THE INNOVATION STATION: A 3D PRINTING VENDING MACHINE FOR UT AUSTIN STUDENTS

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ABSTRACT

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, we 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, we 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 for recreating the station at a new location.

Keywords: 3D printing, design for 3D printing, automatic part removal system

1. INTRODUCTION AND MOTIVATION FOR PROJECT

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 and securely in a public space. Students 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 their parts behind acrylic 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 intended to inspire students to actively create and build and to motivate future engineers, designers, and entrepreneurs. In addition, it allows students to become more deeply engaged in the process of designing parts for manufacturing and to become more entrepreneurial.

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. 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 [2].

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 [3]. The DreamVendor includes four Thing-o-matic 3D printers from MakerBot. Students upload their files by inserting SD cards into the machine and retrieve their parts from slots in the front of the machine. 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. 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 [4].

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, and they have few online resources for file-sharing or blogging. 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.

2. BRIEF OVERVIEW OF THE INNOVATION STATION

As shown in Figure 1, 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 plastic 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 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) also builds an online community around the Innovation Station, including 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. The following sections outline each of the components of the machine.

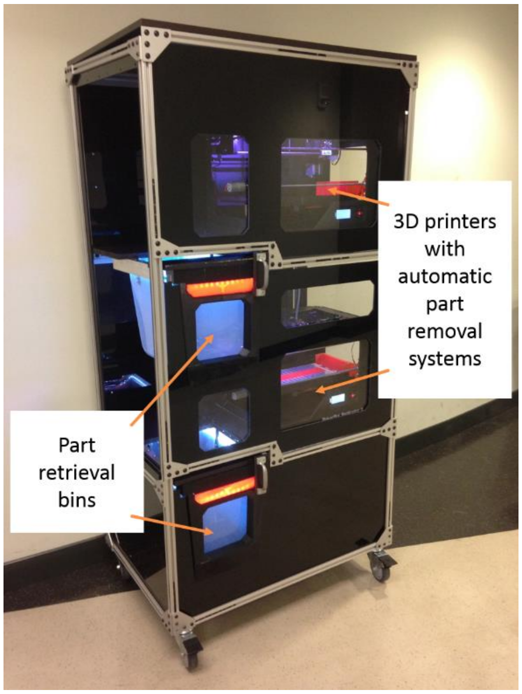
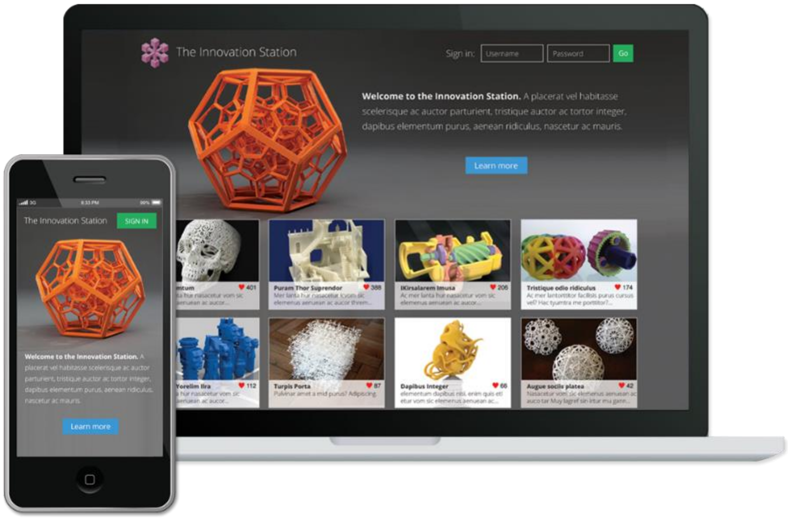


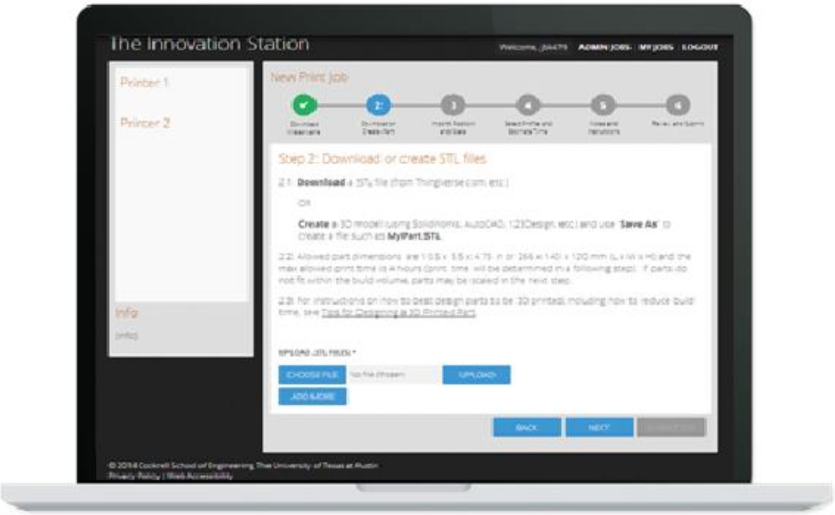
Figure 1: The Innovation Station

3. ONLINE RESOURCES FOR THE INNOVATION STATION



Welcome to the Innovation Station. A placerat vel habitasse scelerisque ac auctor parturient, tristique auctor ac tortor integer, dapibus elementum purus, aenean ridiculus, nascetur ac mauris.

