DESIGN AND FABRICATION OF A POWDER-BASED PERSONAL 3D PRINTER

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Executive Summary

The objective of this project is to design and prototype an open source, open architecture, powder-based three dimensional printer. The group is advised by Dr. Mark Ganter. During the course of the project a prototype system was manufactured and, during subsequent testing, was found to successfully print objects by applying an organic binder to a multi-mode sugar powder.

The prototype system consists of three main subsystems: the enclosure, the powder chambers, and the print carriage. The enclosure is made from a set of interlocking acrylic panels that are joined by threaded fasteners. There are three powder chambers, feed, build, and waste, which store powder in its bound and unbound states. Powder for each layer is transferred from the feed to the build chamber using a manual spreader bar after the feed and build piston are moved vertically by a non-captive linear actuator. The print carriage is supported by a pair of rails and is moved over the powder beds by a rack and pinion gear system. Carriage and print head motion is controlled by stock Lexmark Z735 hardware and software, with only minor hardware modifications.

The main strength of this design is the low total cost compared to all other powder printers and even other open source rapid prototyping systems, with an estimated cost for the end user of $1,600. Due to a small number of parts, the availability of drawings, and a limited number of modifications to the print assembly, maintenance is not only possible, it is simple for an end user to perform. For a first generation prototype, the repeatability, as observed during preliminary testing, seems very promising.

Despite the strengths, many aspects of the first generation design could be improved. Adding a return mechanism would be the first step in fully automating the build process. An improved and automated spreader bar would also allow thinner layers. Finally, a more secure method of mounting to the rails would improve the repeatability.

The P3P represents a significant achievement to be realized in ten weeks. The P3P promises an open source system that allows hobbyists, educators, and anyone with an interest in free-form fabrication to experiment with a smaller investment of time and money than any other platform currently allows.

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Introduction

Background

Rapid prototyping (RP) has been in development in the late 80s as a means to assist the engineering design process by giving engineers the ability to obtain physical representations of the drawings to check size and shape. The immediate advantages of the rapid prototyping include fabrication of parts with complex geometries, low lead times, and the ability to perform small batch runs of products.

The main "printing" mechanism used in RP today is layer-based printing. The RP printer will print successive connecting layers of two dimensional cross sections. The means by which RP machines print layers are varied, including laser sintering or stereo lithography. Parts can be printed in a range of materials including sugar, thermoplastics, and metal powder.

The p3p project uses an inkjet printer to print layers onto a print medium. This is the identical method used by Z Corp, a leading developer and manufacturer of 3D printers. This process is faster, cheaper, and easier to maintain than other RP processes.

As the technology progresses and the new materials become available, the field of rapid prototyping becomes a more viable option in a market saturated by traditional machining processes.

Purpose

The objective of this project is to design and prototype an open source, open architecture, powder-based three dimensional printer. The group is advised by Dr. Mark Ganter.

Problem Definition

The following sections, need, goal, and constraints define the scope and requirements for this project. The functional analysis diagram allowed us to break down the project into pieces that could be tackled by individual team members. The QFD chart guided our design decision as the project progressed.

Need

There is currently no low cost powder-based rapid prototyping system on the market.

Goal

Our goal is to build a low cost powder-based 3D rapid prototyping system (P3P), in the same vein as the Cornell built Fab@Home system. The system should be easily constructed, repaired, and maintained by the eventual users.

Objectives

Table 1 lists the objectives and criteria that for the P3P project. Objectives 5 and 6 should be evaluated using a standard test specimen such as the one developed to benchmark the Z Corp printer.

Table 1 Objectives and Criteria for Project

Objective		Basis of Measurement	Criteria	Units
1.	Inexpensive	Manufacturing cost for one unit	Cost	Dollars
2.	Easily Operated	Number of manual print tasks	Operability	Number
3.	Easily Constructed	Construction and fabrication time	Constructability	Minutes
4.	Easily Maintained	Annual maintenance cost	Maintenance cost	Dollars
5.	Printer resolution	Minimum feature size	Resolution	mm
6.	Small Layer thickness	Minimum feature size	Layer thickness	mm

Constraints

- The total cost for the P3P system must be less than 2000 dollars. This includes parts and fabrication assuming no discounts. Costs also do not include a computer.
- The build envelope may rectangular or circular but must be larger than a five inch cube.
- The material inputs (powder and binder) must be non-toxic.
- The system hardware and software must be open source and open architecture.

Functional Analysis Diagram

A function analysis diagram for this project is shown below in Figure 1. Material inputs and outputs to the system, represented by the dashed line, are thick arrows, while information inputs and outputs are represented by thin arrows.

