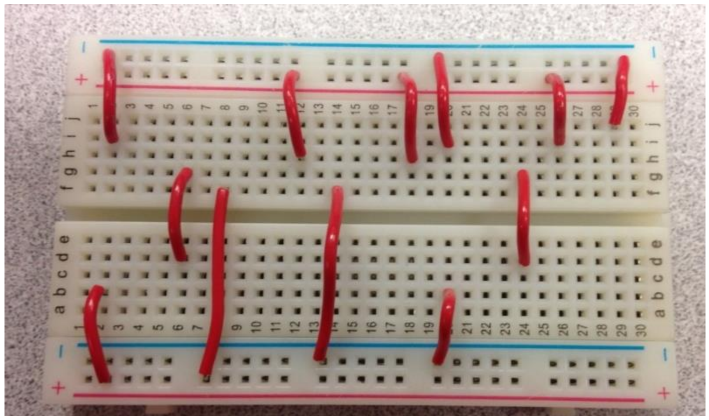


Figure D.17: Bread board with the jumpers installed

Figure D.18 shows the wiring diagram that documents where the wires for the motor, fan, and limit switches connect into the bread board.

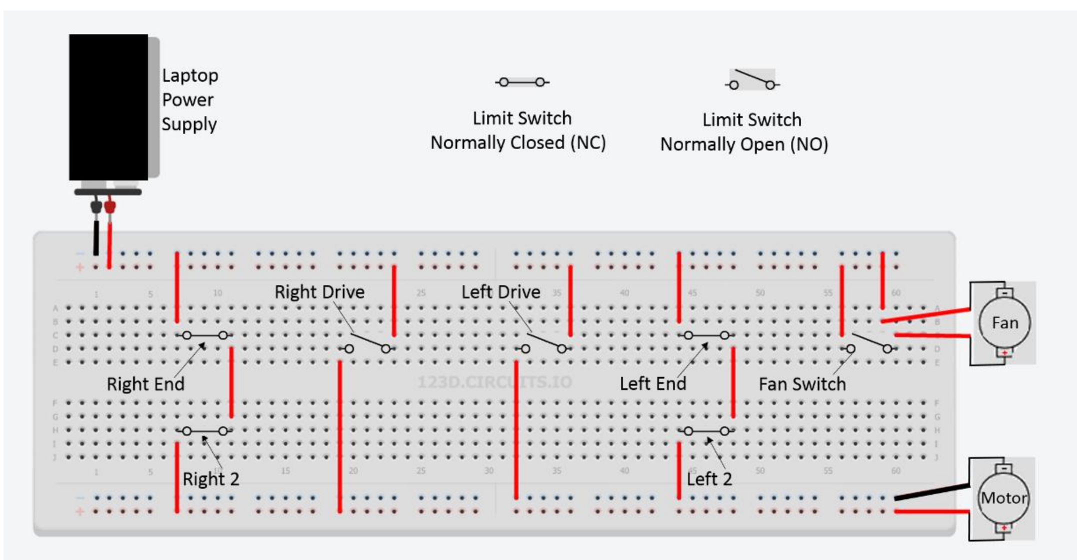


Figure D.18: Wiring diagram

Figure D.19 shows wires installed to a limit switch in the normally open (top picture) and the normally closed positions (bottom picture). Figure D.20 shows the names and locations of the limit switches that match the wire lengths and the labels in the wiring diagram. Figure D.21 shows how the fan wires are installed.

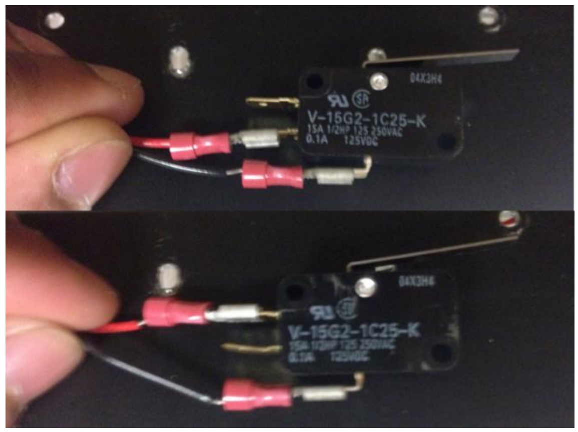


Figure D.19: Limit switches wired to be normally open (top picture) and normally closed (bottom picture)

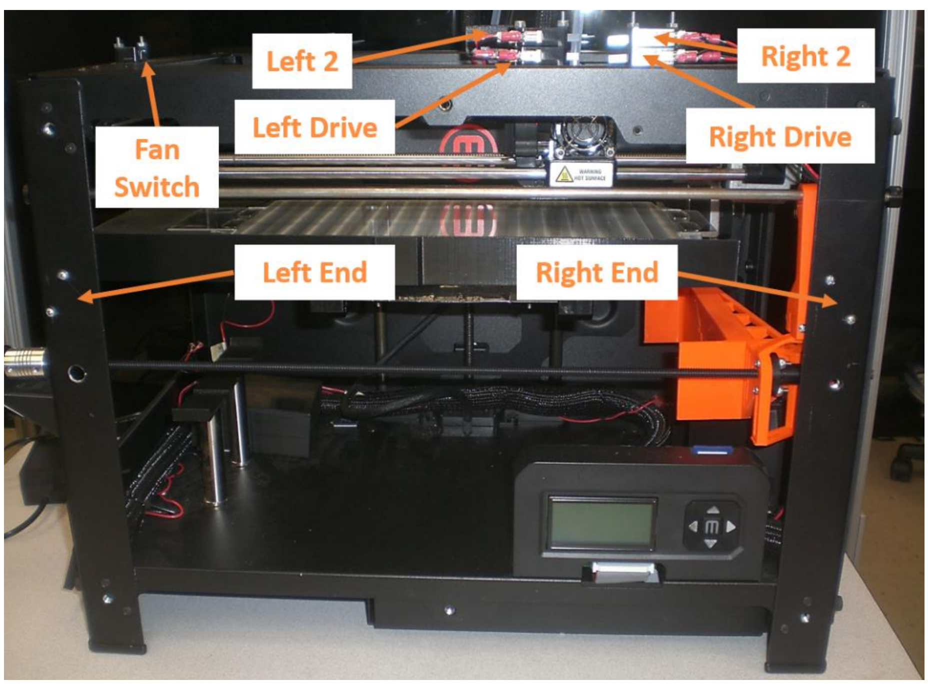


Figure D.20: Names and locations of limit switches for wiring purposes

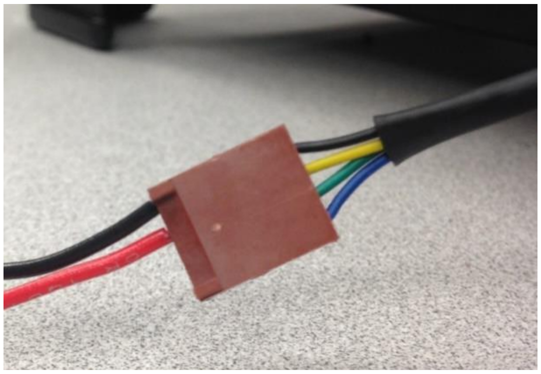


Figure D.21: How the fan wires are
installed

16. Now the wires should be positioned and constrained so that they are out of the way. The two black, wrap-around cable sleeves go over the mass of wires on the floor of the 3D printer, the shorter one on the left side and the longer one on the right side. This can partially be seen in Figure D.20, and more clearly in Figures D.22-D.23. Zip ties and the adhesive cable tie holders can be used to secure the wrap-around sleeves to the floor of the 3D printer. They can also be used to keep the wires from