Figure 2: Front page of the Innovation Station website



Step 2: Download or create STL files

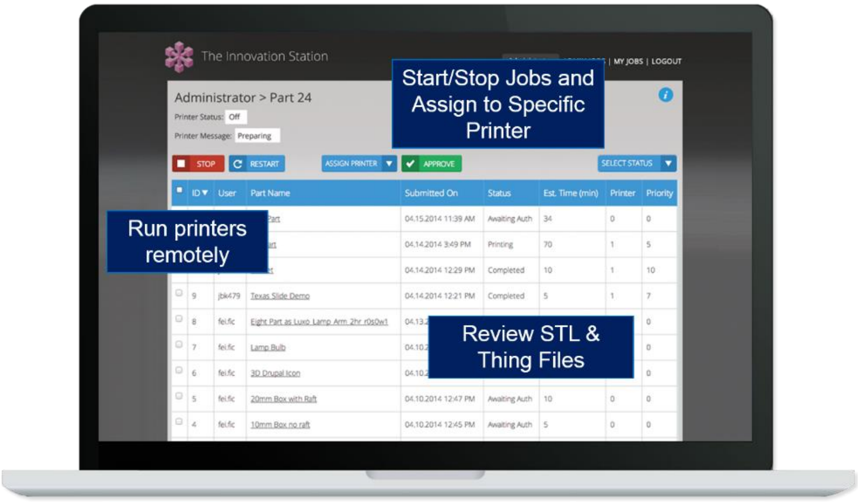
Figure 3: Part submission page

Students can access the 3D printers via a web portal (Figure 2) by logging on with their student IDs. 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.

As shown in Figure 3 students submit two files associated with their part. The .STL file is uploaded to the online database so that other users can view, download and be inspired by all the parts that are printed in the Innovation Station. 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 printers, and make suggestions for corrections as needed. It is generated by MakerWare software, which is freely available to students from MakerBot. The .THING file is used by MakerWare software to create the machine code that runs the printer, and that code is transferred directly to the station at the time of the build. Special modifications to printer profiles operate the heated build plate and the part removal system. Finally, users also upload an estimate of the print time, which is provided by MakerWare software.

As shown in Figure 4, 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 can check submitted parts for appropriateness, proper build orientation, and build time. 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 will receive a text or email informing them that their part is printing. They then can view their part printing online via a webcam or go to the lobby of the mechanical engineering building to watch their part print in person. The administrator can monitor a webcam throughout the day and remotely stop the queue if any failures are detected.



Administrator > Part 24

Printer Status: Off

Printer Message: Preparing

☐	ID	User	Part Name	Submitted On	Status	Est. Time (min)	Printer	Priority
				04.15.2014 11:39 AM	Awaiting Auth	34	0	0
				04.14.2014 3:49 PM	Printing	70	1	5
				04.14.2014 12:29 PM	Completed	10	1	10
☐	9	jbk479	Texas Slide Demo	04.14.2014 12:21 PM	Completed	5	1	7
☐	8	fei.fic	Eight Part as Luxo Lamp Arm 2hr r0s0w1	04.13.2				0
☐	7	fei.fic	Lamp Bulb	04.10.2				0
☐	6	fei.fic	3D Drupal Icon	04.10.2				0
☐	5	fei.fic	20mm Box with Raft	04.10.2014 12:47 PM	Awaiting Auth	10	0	0
☐	4	fei.fic	10mm Box no raft	04.10.2014 12:45 PM	Awaiting Auth	5	0	0

Start/Stop Jobs and Assign to Specific Printer

Run printers remotely

Review STL & Thing Files

Figure 4: Queuing page as seen by the administrators

Designing parts for 3D printing is a different way of thinking about design and for many students requires some extra instruction. For this purpose, we have created a designer’s guide for 3D printing and posted it on the Innovation Station website. The guide includes the tolerances, minimum feature size, minimum angle, maximum length of overhangs, and maximum length for bridging for a Replicator 2 3D printer. As an example of the type of information provided in the designer’s guide, we have 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 thermal expansion and other factors, 3D printed parts tend to expand into holes that are printed. This means that if you want a ¼” hole you must have a larger dimensioned hole in your CAD model so that the 3D printed hole is actually ¼”. As shown in Figure 5, our experiments indicate a linear relationship between the intended and as-printed diameter of the hole. Other important considerations such as part orientation, part positioning on the build plate, and how to reduce warping are also included on the website.