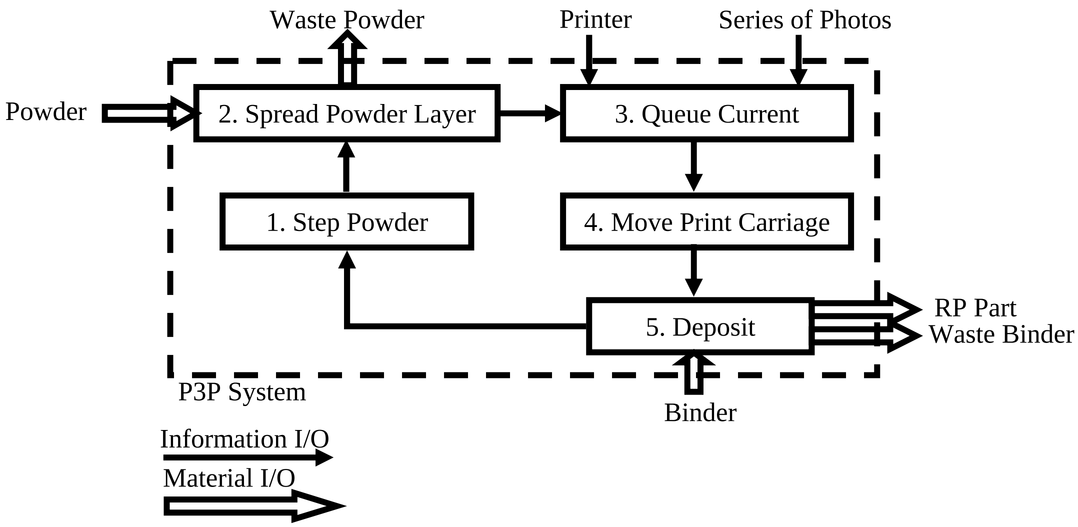


Figure 1 Functional Analysis Diagram

QFD Chart

A QFD chart for this project, shown below in Figure 2 serves to summarize the project objectives and criteria, as well as the constraints. The chart also highlights the areas of concern for this project, cost, maintenance, and esthetics, where the P3P may perform better than commercial systems.

		Engineering Requirements									Benchmarks	
		Component Costs	Print Resolution	Layer Thickness	Interconnecting Parts	Part CAD/Drawing Files	Fully Automated Movement	Limit Switches	Removable Waste Bin	Accessible Components	P3P Current State	Z-Corp 310
Customer Requirements	Inexpensive	X									O	
	Easy Operation						X	X				O
	Easy Maintenance								X	X	O	
	Easy Assembly				X	X						O
	Part Accuracy		X	X								O
	Esthetically Pleasing				X						O	
	Units	$	dpi	inches	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No		
		<2000	>100	<0.005	Yes	Yes	Yes	Yes	Yes	Yes		
		Engineering Targets										

Figure 2 QFD Chart Used for Design Development

Project Timeline

Below in Figure 3 is the proposed original timeline used in the 9 week project timeline set on April 14th, 2008:

14-Apr	16-Apr	18-Apr	21-Apr	23-Apr	25-Apr	28-Apr	30-Apr	2-May	5-May	7-May	9-May	12-May	14-May	16-May
Presentation Preparation														
	Final Problem Statement + Fabrication and Assembly Considerations													
		Finalize Design Concepts and Make Final Task Assignments												
			Begin Prototype Design/Fabrication (Powder Platform)											
			Begin Prototype Design/Fabrication (Printer)											
										Platform + Printer Integration				
							Prepare Progress Report							
								Interim Progress Review						

19-May	21-May	23-May	26-May	28-May	30-May	2-Jun	4-Jun	6-Jun	9-Jun
Testing and Evaluation									
			Final Paper + Final Presentation Preparation						
								Final Presentation	
									Final Paper

Figure 3 Proposed Original Timeline for Project

It was assumed that it would take two full weeks to completely design and fabricate the powder platform (which includes the housing). The printer assembly was given an extra week for design and fabrication. Though after the powder platform was completed, it was assumed the platform and printer integration would immediately begin followed by testing and evaluation.

The corrected timeline to reflect the actual project schedule is illustrated below in Figure 4:

14-Apr	16-Apr	18-Apr	21-Apr	23-Apr	25-Apr	28-Apr	30-Apr	2-May	5-May	7-May	9-May	12-May	14-May	16-May
Presentation Preparation														
	Final Problem Statement + Fabrication and Assembly Considerations													
		Finalize Design Concepts and Make Final Task Assignments												
			Begin Prototype Design/Fabrication (Powder Platform)											
			Begin Prototype Design/Fabrication (Printer)											
							Prepare Progress Report							
								Interim Progress Review						

19-May	21-May	23-May	26-May	28-May	30-May	2-Jun	4-Jun	6-Jun	9-Jun	11-Jun	13-Jun
			Platform + Printer Integration								
							Testing and Evaluation				
							Final Paper + Final Presentation Preparation				
										Final Presentation	
											Final Paper

Figure 4 Actual Project Schedule for Project

The original timeline was more optimistic than originally expected. The powder platform and printer assembly took until the beginning of June to be fully completed due to the long lead times for ordered parts such as the rack and linear actuators, and waiting to for the parts to be water jet cut from the large stock pieces of acrylic. Also, coordinating free time with team members and balancing other workloads caused slow down in the progress. As the quarter drew to a close, progress ramped up due to more free time. The final presentation and paper were pushed back an extra week to accommodate additional testing time. Printing and calibration was performed June 10th, the day before the final presentation was delivered.

Current Technology

The technology for 3D printing revolves around US Patent Number 5204055. This patent, entitled "Three-Dimensional Printing Techniques," outlines a process for making 3D parts using a device that prints binder onto a layer of powder and repeats the process until enough layers have been deposited and bound to form a complete part. The patent was filed by Emanuel Sachs at MIT on December 8, 1989 and the technology has been licensed to the Z Corporation. The Z Corporation currently offers three lines of 3D printers: the 300 series, the 400 series, and the 500 series.