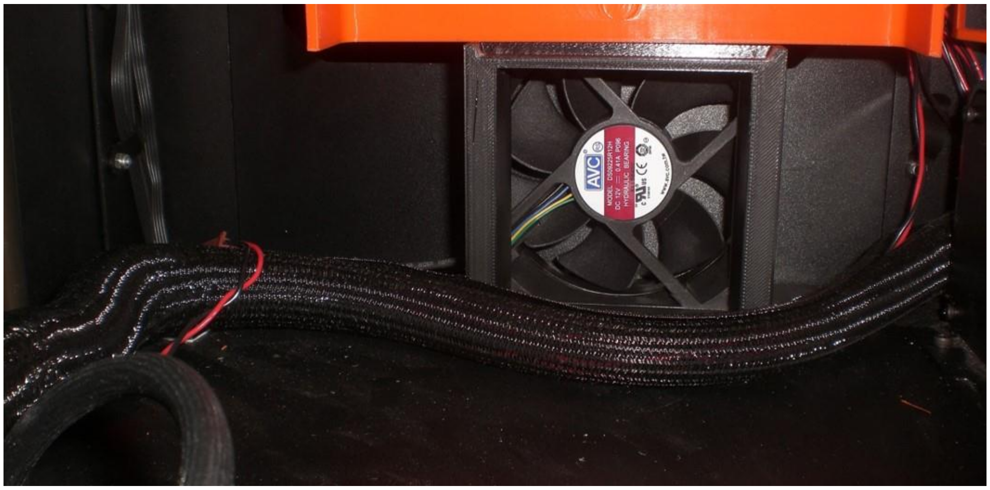


Figure D.22: Right wrap-around sleeve

the limit switches on top of the 3D printer out of the way as can be seen in Figure D.24.

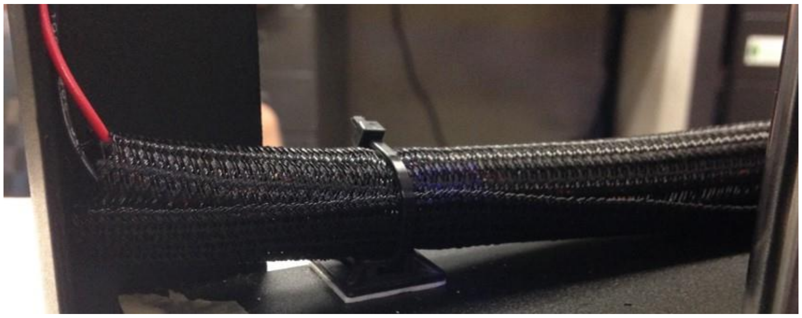


Figure D.23: Left wrap-around sleeve secured with zip tie and adhesive tie holder

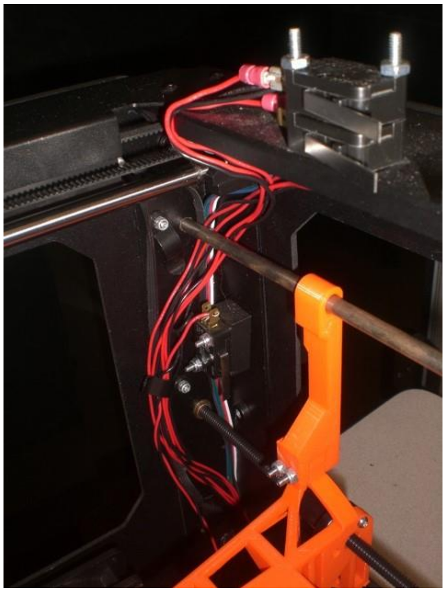


Figure D.24: Wires positioned to be out of the way of the sweeper and mostly out of sight

17. Next, take the plastic paper off the bottom of the bread board and adhere it to the back, left corner of the 3D printer floor. If you choose to print the bread board cover you can position it over the bread board to hide it from view. This is purely

for aesthetics, it serves no other function. The positioning of the bread board can be seen in Figure D.25. The bread board hidden by the bread board cover can be seen in Figure D.26.

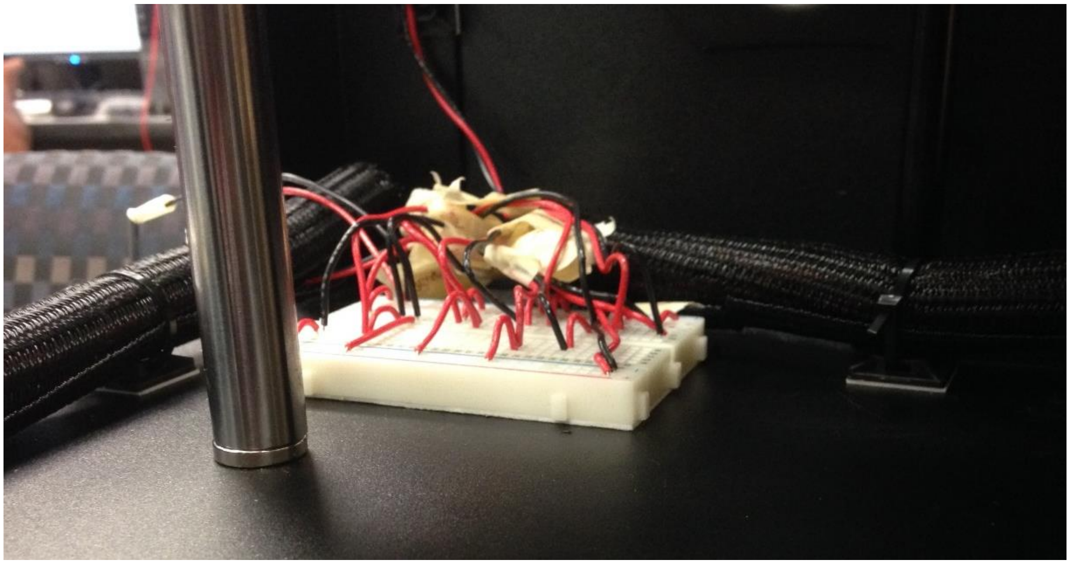


Figure D.25: Position of bread board with all wires in place

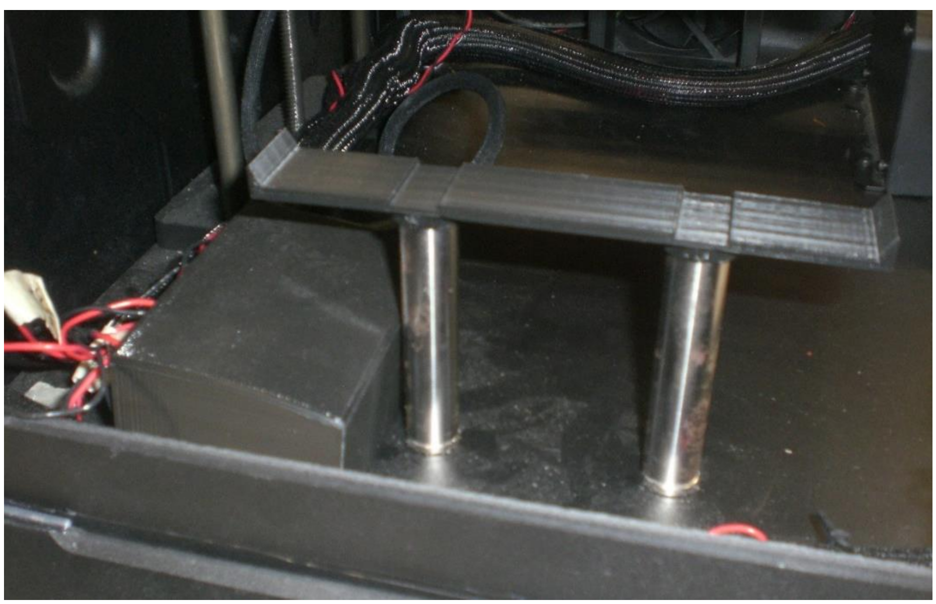


Figure D.26: Bread board hidden by bread board cover

18. Next, it is time to install the sweeper rod guide. To do this cut the low carbon steel rod to 19.5 inches long and sand both ends. Then you will need to drill two holes in the side of the 3D printer. Take off the side panels by unscrewing the bolts as can be seen in Figure D.27. Figure D.27 also shows the position of the holes that need to be drilled. Use a ¼" drill bit and make sure that all the wires are out of the way when drilling.