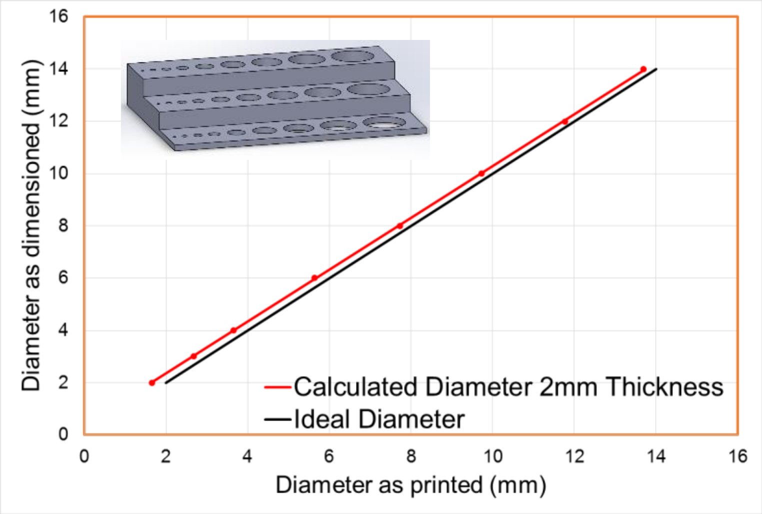


Figure 5: Graph of adjusted diameters for vertical through holes

4. PART DETACHMENT

The most significant hardware challenge for this project was reliably removing all parts from the build platform so that the entire build process could be automated. Due to its simplicity and ease of integration into the 3D printer, a thermal cycling approach is used for part detachment.

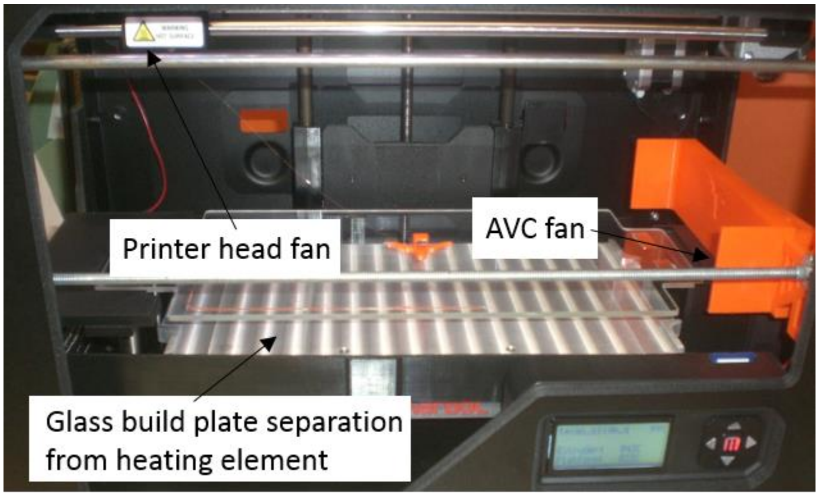


Figure 6: Automatic part removal system

A heated build plate was integrated into the 3D printer. The build surface 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 to approximately 70 C during the build process because PLA parts adhere to a glass build surface only when it is heated. The glass build surface detaches easily from the aluminum surface as shown in Figure 6. 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 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 activates switches that are mounted on top of the 3D printer as can be seen in Figure 7. These switches simplify the design so that no external microcontrollers are needed.

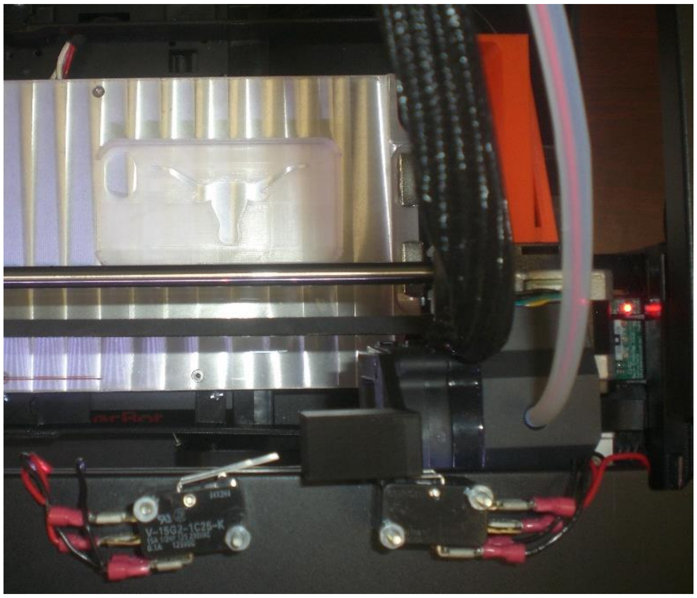


Figure 7: Printer head activating switches that turn on the fan and move the sweeper

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. 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.