The current 300 series is the Z310 and has the following features and characteristics (from the Z Corp website):

- $19,900 MSRP
- 300x450 dpi horizontal resolution
- 8x10x8 in. build space
- 0.0035-0.008 in. layer thickness

The current 500 series is the Z510 and has the following features and characteristics (from the Z Corp website):

- Full color printing
- 600x540 dpi horizontal resolution
- 10x14x8 in. build space
- 0.0035-0.008 in. layer thickness
- MSRP not listed (if you have to ask, it's too expensive)

The state of the art device in the 3D printing field is the Z510 since Z Corporation is the only company licensed to sell products covered by the MIT patent. The Z510 has incorporated multi-color printing by increasing the number of print heads from one (for monochrome printing) to four.

Concept Generation and Final Design

Operation Overview

The P3P generates three dimensional parts by fabricating and joining a series of layers; each layer is created through an identical cycle. The first step in the cycle, whether at the first layer of a part, or mid-part, is to step the powder beds. A signal is sent to the stepper motor controller to step the feed piston upward a sufficient height to provide the volume of powder needed for a layer, plus an additional amount to account for powder that is lost as waste during spreading. The build piston is stepped downward by the specified layer thickness. Next, powder is spread from the feed chamber, over the build chamber, and into the waste bin using a spreader. The carriage, previously located at the end of the rack, is moved into position near the first limit block, and a print is initiated.

The carriage, positioned by the rails and rail guides, is moved backwards by the drive train until the paper sensor switch is tripped by the limit block, whereupon the carriage moves forward. The print head is passed over the build chamber and deposits binder where material for the current layer is desired. When the print has completed, the carriage moves forwards to the end of the rack, and the second limit block resets the paper sensor to its original position. The cycle is then repeated for successive layers.

Powder Team

Piston Actuation

The size of the build envelope and the minimum layer thickness were the two main requirements that guided the design of piston actuators. The build envelope determined the amount of powder, and thus the load that the actuator must support. The weight of the material, found using the build chamber volume, sugar density, and a factor of safety, was estimated to weigh 4.9 lbf [3]. A factor of safety of 2.0 was applied to account for the weight of the piston and additional load due to friction between the piston and chamber. The build envelope also determined the stroke of the piston actuator. A five inch build height and a 1.25 inch thick piston required the stroke be greater than 6.25 inches, plus the thickness of the motor.

Two methods of actuating the pistons within the chambers were considered before a final design was chosen. The first method was a rack and pinion system. The pinion gear was mounted to a captive stepper motor, and the rack was attached to the piston. This was deemed too complicated, requiring too many points of constraint and sources of binding when powder was present. The rack and pinion and was dismissed in favor of a system involving a non-captive linear actuator. A non-captive linear actuator generates movement of a lead screw by turning a captive internal nut. This actuator provides motion with no external moving parts.

A search for actuator suppliers resulted in three possible sources: ElectroCraft, Anaheim Automation, and Haydon Switch and Instrument. A representative from ElectroCraft did not respond to inquiry soon enough, and was excluded from the list of suppliers due to time constraints. The Anaheim Automation model 23A linear actuator met the load requirements and was available with custom stroke lengths, but cost $215 dollars each. Haydon Swich offered several hybrid linear actuators that satisfied the design requirements. The 21000, 28000, and 35000 series actuators were compatible with the stepper controller board, exceeded the load requirements, and were available in custom screw lengths. Ultimately the 35000 series was chosen for the lowest cost, $110. The custom lead screw was 7.5 inches long with a type B thread, which allowed for a travel of 0.000625 inches per step.

Housing Design

Revision 1

The first revision, shown in Figure 5, characterizes the primary components of the final printer. The components include the railing and powder chambers that are used in later revisions. The powder chambers are a fixed component to the top component, which was removed in favor of the easily removable powder chambers. There is no proper housing, waste container, drive train, or linear actuator mounts.

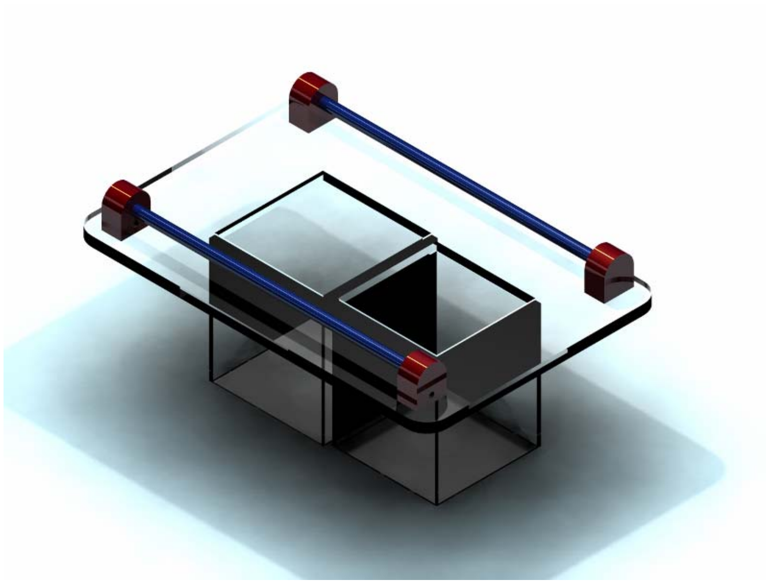


Figure 5 Revision 1 of the P3P Housing with Attached Rails and Fixed Chambers. Trimetric View (left)

Revision 2

In the second revision, shown in Figure 6, the top panel was supported by tall housing walls which gave the printer the height to accommodate the 7.5" long drive shafts used in piston actuation. The two larger housing walls (left and right) supported two linear actuator braces bridged across the two walls. Both larger walls had large access openings to allow for easy maintenance of parts inside the housing. All of the housing walls have several blank areas to attach any required circuitry. A wide waste bin was now available at the front of the housing that could be easily slid out of the housing. The rail supports that were originally a separate component at the top of the frame now were replaced by fixed acrylic pieces on the housing. The material planned for this revision was ½" acrylic.