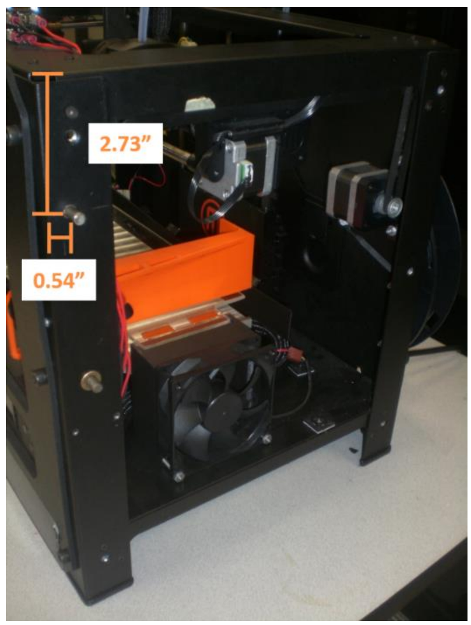


Figure D.27: Position of rod hole

19. Push the cut rod into one of the holes you just drilled. Before sliding it into the other hole, slide on the sweeper rod guide that you 3D printed. Then slide the rod through the other hole. This can be seen in Figure D.28. Then move the sweeper

forward and mount the sweeper rod guide to the sweeper using 4-40 x 1.25 inches and locknuts as can be seen in Figure D.29.

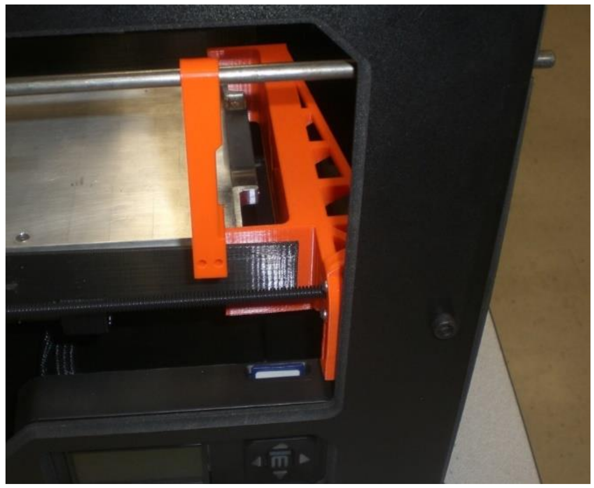


Figure D.28: Sweeper rod guide installed on the rod

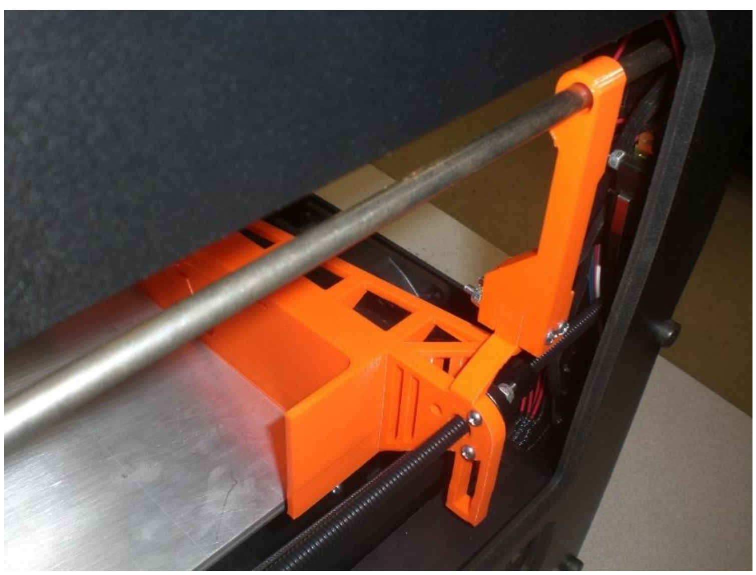


Figure D.29: Sweeper rod guide mounted to the sweeper

20. Now a hole needs to be drilled in the right side panel for the sweeper rod that was just installed. You only need to drill the hole in the right side panel because the left side panel will be modified later. The position for this hole can be seen in Figure D.30. Once the hole is drilled, reattach the right side panel to the 3D printer. Fix the small ¼" diameter shaft collars on each end by tightening their set screws. The collar in position on the rod can be seen in Figure D.31.

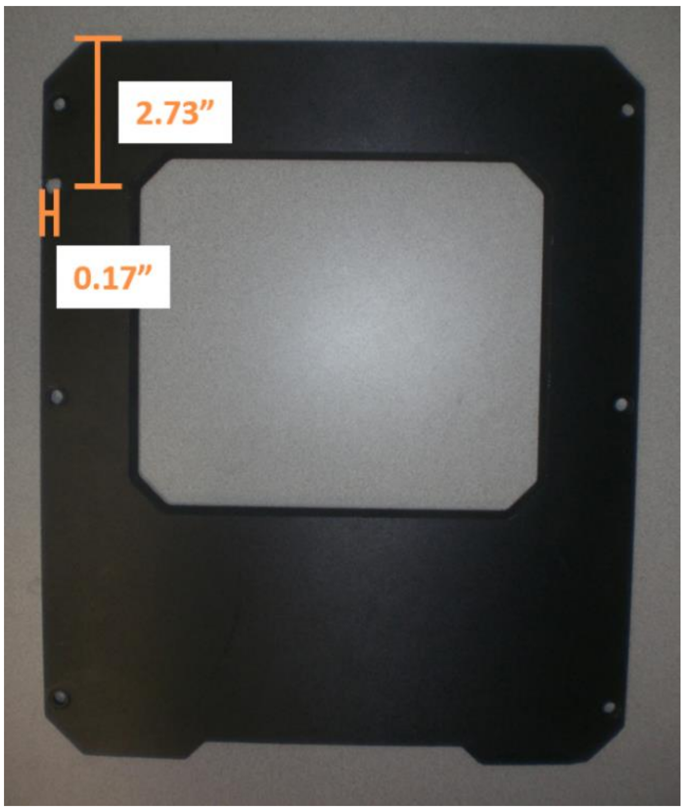


Figure D.30: Position of hole for right side panel

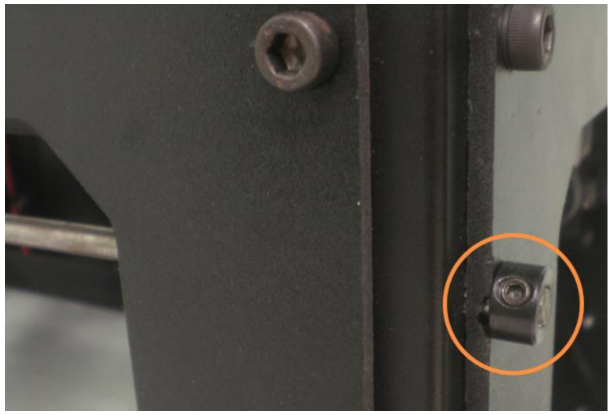


Figure D.31: Collar attached to the sweeper rod guide with set screw

21. Now the left side panel needs to be cut so that it doesn't get in the way of the automatic part removal system. Figure D.32 shows the where the side panel needs to be cut. A band saw can easily cut these pieces. If the 3D printer is going to be