Figure 8: 15 mm square and 36 mm cylinder test parts

Early in the design process part removal experiments were conducted to investigate the feasibility of thermal cycling as a part detachment method. As shown in Figure 8, small 15 mm squares and cylinders with a diameter of 36 mm were used 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 for the part to stick to the build plate during printing. Experiments were performed on the experimental heated build plate shown in Figure 9. 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 builds. All the layers were held together using binder clips.

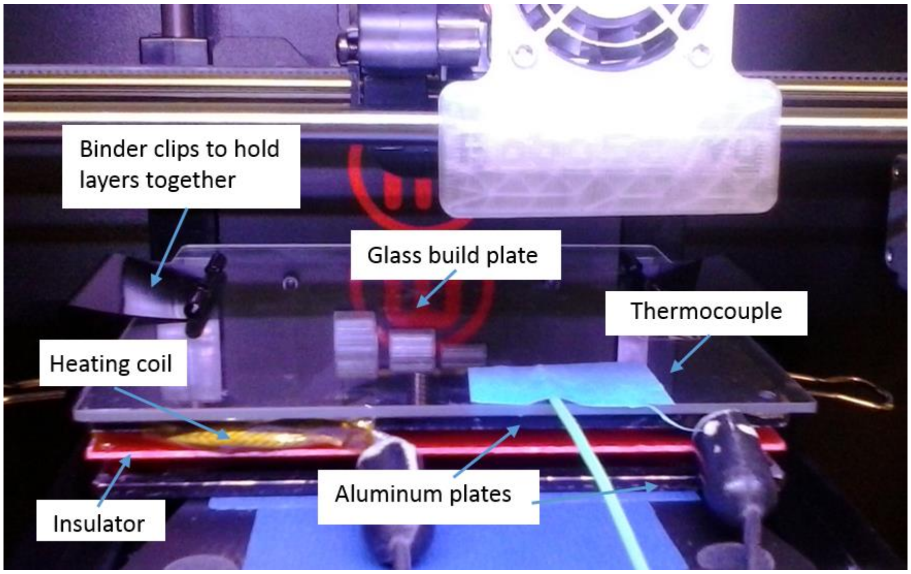


Figure 9: Prototype heated build plate

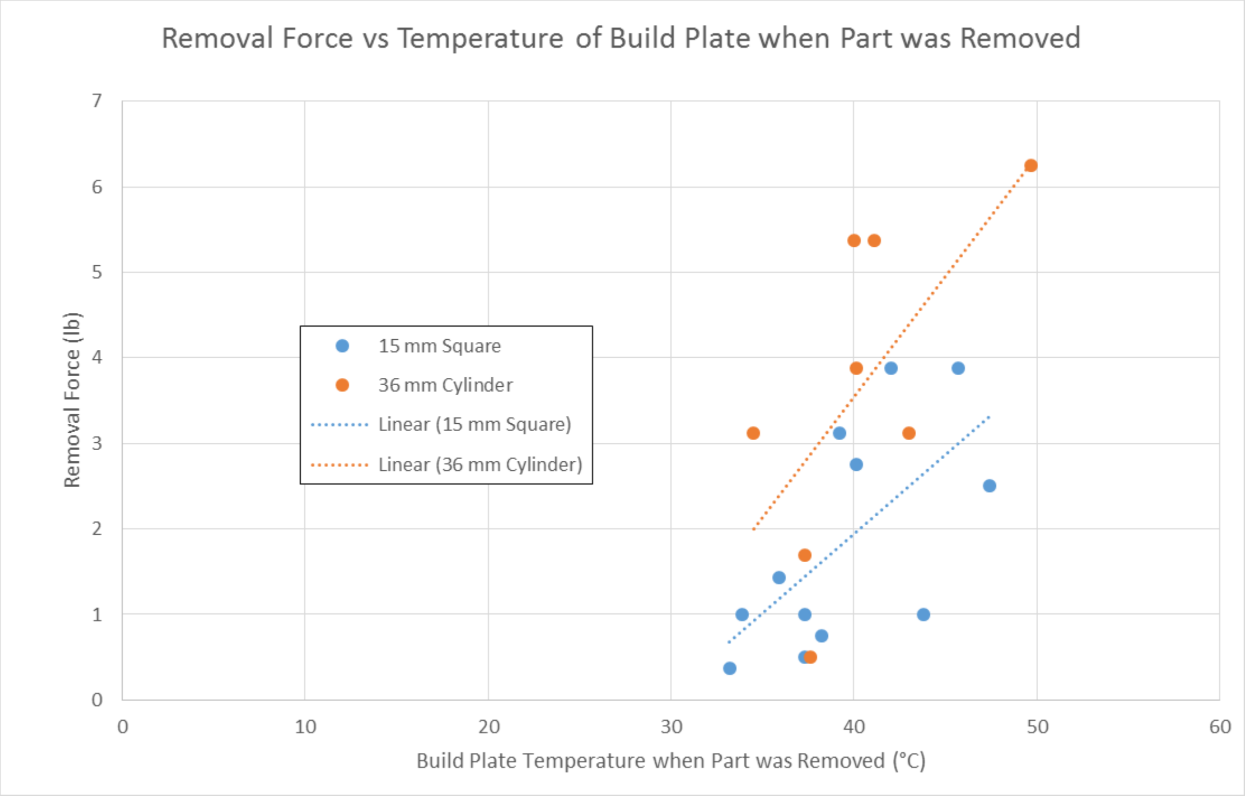


Figure 10: Part removal force versus build plate temperature when a part is removed