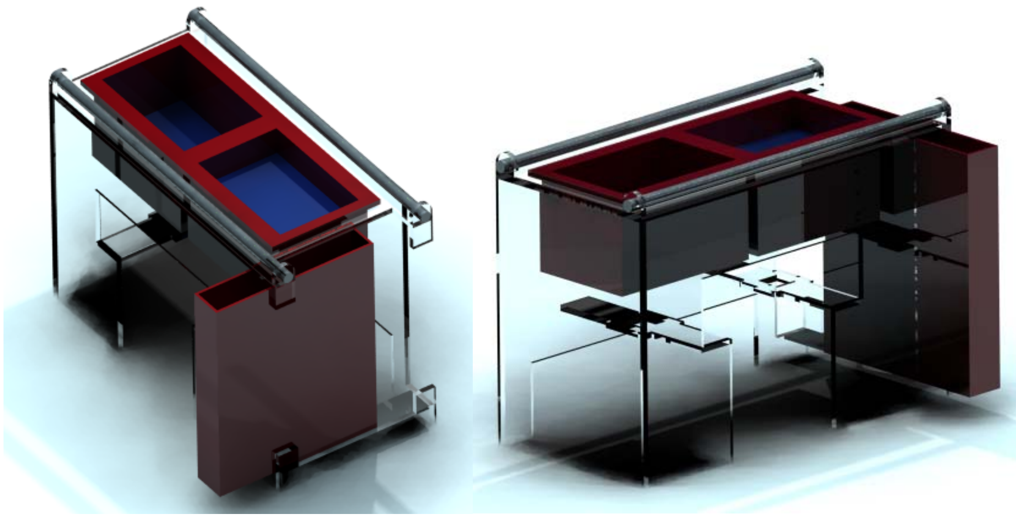


Figure 6 Revision 2 of the P3P Housing with Attached Rails, Chambers, Pistons, and Waste Container. The linear actuators are not pictured. Trimetric View (left). Rotated back view (right).

There were several reasons for the rejection of this revision. The chambers were easily removed but sat above the top surface, which would make it more difficult to spread powder due to the higher elevation of the print chambers. This revision was not wide enough to accommodate the size print head used and does not include a linear drive system. The motor mounts were determined to be extraneous and difficult to position into the chambers. Lastly, this model assumes that all of the components glued to each other without any fasteners.

Revision 3

The third revision widens the entire housing in order to better accommodate the printer carriage. As can be seen in Figure 7, the left wall of the housing was composed of the linear actuator mounts and two hinged doors that were attached to the front and back walls of the printer. The doors would allow protection from dust when the printer was actively printing. The components within the printer could be easily reached when the doors were opened. The doors were designed to be held closed by a set of magnets. The opposing wall was provided a large surface to attach the required circuitry. A hole was cut in the center of the wall to feed any wires, such as the power or USB cords, through the housing. The rail supports were moved to the far sides of the housing and moved below the top panel surface due to the shape of the print carriage. The chambers were now flush to the top panel surface due by using braces attached to the underside of the top panel. Each chamber has front and back flanges that rest on the braces.

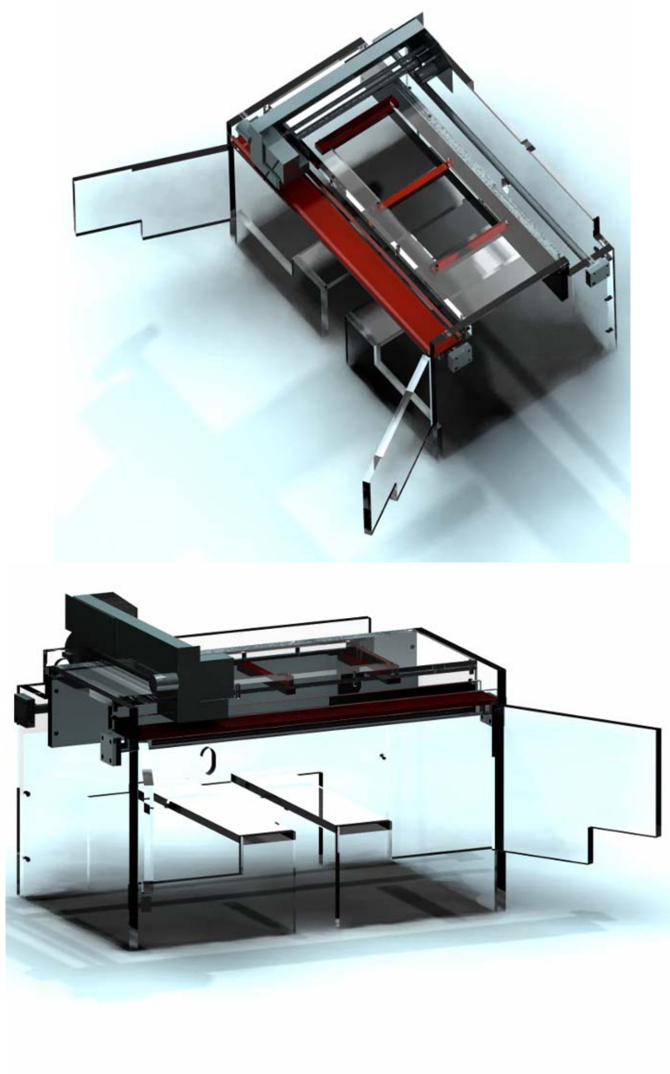


Figure 7 Revision 3 of the P3P Housing with Attached Rails and Printer Head. The doors are in the open configuration. The chambers and linear actuators are not pictured. Trimetric View (left). Rotated back view (right).