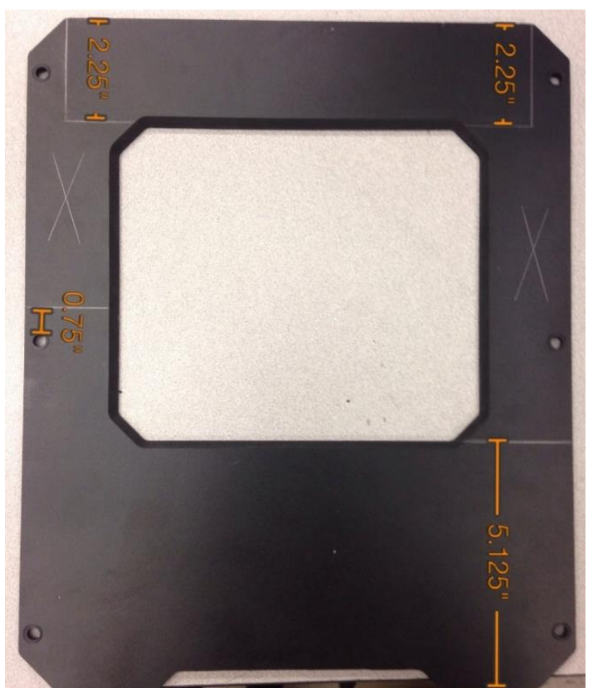


Figure D.32: This left side panel is marked where it should be cut. The Xs show material that can be thrown away.

installed into a 3D printing vending machine, it is recommended that you use the rectangular piece that you cut out of the side panel to form a ramp. First, you will need to mount two small L brackets to the bottom of the left side panel that you cut. The position for the screws can be seen in Figure D.33. Then use a glue gun to

Figure D.33: Location where the L brackets should be screwed into the left side panel

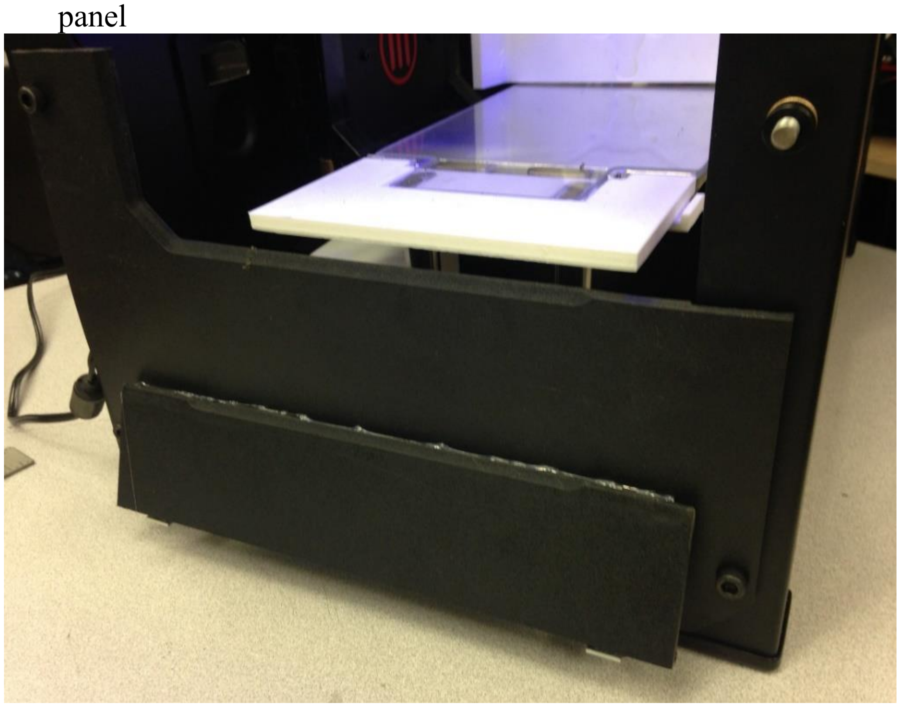


Figure D.34: Ramp installed on the left side panel and the left side panel reattached to the 3D printer secure the rectangular piece of the side panel to the left side panel as can be seen in Figure D.34 to make a ramp. Then reattach the left side panel to the 3D printer.

22. Next, add an extension to the glass build plate so that the parts can be swept all the way out of the 3D printer. To do this, you will need to super glue the extra 2 rectangular magnets that came with the heated build plate to the end of the glass as can be seen in Figure D.35. Make sure you press the magnets down tightly when gluing because they will be attracted to the other magnets glued to the glass nearby.

Figure D.35: The 2 additional magnets super glued to the corners of the longer glass extension

23. Now place the newly glued magnets into the rectangle cut outs for them in the build plate extension and put magnets on the bottom side of the extension to keep the build plate extension attached to the glass. These steps can be seen in Figure D.36.

Figure D.36: Build plate extension attached to the glass build plate by magnets

24. Before you put the glass back in the 3D printer, place the left glass holder in position. Do this by placing a neodymium disc magnet to the base of the 5/8" diameter shafts (make sure that you wipe the grease off the shaft first). Then put the magnet with the steel shaft attached to it on the floor of the 3D printer on the left side. Repeat with another magnet and shaft. Then place the left side glass holder on top of the two shafts and position this assembly as shown in Figure D.37.

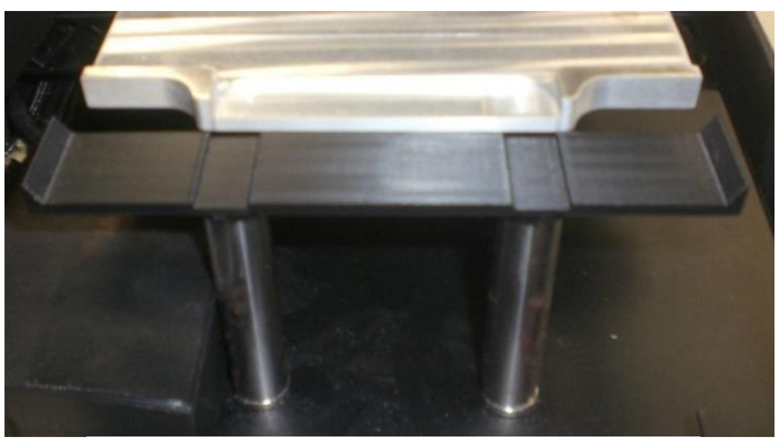


Figure D.37: Left glass holder in position

25. Now place the glass build plate with the build plate extension back into the 3D printer and set it into the aluminum heated build plate surface. Figure D.38 shows the glass in position in the 3D printer. Test to make sure the left and right glass holders are in the correct position by Jogging in the Z-axis. Adjust their positions until the glass plate raises and lowers back into the aluminum heated build plate smoothly. Then place the Jog and Switch Tests .X3G files on your SD card and run these files to make sure the automatic part removal system is running correctly.