This functional prototyped yielded the data illustrated in Figure 10. From this data, it is apparent that the lower the temperature when the part is removed the lower the removal force. These experiments indicated that thermal cycling was a viable technique for part removal, but additional experiments were needed to fine tune the process.

A commercially available heated build plate was integrated into the 3D printer and additional experiments were conducted to determine the optimal build plate temperature and the required cooling rate and duration at the end of the build for ideal part detachment. As shown in Figure 11, the experiments indicated that higher build plate temperatures correlated with higher part removal forces. Additional experiments were conducted to determine the lowest possible build temperature at which all parts adhered to the build plate. Challenging parts were built as part of these experiments, including the tall parts in Figure 12, which are the most difficult to adhere to the build plate during printing (and therefore prone to failed builds), and the parts with expansive coverage of the build platform in Figures 13 and 14, which are the most difficult to remove from the build plate after printing.

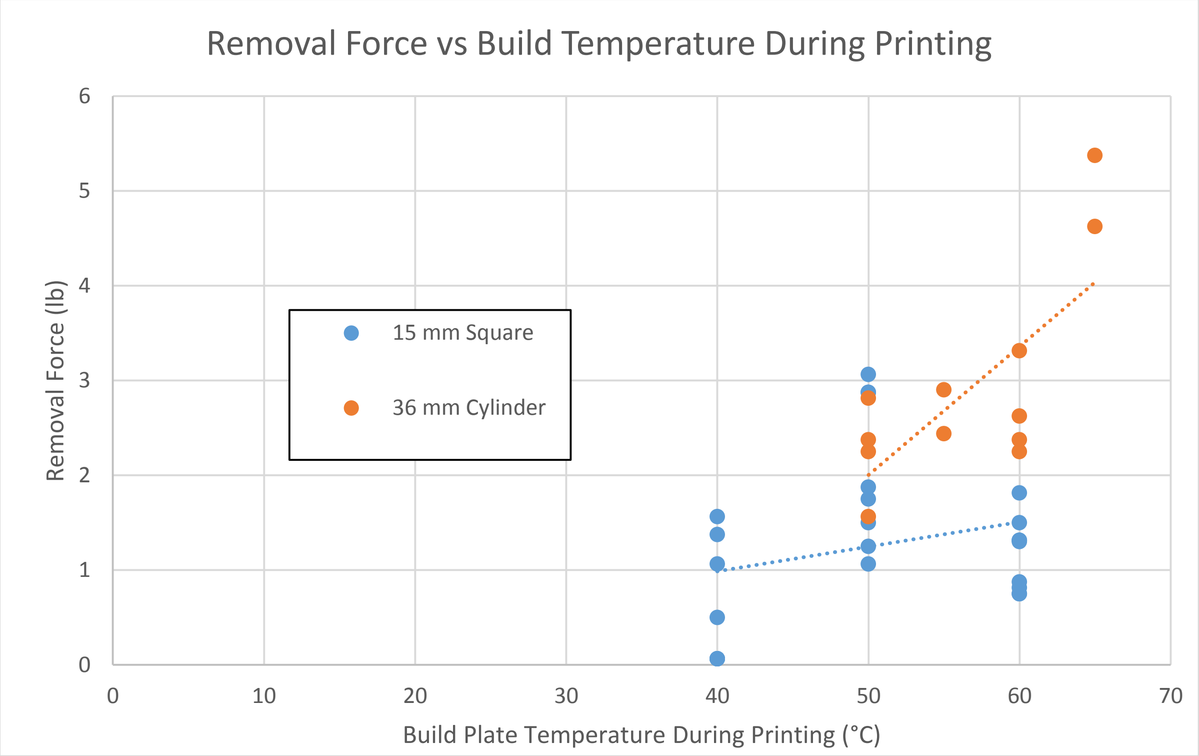


Figure 11: Graph charting how the change in build plate temperature during printing affects part removal force

Figure 12: Tall part with small 7.5 mm square base, used for testing adhesion while building parts