Revision 3 greatly resembles the final design with several key distinctions. The linear actuators were still attached to the frame itself which made it difficult to position correctly into the chambers, which caused the motors to be moved to the underside of each chamber. While the doors provided easy access to the inside of the housing, they were determined to be extraneous and difficult to implement. A sponge tray, colored red and located on the left side of the housing, was designed to prevent ink leakage from the carriage at the resting position. Like the second revision all of the frame components are assumed to be glued not fastened. Lastly, there is no waste container was removed in this revision of the housing.

Chosen Design: Revision 4

The final design, or revision 4, is simplified version of the revision 3 with the major difference being the new position of the linear actuators. Many of the general features from revisions 2 and 3 are used in revision 4, such as open space on the left side of the frame for easy access, the large right side wall for any circuitry, the use of braces to make the chambers flush to the top surface, and a removable waste container (see Figure 8).

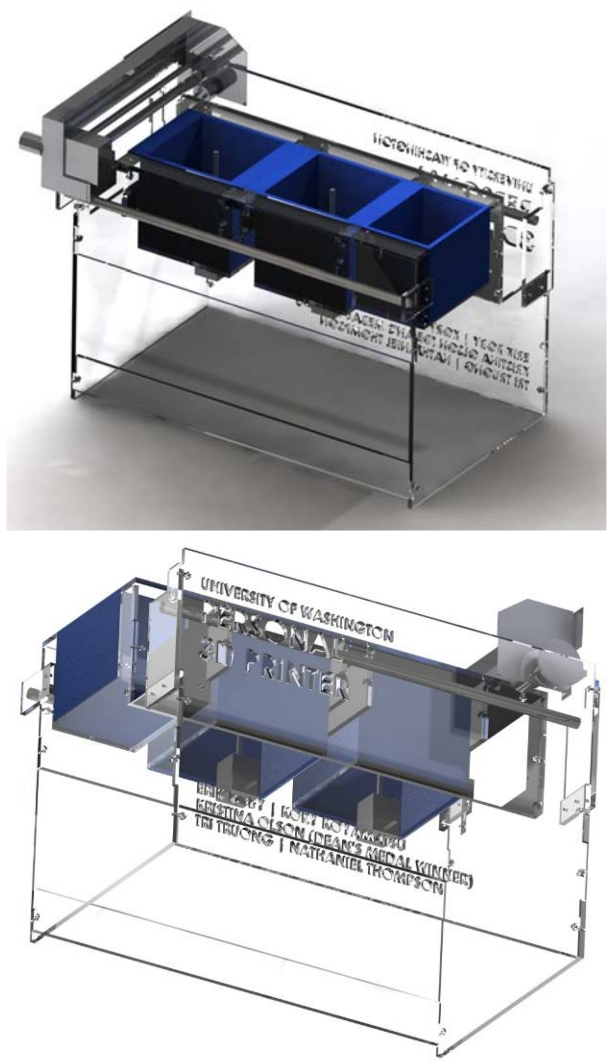


Figure 8 Revision 4 of the P3P Housing with Attached Railing, Waste Containers, Chambers, Linear Actuators, and the Printer Carriage.
The rack, limit switch blocks, and rack are not pictured. Trimetric View (left). Rotated back view (right).

One of the most important objectives in the design was keep costs at minimum. In terms of the housing, less material with less complicated geometries were ideal to the maintaining the low cost. The linear actuators were moved from the original bridged motor mounts and fastened to the underside of the chambers in an effort to reduce material usage. The overall frame is slimmer due to implementation of the separate rail mounts that are later fastened to the frame. Previously, the rail mounts were cut directly into the front and back walls, as seen in revision 3 (Figure 7), which forced a larger amount of material to be used for no purpose.

In an additional effort to save costs, the original ½" thick acrylic used in revision 2 and 3 was replaced with the 1/4" thick acrylic. Since the acrylic was thinner causing the rigidity of the overall frame to come into question, so several extra features were added in an attempt to make the entire housing stronger. Four cross braces which spanned the left and right walls were attached within the main frame, each directly underneath each of the four chamber lips. Small slots were cut into the sides of the braces into the chamber braces and the left and right walls to ensure proper constraint in addition to using fasteners. A majority of the housing pieces used similar slotted patterns to increase strength of the frame by allowing the pieces to rest against each other.

In addition to the strength increase caused by the slotted features, the features also simplify the assembly process. With the exception of the top panel and the waste container frame, most of the other features interlock in only one specific configuration. When pieces were interlocked, they can be fastened together using screws. An example of this slotted design is illustrated in Figure 9.