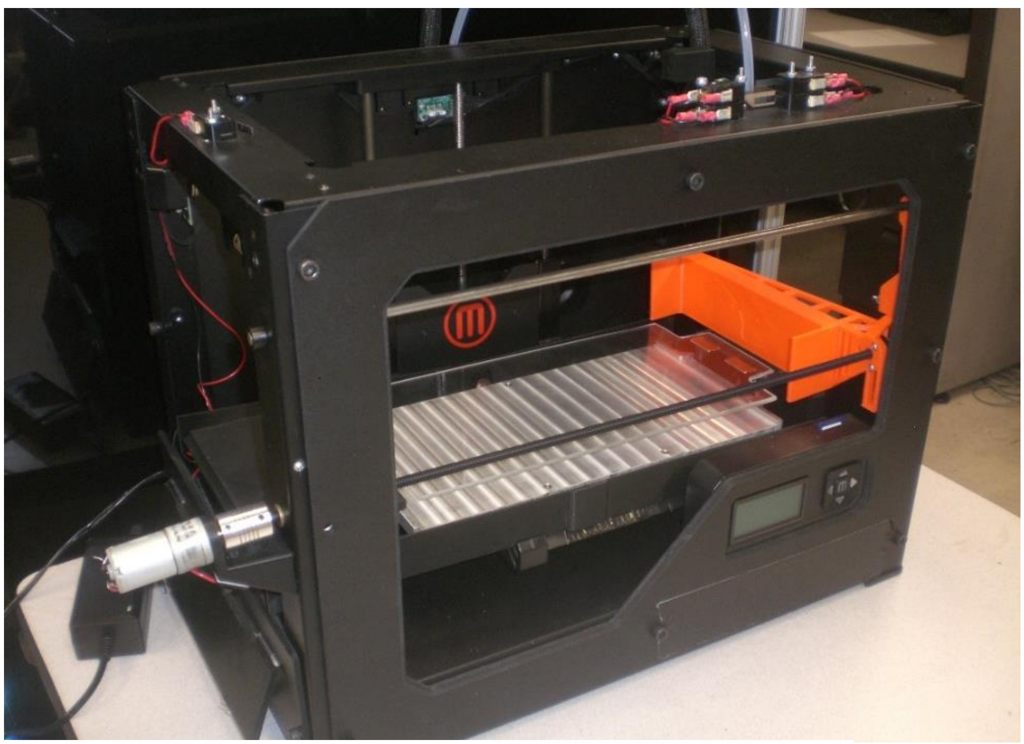


Figure D.38: The automatic part removal system in full working order

NOTES ABOUT USING THE AUTOMATIC PART REMOVAL SYSTEM

The automatic part removal system functions correctly only when used with profiles provided in the download. These profiles need to be copied and pasted in your Profiles folder in your My Things folder which can be found at this location on your computer C:\Users\[your user name]\My Things\Profiles Once in this location you can chose these profiles in MakerWare under the profiles drop down selection as can be seen in Figure D.39.

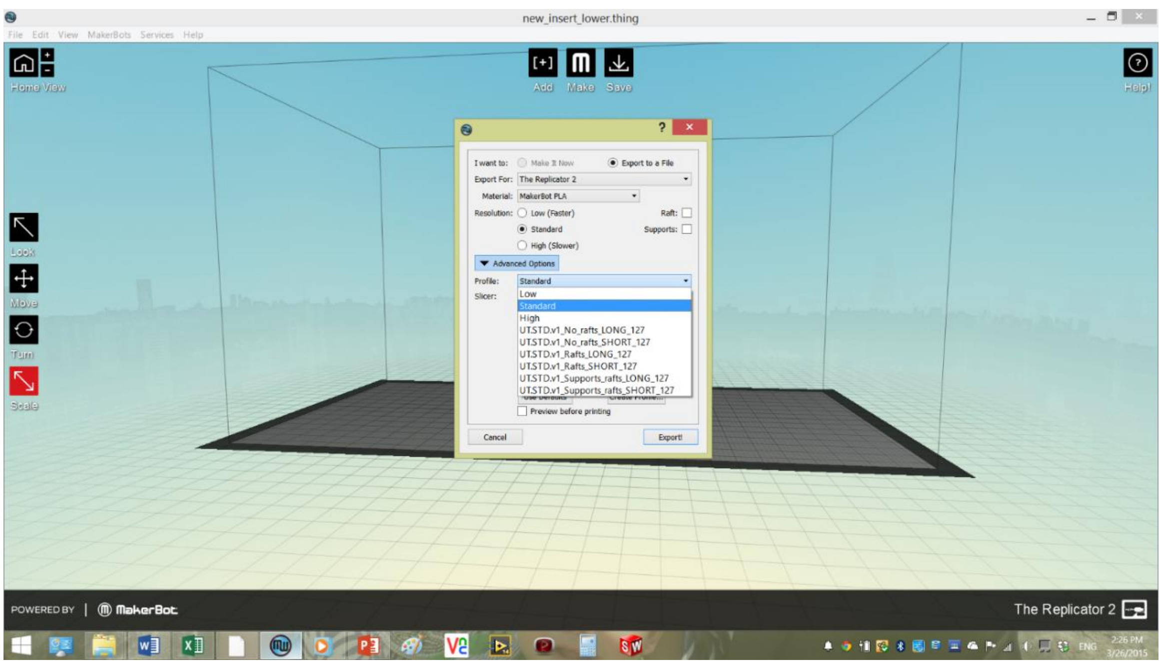


Figure D.39: Location of profiles that need to be used with the automatic part removal system

These profiles require that you use a certain version of MakerWare the most current version that you can download from MakerBot are not compatible with these profiles. The correct versions of MakerWare can be downloaded from https://innovationstation.utexas.edu/open-source-files

In addition to the profiles you can download the software used by us to run a queuing system, but recognize that this software is not plug and play and you will need some understanding of programming to be able to use it in your situation. The software team that developed this software have full time jobs that do not allow them time to answer questions about the code specifics, but feel free to take the code and use it and develop it for your situation.

Appendix E: FMEA

Failure modes and effects analysis (FMEA)

Project: **3D Printing Vending Machine**

Date: **9/17/2014**

FMEA Team:

Prepared by: **Joshua Kuhn**

SEV = How severe is effect on the customer?
OCC = How frequent is the cause likely to occur?
DET = How probable is detection of cause?
RPN = Risk priority number in order to rank concerns; calculated as SEV x OCC x DET