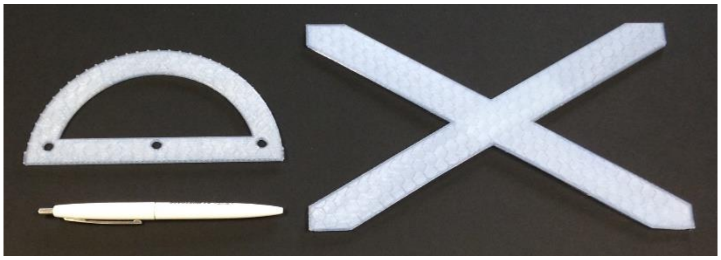


Figure 13: Protractor and large X part used for testing ease of removal after printing

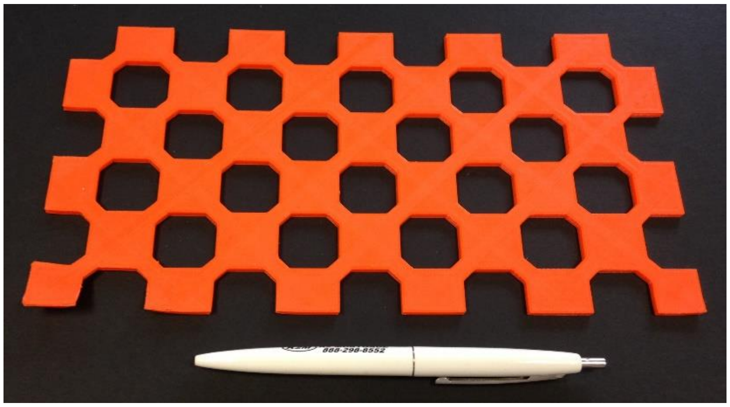


Figure 14: Max size checkerboard part used to determine if build profile parameters were optimized for part removal

Figure 15: Octopus built with rafts to decrease warping

Figure 16: Standard raft on right and modified raft on left for easier part removal. The modified raft is less dense and has thinner lines.

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. 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 0.05 mm Z offset is used. This combination of nozzle distance from the build plate decreases part adhesion for the parts to detach more easily from the build surface after a cooling cycle.

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 15 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 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 16. 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 little to no removal force.

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 17 and 19.

Figure 17: Cat part printed with supports in order to print its overhangs [5]

5. PART REMOVAL

After the thermal cycling process detaches parts from the build plate, a mechanism must deposit them into a retrieval bin so that users can access their parts. As shown in Figure 19, the first sweeper prototype was designed to attach to the printer head. It swept across the build plate at the highest possible part level, then lowered 8 mm and swept again, and continued this process until it swept at the level of the build plate. While this sweeper worked well for most parts, it jammed occasionally because it swept at different heights. Also, it was limited to 5 lbs of removal force and required 3 minutes to complete the removal process.

Figure 18: Cat part with the support structure removed [5]

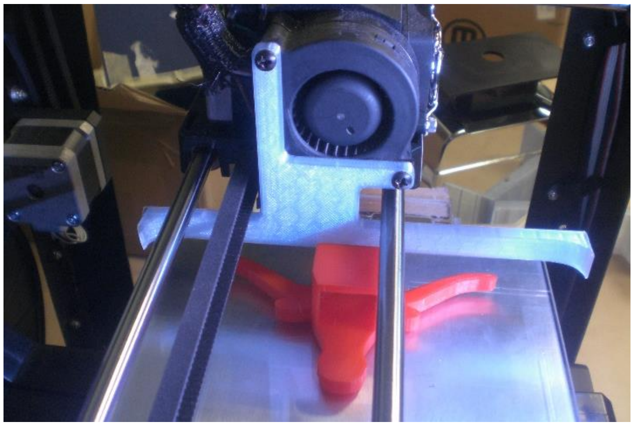


Figure 19: Test sweeper mounted to printer head

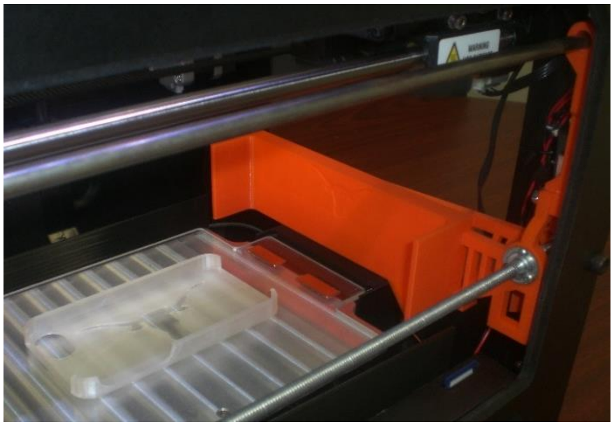


Figure 20: Final version of sweeper

As shown in Figure 20, the final version of the sweeper is powered by an external motor which is activated by the printer head pushing a switch on the top of the 3D printer. The motor is attached via a coupler to a lead screw that propels the 3D printed sweeper across the build plate. The sweeper is also attached to a guide rod to hold the sweeper flat against the build plate. This mechanism solved multiple problems associated with the first sweeper, making it much more reliable. The new sweeper routine requires 1 minute 20 seconds, less than half the time of the original one. It incorporates hard stop switches on each end to insure that it 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.