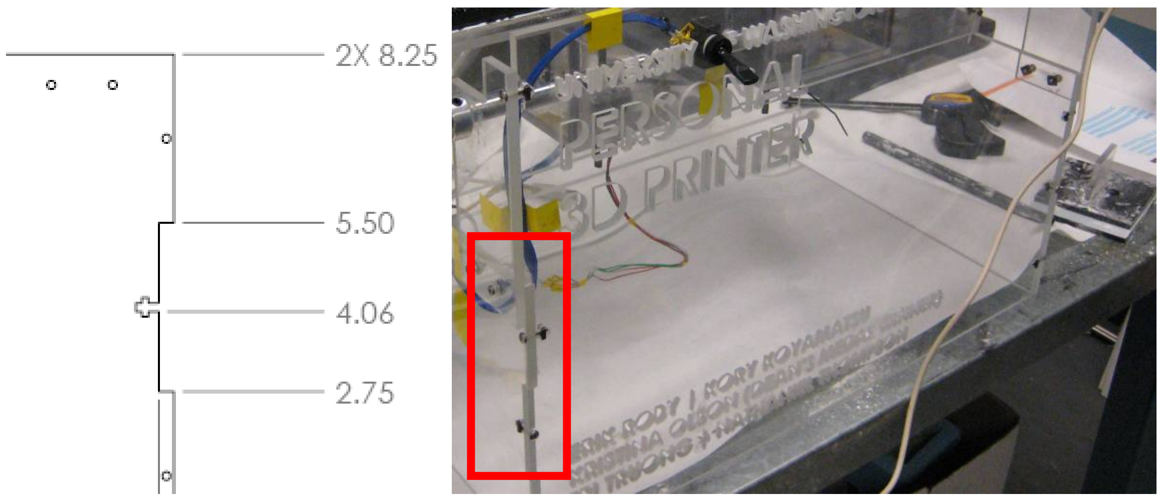
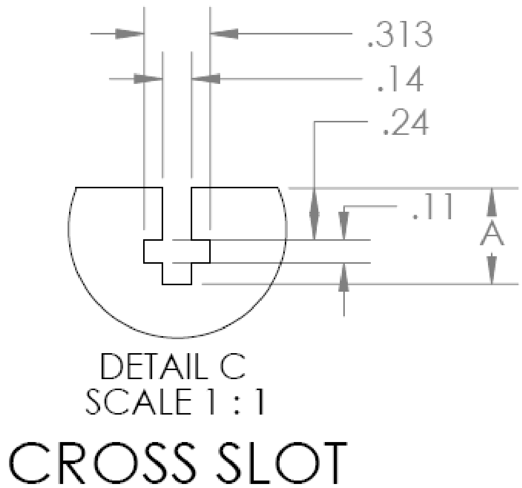


Figure 9 Example of the Slotted Features.
Pictured above is the (left) front end panel (015) and the (right) same paneled assembled with the right side wall and the right rail brace.

The frame utilizes a unique cross slot pattern to fasten all of the pieces together, featured in Figure 10. The advantage of the cross slot frame is to negate the requirement of tapping the separate pieces. The pieces are fastened using a combination of the screw and a square nut instead. The housing uses 6-32 screws at a combination of lengths, though a majority of the screws are 5/8" in length in order to maintain the simplicity of the design.



	DIM A
CROSS SLOT - TYPE 1	.38
CROSS SLOT- TYPE 2	.45

Figure 10 Geometry of the Cross Slots and the Dimensions for the Two Types Used in the Housing Assembly

There is a channel between larger right side wall and the right side print wall to accommodate future attachments including our rack, rack spacers, and limit switch blocks. Since they were future additions they do not take advantage of the cross slot feature, instead the components are attached to the main housing using glue or a screw and nut combination.

Powder Chambers

The P3P uses three powder chambers: feed, print, and waste. The feed chamber stores fresh powder to be spread into the build chamber, in which layers are printed. The waste chamber stores powder that was not used in the build chamber, or was cleaned off from a finished print. The internal size of the build and feed chambers, defined by the build envelope, was 5 inches square by 6.25 inches tall. An extra 1.25 inches was added as clearance for the pistons. The waste bin size is arbitrary and was chosen to be the same width as the other chambers, but only 4.125 inches long.

The original design concept called for two identical chambers for the build and feed. The four side-walls were a single piece with flanges attached at the top to seat the chamber on to the enclosure. The internal corners of the cambers were filleted to improve contact with a piston seal, and the bottom was removable to service the piston drive system. The waste bin was a simple single-piece box. The waste, feed, and build chambers would be rapid-manufactured on the Stratasys Dimension system.

Due to their large volume, the chambers required too much material and build time to rapid manufacturing. An alternate design was selected to replace the single piece side-walls with four polycarbonate plates. The end of each plate butted against one the face of the next to ease fixture during bonding. The choice of polycarbonate as a build material was driven by its machinability, but was later found to present difficulty during bonding.

Pistons

The build and feed cambers each contain a centered piston. The purpose of the piston in the feed chamber is to feed a specified amount of powder above the top plate, which is then spread into the build chamber. In the build chamber the piston also serves as the build surface.

The original design for the pistons involved a block, with 1/8th inch clearance between the piston and all walls. Two semi-circular stacked grooves around the perimeter of the pistons were filled with ¼ inch foam that sealed against the chamber walls. The double groove minimized out of plane movement that could potentially damage the lead screw and motor. The pistons were to be fabricated using the Dimension system.

Large material costs, and the choice to manufacture the cambers by hand led to a redesign of the pistons to mimic the chambers. The updated design involved a stack of five polycarbonate plates, with two smaller plates providing a ¼ grove for the foam. A threaded insert was captured between the bottom two plates and was used to attach the lead screw to the piston. Sandpaper was adhered to the top surface to hold the powder in place. When the full-size foam proved to cause too much friction between the piston and chamber the foam seals were split in two and sandwiched the central plate.