Potential failure mode	Potential failure effects	SEV	Potential causes	OCC	Current process controls	DET	RPN	Actions recommended	Responsibility (target date)	Actions taken	New SEV	New OCC	New DET	New RPN
In what ways can the step go wrong?	What is the impact on the customer if the failure mode is not prevented or corrected?	10	What causes the step to go wrong? (i.e., How could the failure mode occur?)	10	What are the existing controls that either prevent the failure mode from occurring or detect it should it occur?	10	**1000**	What are the actions for reducing the occurrence of the cause or for improving its detection? You should provide actions on all high RPNs and on severity ratings of 9 or 10.	Who is responsible for the recommended action? What date should it be completed by?	What were the actions implemented? Include completion month/year (then recalculate resulting RPN).	10	10	10	**1000**
Part does not detach from build plate	Part could be ruined, printer would mechanically jam when next print starts	8	Build plate leveled too tightly	5	Build plate leveled with 0.06 mm feeler guage at beginning of each day	5	**200**	Fix leveling bolts from loosening/tightening during print jobs (look into z axis zeroing position)						**0**
			Estimated build time not entered correctly	5	TA checks est. build time for each part before authorizing them	1	**40**							**0**
			Cooling times not long enough	5	Testing on max size parts	3	**120**	More testing to verify build profiles	Josh Kuhn (9/1/2014)					**0**
Part detaches from build surface while printing	Part ruined	4	Build plate temperature not high enough	3	Tests on problem parts to determine optimal build plate temperature	2	**24**							**0**
			Plate leveled too loosely	5	Build plate leveled with 0.06 mm feeler guage at beginning of each day	5	**100**	Fix leveling bolts from loosening/tightening during print jobs (look into z axis zeroing position)						**0**
	Part fails to be swept off the build plate completely, which causes next print job to fail	4	Build plate temperature not high enough	3	Tests on problem parts to determine optimal build plate temperature	2	**24**							**0**
			Plate leveled too loosely	5	Build plate leveled with 0.06 mm feeler guage at beginning of each day	5	**100**	Fix leveling bolts from loosening/tightening during print jobs (look into z axis zeroing position)						**0**
	Filament melts onto the nozzle and causes future print jobs to fail	6	Build plate temperature not high enough	3	Tests on problem parts to determine optimal build plate temperature	2	**36**							**0**
			Plate leveled too loosely	5	Build plate leveled with 0.06 mm feeler guage at beginning of each day	5	**150**	Fix leveling bolts from loosening/tightening during print jobs (look into z axis zeroing position)						**0**
Sweeper does not sweep part out of 3D printer	Part not swept off and printer would mechanically jam when next print starts	8	Sweeper not powerful enough	5	3 A power supply, 1000 RPM motor (roughly 5 lbs pushing force)	3	**120**	Measure the current drawn from motors (if necessary buy new power supply), possibly buy new motors for more robust design		Lead screw replaced all thread	8	3	3	**72**
		7	Sweeper does not push part all the way out of the 3D printer	2	Sweeper goes to the edge of build plate extension	1	**14**							**0**
		8	Sweeper catches onto the part and drags it back onto the printer	6	Sweeper goes to the edge of build plate extension	1	**48**	Sweeper goes past build plate extension (length of helper disk/raft)		Build plate extension extended and ramp added	8	3	1	**24**
					Keep sweeper low to build surface by keepinng lead screw straight & rod guide aligned properly	3	**144**	Replace all thread with lead screw		Lead screw replaced all thread	8	4	3	**96**
		3	Part falls off the side of the build plate and onto the bottom of the 3D printer	3	Sweeper guides as close to build plate as possible, TA can rearrange THING file to position parts so this does not happen	2	**18**	Create orientation guidelines for TA and possibly students		TA has the ability to adjust position of parts on build plate, ramp on sweeper helps prevent this	3	2	2	**12**
		8	Glass does not connect correctly with aluminum and sweeper jams on it	7	Strong magnets to keep holders in place, standardized heights of glass holders, TA do a "jog" test to make sure glass aligns before starting queue	5	**280**	Add bevels to aluminum, add bevels to 3D printed holders, create SD card program for "jog" test		Bevels added to 3D printed glass holders, SD card program created for "jog" test	8	3	5	**120**

		8	Sweeper jumps part instead of pushing it	4	TA checks z height of parts	2	**64**	Move fan to lower position		Fan moved to lower position	3	4	2	**24**
		8	Sweeping switches not activated by printer head	6	TA checks if switches are bent	2	**96**	Create external sweeper test to test sweeper switches (run weekly?)		External sweeper test created to test sweeper switches (ran daily)	8	2	2	**32**
		7	Sweeping g-code not long enough for parts that jam partially before sweeping off	3	Testing, additional time added in case of jamming	1	**21**							**0**
		4	PLA string lifts parts over sweeper	2	Heating Cycle before sweeping	1	**8**							**0**
		8	Part pushed over sweeper guides and jams	2	Testing	1	**16**							**0**
		3	Parts fall into the 3D printer because build plate extension is not long enough	2	Testing, build plate extension past 3D printer	1	**6**							**0**
Parts do not fall into drawer	Student has to retrieve part from TA the next day	3	Part bounces off closed drawer cover	2	Installed ramps	1	**6**							**0**
		3	Part slides under ramp on printer	2	Installed ramp stopper, TA checks position of 3D printers	1	**6**							**0**
		8	Part caught on motor wires	3		1	**24**	Zip tie motor wires		Motor wires zip tied	8	1	1	**8**
Drawer slider jams	Student has to retrieve part from TA the next day	3	3D printer not in the right position	6	TA pushes printer against blocks	2	**36**							**0**
		3	Acrylic sliders in wrong position	3	Testing	4	**36**							**0**
		2	Drawer in the way	7		2	**28**	Instructions on monitor for drawer usage		Instructions on monitor for drawer usage	2	5	2	**20**
Drawer handle breaks	Student cuts hand	9	Student vandalizes machine	4	Webcams	5	**180**	Fake security camera						**0**
Someone breaks into the vending machine	Steal 3D printers, etc	8	Malicious intent	5	Webcams, security screws	1	**40**	Fake security camera, buy additional security screws (different type)						**0**
	Hurt themselves	9	Burns themselves	3	Webcams, security screws, drawer cover	1	**27**	Fake security camera, buy additional security screws (different type)						**0**
	Destroy vending machine	8	Malicious intent	5	Webcams, security screws	1	**40**	Fake security camera, buy additional security screws (different type)						**0**
Problems with the queue	Queue does not start next part	3	Queuing algorithm	6	Testing	3	**54**							**0**
	Queue does not start correctly	2	Unknown	5	Reset conveyor by running small part in MakerWare	3	**30**							**0**
Trouble with part submission	Students submit parts that cannot 3D print	4	Lack of knowledge about 3D printing	9	Instruction guides	3	**108**	Add designer guides		Designer guide added to online portal	4	7	2	**56**
			Instructions unclear	7	Instruction guides	3	**84**	Improve instructions using beta testers		Instructions improved	4	5	2	**40**
Printer head catches on switch wires	Changes position of part on build plate and part could be ruined	4	Switches not mounted in correct position	4	Testing to make sure printer head doesn't catch switch	3	**48**							**0**
			Switch wires not zip tied or zip tied incorrectly	4	Testing to make sure printer head doesn't catch switch	3	**48**							**0**
Motors overheating	Motors burn up and become useless	8	Continous printing in an enclosure without enough ventalization	5	Touching the motors to feel how hot they are	4	**160**	Drill holes in shelves and roof and add fans for ventalation		Holes drill in shelves and roof and fans added to bottom and top to blow air out of enclosure	8	3	4	**96**
Wires coming out of bread board	Fan and/or sweeper do not run	8	Moving printer	3	Limit movement of printer in and out of Innnovation Station	6	**144**	Create external sweeper test to test sweeper switches (run weekly?)		External sweeper test created to test sweeper switches (ran daily)	8	3	2	**48**
Nozzle clogging	Part does not print correctly	4	Nozzle not completely unclogged from previous clog	7	Following standard procedure to fully unclog nozzle every time	7	**196**	Have replacement nozzles to decrease printer down time		Replacement nozzles on hand to decrease printer down time	3	7	7	**147**
			Part has thin/pointed feature which causes air printing	6	TA asks user to modify part	5	**120**	Have replacement nozzles to decrease printer down time		Replacement nozzles on hand to decrease printer down time	3	6	5	**90**
Drawer slider handle breaks	User pulls it wrong direction	6	Handle mount too thin and made of particle board	6	Instructions on monitor about how to use drawer slider	3	**108**	3D print new handle and change mount to remove particle board		Handle 3D printed and mounted without particle board	6	3	3	**54**

Appendix F: Designer's Guide

TIPS FOR DESIGNING 3D PRINTED PARTS

How 3D Printing Works:

3D Printing is a type of additive manufacturing in which a part is constructed layer by layer until the part is finished. The 3D printers used in the Innovation Station are modified Replicator 2s, made by MakerBot. They use an extrusion process called Fuse Deposition Modeling (FDM) to create parts. PLA plastic in wire form is loaded into the printer head where it is heated up to 230°C and extruded out of a nozzle. This molten plastic is positioned on the build surface based on instructions the printer receives from a program that slices CAD models into layers. The following video is a good introduction to 3D printers and how they work. https://www.youtube.com/watch?v=YQYW59ALPoE

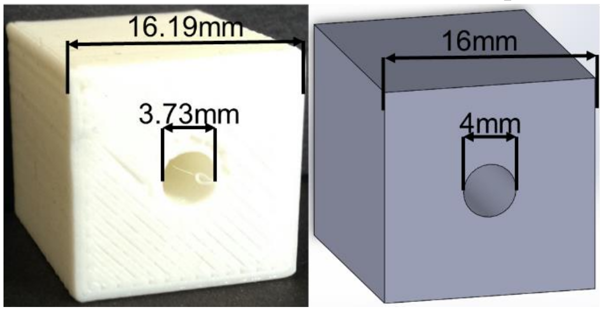
Dimensional Constraints:

As in all manufacturing processes 3D printing has constraints that are necessary to understand in order to print parts correctly. Below are listed some key constraints that you might be interested in.