Figure 21: Multiple 3D printed sweeper iterations

Multiple sweeper shapes were tested until the most reliable shape was identified. Figure 21 shows some of the iterations. All the sweepers were designed so that they did not require supports in order to print 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 22, incorporates a ramp on the front 1.25” of the build plate, to pry large parts off of the build surface as needed. The majority of parts contact the main face of the sweeper directly, providing a more distributed transfer of force to taller parts.

Figure 22: Sweepers with ramps for prying parts

Sweeper guides were added to the build platform because long parts sometimes jammed when they were swept out of the 3D printer. These sweeper guides can be seen in Figure 23. Another problem was that some parts were still attached to the extruder via a small string of PLA after printing. For smaller parts, this string would pull the parts up and over the sweeper during a sweep cycle. To fix this problem, the printer profiles heat the extruder after cooling, which cause the string to detach from the extruder nozzle when the parts are swept out of the 3D printer.

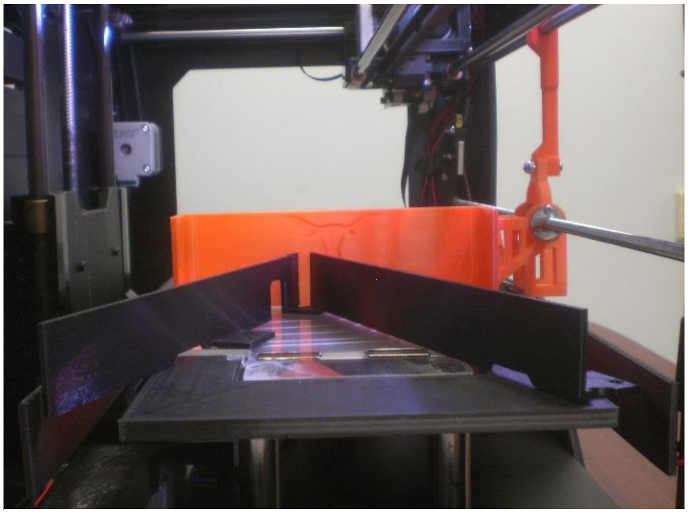


Figure 23: Sweeper guide ramps being swept off the build plate. The mounted sweeper guide ramps keep long parts from jamming as they exit the printer.

6. VENDING MACHINE ENCLOSURE AND PART RETRIEVAL

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. The CAD model of the enclosure can be seen in Figure 24, alongside the actual vending machine in Figure 25. 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. 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.

Figure 24: CAD model of the Innovation Station

Figure 25: Innovation Station in the lobby of the Mechanical Engineering building at the University of Texas at Austin

After parts

are printed, they are swept off the build plate, out of the 3D printer, and into a retrieval bin. 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 26 and 27. 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 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 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.

The vending machine uses as 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 Innovation Station sign was fabricated with a selective laser sintering machine and also shows a unique feature of additive manufacturing. The sign is made so that the words “Innovation Station” are etched into the inside of the sign in layers thin enough to glow when back-lit by LEDs.

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 as can be seen in Figures 28 and 29. A simplified, one printer or two printer vending machine is expected to cost approximately $2,000 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 $450 per printer to add the automatic part removal system.

Figure 26: Vending bin open on the top to receive parts. In this position the drawer cannot open because it is blocked by the handle.

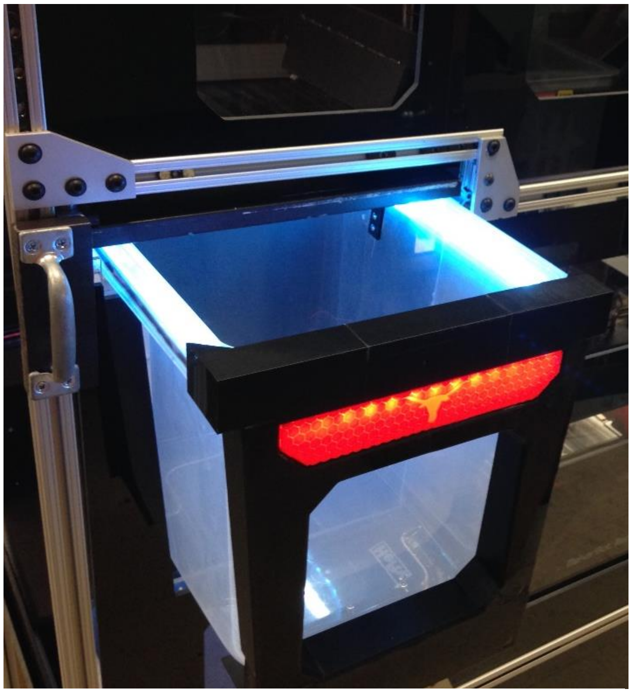


Figure 27: Vending bin closed on the top to prevent vandalism and user injury while the drawer is open