Printer Team

Printer Selection

In order to use a printer for the P3P project with as little modification as possible, great care had to be taken to choose a printer with desirable qualities. These qualities included the following:

- Simple design
- USB interface
- Lightweight design
- 1 print head/cartridge
- 1 paper sensor

The original intention for the project was to use a compact photo printer to print the binder onto the powder. It was believed that the small size would equal significantly less weight and allow the entire P3P assembly to be more compact. However, after inspecting many different printers, it was found that the photo printers did not offer any significant weight reduction. Also, the photo printers were so small that the mounting hardware needed to be mounted on the outside of the print carriage thereby negating any reduction in assembly size.

The following table provides a list of the 10 printers considered for use on the P3P along with the pros and cons of each printer.

Table 2 Pros and Cons of Different Printers Considered for Use on the P3P Project

Printer	Pros	Cons
Canon Pixma iP3000	-USB interface	-Complicated design -Complicated paper feed mechanisms -4 print cartridges
Epson Stylus Photo R800	-USB interface	-Complicated design -6 print cartridges
Canon BJC-4300	-Simple design -1 print cartridge	-Parallel interface -Old hardware
Lexmark P315	- Lightweight -USB interface	-Too small -2 paper sensors -2 print cartridges
Canon i455	-USB interface	-2 print cartridges
HP Deskjet 3845	-USB inteface	-Front load paper tray -2 print cartridges -Large and heavy
HP Deskjet 3820	-USB interface	-2 print cartridges -Large and heavy
Lexmark Z735*	-USB interface -1 print cartridge -Lightweight -1 paper sensor	
HP PhotoSmart A310	-Lightweight -USB interface	-Too small -Complicated design -Battery under print head assembly
Lexmark Z35	-Lightweight -USB interface -1 paper sensor	-2 print cartridges -Stepper for paper feed

One of the common problems faced by many printers was a complicated design. The complicated designs allowed the printers to have many robust printing options, but these add-ons cluttered the print carriage and introduced complicated electronics that had to be bypassed or taken out. The cluttered carriage was also a problem with the printers that had front-loading paper trays and batteries underneath the print head where the P3P needed to be. These extra devices would require undesired modification for removal.

Another problem faced by almost all of the rejected printers was the presences of multiple paper sensors. The drawback of the sensors was that each of these sensors needed to be “tricked” into “thinking” that an adequate supply of paper was in the paper feed chamber or that paper was being fed through during printing. The more paper sensors on the printer carriage, the more sensors that needed to be tricked during each layer print. Luckily, it was found that the full sized Lexmark printers used only one paper sensor and that the sensor could easily be manipulated to tell the circuit board that paper was being fed through the carriage. This was a major factor in choosing the printer for P3P.

The printer chosen for the P3P project was the Lexmark Z735. The Z735 had only one print cartridge, only one paper sensor, and a USB interface for use laptops. The Z735 also boasted a simple design and, because of the absence of robust extra features, was able to provide a full-sized printer carriage with just as little (if not less) carriage weight than the compact photo printers. The Lexmark Z735 was easily disassembled and required little modification to integrate into the P3P assembly.

Drive Train Method

The first variation of the drive train for the P3P involved placing the printer carriage on a flat, raised surface and letting the paper-feed roller roll across the surface pulling the printer as it rolled. This rough system verified that the paper-feed motor on the printer did indeed have enough power to move the print carriage along as necessary for printing. However, there were two main issues with this roller based drive system.

The first concern was that if powder spilled on the roller or rolling surface, the roller might slip and cause skewed print jobs. This problem was solved by using a rack and pinion system. The roller was replaced by a pinion gear and the rolling surface was replaced by a rack so that even if the teeth of the gear and rack collected debris, the system would still be able to maintain traction. Because the roller was designed to feed paper through at the speeds required to print, the pinion gear needed only to have a pitch circle diameter equal to the diameter of the paper-feed roller in order to maintain the proper rotational motion to linear motion conversion.

The second concern with using the printer motor to drive the carriage was that using the printer roller or a single pinion gear caused the carriage to move in the wrong direction with respect to the print surface. When paper is fed through the print carriage, it passes over the top of the paper feed roller. This causes the print surface to move in the direction shown in Case (a) of Figure 11. Unfortunately, when the paper-feed roller was placed directly on the print surface, the direction of print surface movement relative to the print head was backwards (Case (c) of Figure 11). Because the printer prints an image in sections, the reverse direction caused the printed image to look like Printed Section (b) from Figure 11.

In attempting to solve this particular reversal issue, many actions were taken. First, the leads on the DC paper-feed motor on the printer carriage were reversed. It was thought that reversing the polarity of the current passed through the motor would reverse its direction. This was true, but the optical comparator used in conjunction with this DC motor recognized the direction of rotation and caused the printer to stop working. The next step was to remove and remount the optical encoder wheel in the opposite direction. Unfortunately, this also failed as the printer controller board still realized a difference in configuration. The motor leads and optical encoder wheel were promptly returned to their original configuration.

The final solution to the drive train direction problem was to add another gear to the train. This intermediate gear served to re-reverse the direction of linear movement to match that of the original, paper-based printing configuration. A schematic of this two-gear design is illustrated in Case (c) of Figure 11.