- Max size part = 10.5 x 5.5 x 4.75 in or 266 x 140 x 120 mm (L x W x H)
- Minimum surface area resting on build plate = 0.295" x 0.295" or 7.5 mm x 7.5 mm
- Minimum thickness (height in the Z axis) = 0.1" or 2.54 mm
- Minimum Resolution (X/Y axis) = 0.01575" or 0.4 mm
- Minimum Resolution (Z axis) = 0.00787" or 0.2 mm
- Minimum Wall size = 0.0197" or 0.5 mm

Dimensional Changes from CAD Model to Printed Part:

Because of thermal expansion of plastic there is dimensional variation in parts. In order to create dimensionally accurate parts, adjustments must be made to CAD models. Outer features expand and inner features shrink as shown in the pictures below.

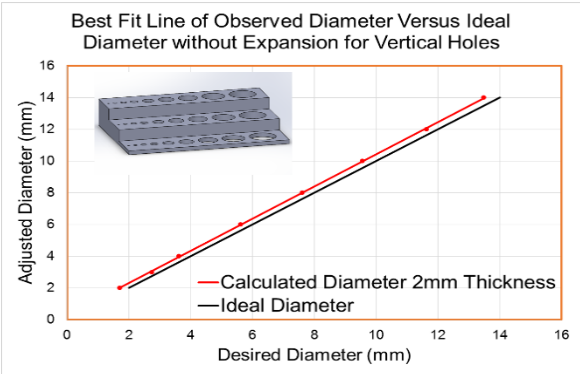


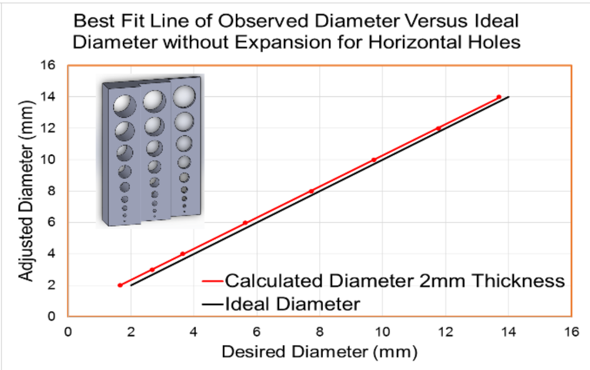
Example of dimensional variations from modeled diameter

Two formulas have been identified for hole diameter and shaft diameter.

To use these formulas, the x value is your desired diameter (for example 4mm) and the y value is the adjusted diameter for your CAD model (in this case 4.34mm). Use the vertical hole formula if the axis of the hole is on the z axis of the build plate and the horizontal hole formula if the axis of the hole is on the x or y axes. Both of these formulas are for millimeters.

- $y = 1.0155x + 0.2795$ vertical
- $y = 0.9927x + 0.3602$ horizontal





The formula for shaft diameters works the same way; the x value is your desired diameter and the y value is the adjusted diameter for your CAD model.

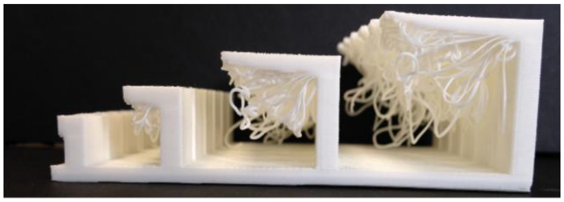
Reducing Build Time:

The cost of plastic filament and the running costs of 3D printing are low. Because of this, the real cost of 3D printing is the part build time. To allow more users to be able to use the 3D printers in the Innovation Station, there is a 4 hour limit for print jobs. There are various things that you as a designer can do to reduce the build time of your parts.

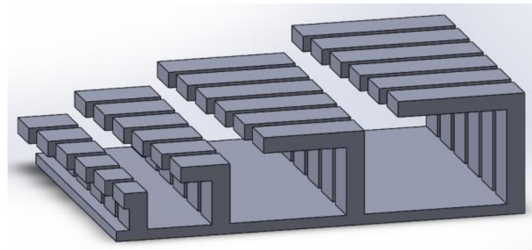
- Decrease the size of parts as much as possible: Any unnecessary material used in a part is just wasted time.
- Scale down parts: If the part does not need to be full size for what you are doing, scaling the part down will significantly reduce build time.
- Place parts close together on the build plate: The closer parts are together on the build platform the shorter the print job lasts because the printer head does not have to waste as much time between parts.

Limits of the 3D Printers:

Because parts are built layer on top of layer they must have something supporting features that are not directly attached to the build surface. These features are called unsupported overhangs and examples can be seen in the pictures. Without any supports these features fail to print correctly as seen in picture of the printed part below.

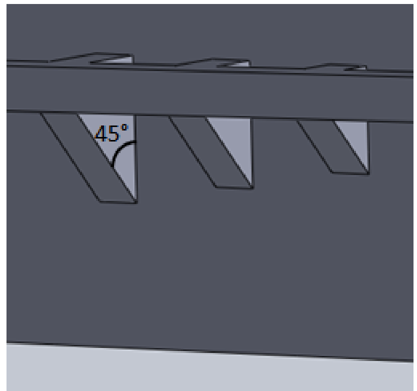


Failed Horizontal Overhangs

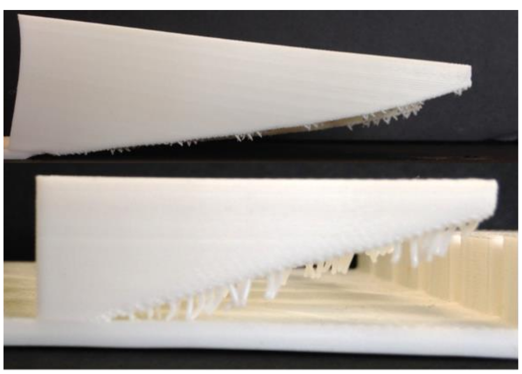


In order to build these parts you can choose to use the “Supports + Rafts” profile when printing your part. This will add support structure for your part while printing and after you received your part you can take off this support structure. An example of a 3D printed cat with supports and rafts and then with the supports and rafts removed can be seen below.