7. CONCLUSION

The Innovation Station will be accessible to all UT students and faculty—anyone with a UT Austin student ID. With two 3D printers and an estimated average part time of one hour, we expect to build approximately 80 parts per week or 4000 parts per year. If demand is high, the machine could be duplicated at a later date to increase throughput. Instructions for creating and uploading parts will be available online, and anyone who wishes to learn 3D CAD modeling could make use of the machine. Students will gain knowledge of 3D computer-aided design and engineering; they will also gain experience in innovation and design-for-manufacturing. More importantly, students will learn to think like designers—to formulate and solve open-ended problems and synthesize a real-world product and its manufacturing process. We expect this project to cultivate a new generation of entrepreneurs.

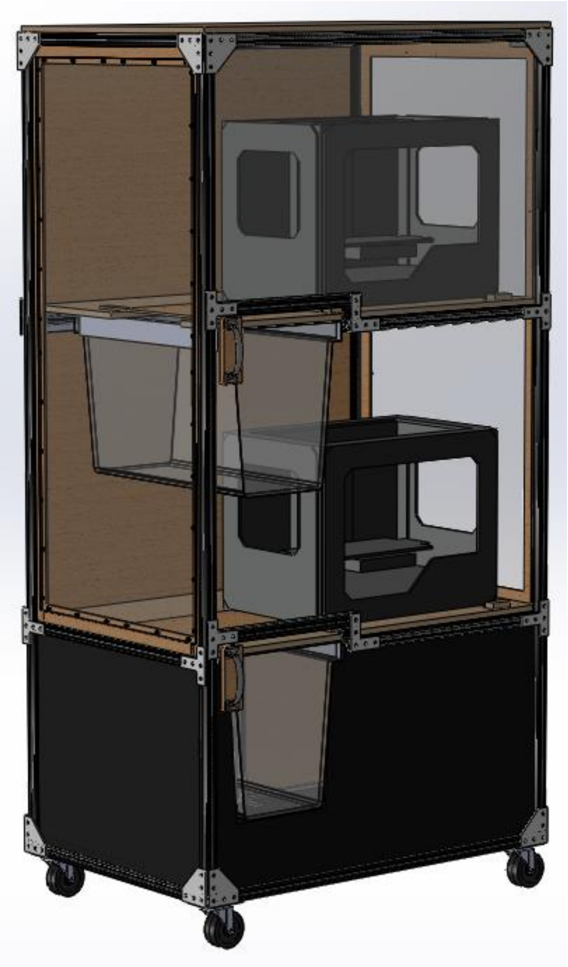


Figure 28: CAD model of the simple, 2 printer vending machine

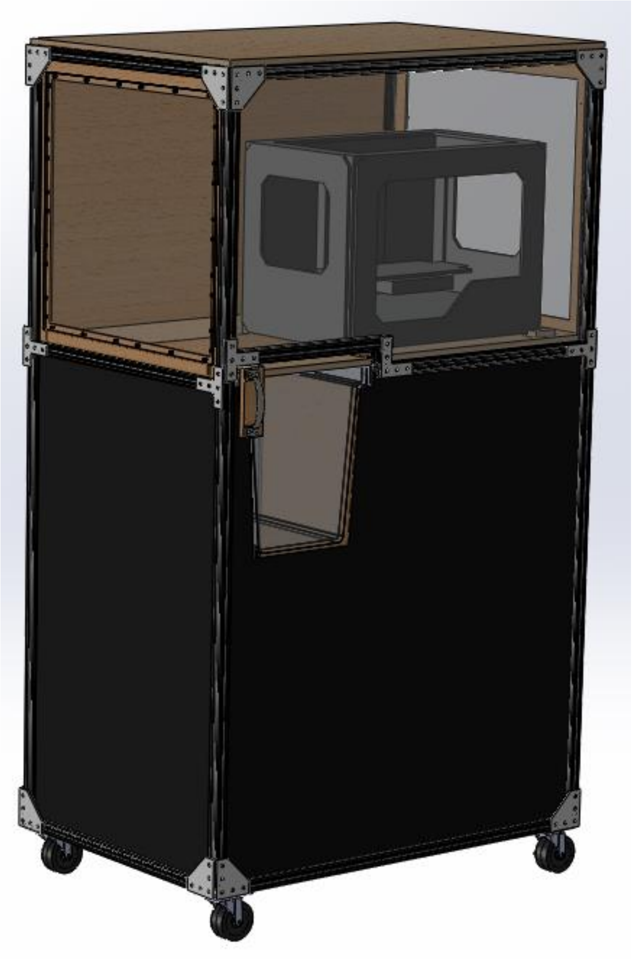


Figure 29: CAD model of the simple, 1 printer vending machine

There is a possibility of continued work on the Innovation Station to add secure part retrieval bays and to provide easily customizable part files on the station's website. By the end of the project some parametric CAD models 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.

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