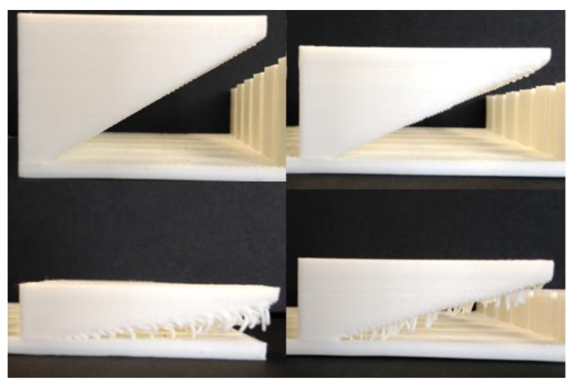
Because supports and rafts can be difficult to take off parts and can lead to unsatisfactory surface finishes many users decide to design parts so that they do not need supports. If overhangs are supported by angled supports they can be self-supporting. It is good practice to use angled supports of 45 degrees or more for the best quality of parts.



From tests done using the 3D printers in the Innovation Station, much lower angles can be used with success, although some additional “whiskers” might have to be trimmed after the part is retrieved. As can be seen from our tests of varying angles. 22.5 degree angled overhangs print successfully every time for any length and are the lowest recommended angle. Lower angles such as 15 degrees successfully print but leave whiskers on the angled edge and also longer 15 degree overhangs droop significantly.



(Top) Whiskers
(Bottom) Drooping

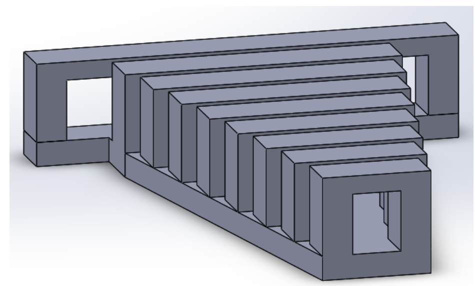


Clockwise from top left
30°, 22.5°, 15°, and 7.5° angled overhangs

Bridges are features where there is a gap that the printer must cross, but are supported on both ends. Supports can be used in these situations but it can be difficult to remove the support structures from the parts.

If designers opt out of supports, filament will be laid across air between the ends of the bridge. This can cause problems for bridges of certain dimensions. As seen in the picture, bridges shorter than 36 mm long print with drooping of 0 - 0.5mm, bridges 36 to 60 mm long print with drooping of 0.5 – 2 mm, and bridges longer than 60 mm long print with significant drooping of 2 - 5mm. Parts must be designed accordingly depending on the need for the bridge.

Clockwise from top left
≤36mm – 0-0.5mm drooping, 36-60mm – 0.5-2mm drooping, ≥60mm – 2-5mm drooping



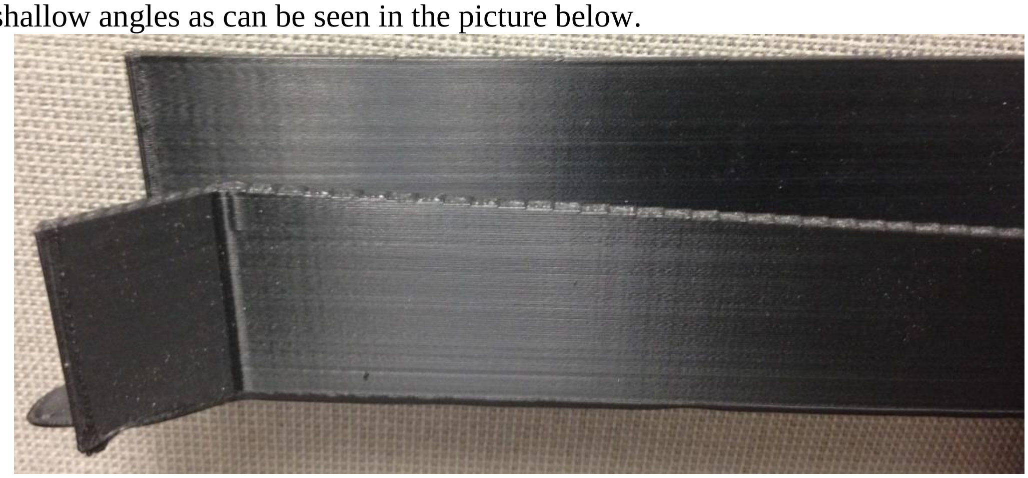
Part Orientation on Build Plate:

Once your part is created, it must be oriented on the build surface. Part orientation greatly influences the quality and the material properties of parts. Below are listed good practices for part placement and orientation that will help you to have successful prints.

- Positioning part on build plate
    - Center parts on the build surface: The closer a part is to the center of the build plate the less it will warp because the build surface is leveled the best at its center. In addition, the heated build surface is cooler on the edges which increases warping the near parts are to the edge.
    - Put parts on the platform: Make sure that the part is positioned on the build plate itself. You can check this by clicking on the “Move” button in MakerWare and making sure the Z position is 0.

- Place parts close together: The closer parts are together on the build platform the shorter the print job lasts because the printer head does not have to waste as much time between parts. Putting parts too close together can ruin multiple parts if one of the parts detaches. It is suggested that parts be placed 5-15 mm apart.
- WARNING: Building multiple parts in the same build can cause other parts to print incorrectly if one of the part fails to print correctly. It is suggested that you limit amount of parts per build.

- Orientation effects on material properties: Because 3D printers print parts layer upon layer the parts printed are the weakest in the Z axis. This is because it is possible to pull layers apart if a tensile force is applied in the Z axis. The interior of parts is filled with a 10% honeycomb to reduce material used, which also effects the material properties of parts.
- Place curves so that they are printed in the XY plane: Curves printed in other planes have a stair-stepping effect. This can most easily be seen in parts with really shallow angles as can be seen in the picture below.



- Avoid tall, thin features; they will likely fall: Parts that have small surfaces areas attached to the build surface are likely to become detached during printing due to the forces exerted on them by the printer head. The taller these parts are the larger the forces they will feel.

Cleaning Parts up after Printing:

Some parts will require cleaning up after printing. If you printed your parts with rafts and supports they will have to be removed before your part will be useable. Using needle nose pliers to pry off supports can be effective. This metal spatulas have also been used successfully to remove rafts. It is suggested that all holes in parts be added before printing in the CAD software. Drilling holes into 3D printed parts can cause parts to collapse if nuts are tightened onto the holes because the interior of parts is made up of a hexagonal structure to reduce material usage and print time.

How to Reduce Part Warping:

3D printed parts all tend to warp a little bit. Warping is where the corners and sometimes edges of parts curl upwards away from the build surface. This occurs because the build plate is not perfectly level and in areas where the build plate is cooler.

To reduce part warping:

- Center parts on the build plate: The center of the build plate tends to be the most level and also is the hottest. Both of these features decrease the warping of parts.
- Change part geometry: Long, thin features in contact with the build plate warp a lot. If you can, change the geometry of your part so that the surface of your part lying on the build plate is not long and thin.

- Print part with rafts: Rafts are a thin layer of plastic that adheres to the build plate more securely than normal parts designed to decrease warping. After the part is printed you can then detach the raft from your part. Below is a picture of a part printed with rafts.

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Vita

Joshua Kuhn was born in Houston, Texas in 1989. Joshua graduated from Clear Creek High School in 2007 and then went to Brigham Young University for a year before serving as a missionary for the Church of Jesus Christ of Latter-day Saints for two years in the Mexico Guadalajara East Mission. After returning to BYU, he finished his Bachelor of Science degree in Mechanical Engineering in June 2013. Joshua participated in the marching band in high school and at BYU as a euphonium player and he also taught Spanish for three years. In high school he was heavily involved in FIRST robotics which helps students to build five foot tall robots within six weeks. Josh is still active in the FIRST community as a mentor and has helped to mentor a team in Utah and in Austin. He began attending graduate school at the University of Texas at Austin in August 2013. He is a proud father of two wonderful boys with a daughter on the way.

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This thesis was typed by Joshua Kuhn.