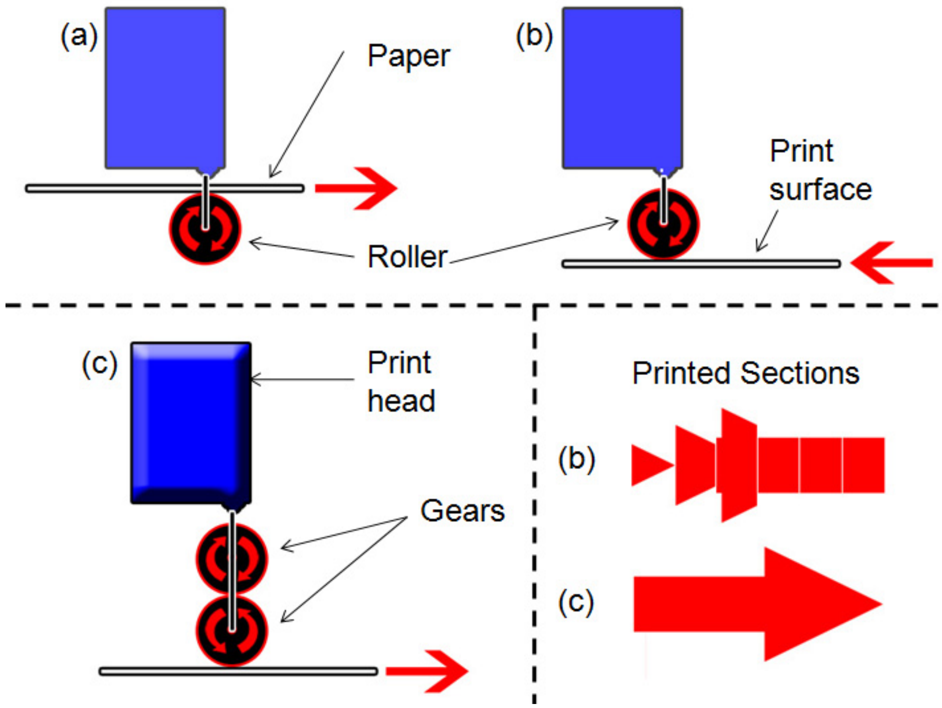


Figure 11 Schematic Diagram of the Drive Train for the P3P
Case (a) shows an unmodified printing configuration. Case (b) shows the reverse-driving roller configuration. Case (c) shows the final dual-gear corrected configuration.

The method for mounting the two-gear drive train was to design a gear bracket that attached directly to the printer carriage. This bracket was made from ABS plastic using the Stratasys rapid prototyping machine. The gear bracket aligned the drive (top) gear in the position of the paper-feed roller—which was cut off to make room. This drive gear was adhered to the shaft that once connected to the paper-feed roller. The intermediate gear was then mounted in the bracket directly below the drive gear. This intermediate gear then interfaced with the stationary rack to drive the system. The drive train system is pictured in Figure 12.

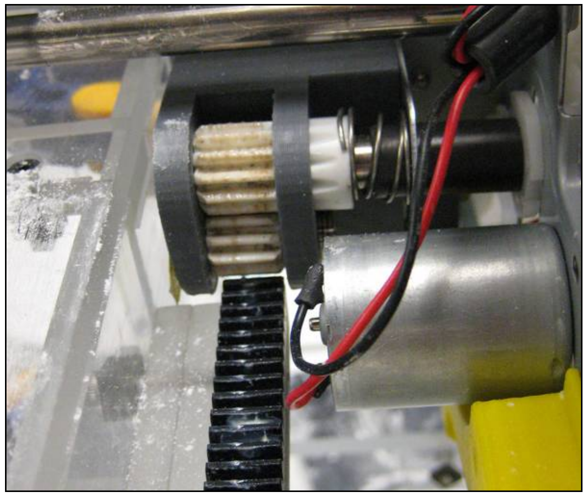


Figure 12 Dual-gear, Rack and Pinion Drive Train System for the P3P

Rail Mounts

The rail mounts acted as the interface between the printer carriage and the printer enclosure. The mounts had two main responsibilities:

- Suspend the printer carriage at the correct height above the print bed
- Maintain printer carriage alignment as the drive train propelled the carriage across the build chamber

Several designs were considered for the rails and rail mounts including an overhead system from which the printer hung. This hanging design was rejected since the overhead rails would make it more difficult to remove a finished part from the build chamber.

It was finally decided to use a system of two rail mounts: one on each side of the printer carriage. These rail mounts attached directly to the metal carriage frame to ensure the ability to support the full weight of the carriage assembly. The rail mounts were designed with slots so that they could slide directly over the sheet metal of the frame. Square nuts and screws were then used to secure the mounts in placed.

Paper Trip Switch

One of the problems with using a stock printer was that we were forced to work with the stock printer drivers. The printer is designed to be able to tell if paper is present, when paper enters, when paper leaves, and if the paper jams. The printer is able to detect a paper jam by two methods, the first type of paper jam is detected if the paper sensor switch is left “on” after the print job has finished. The second method is if the optical encoder on the paper feed rod is stopped by the gear train jamming. All of these situations had to be accounted for in order to force the printer to print without paper.

The paper sensor is an optical gate on the main circuit board that has a piece of plastic blocking the gate when there is no paper. When paper enters it causes the plastic to move out of the way and open the gate. After considering several mechanisms to actuate the plastic part, it was decided a much easier solution would be to solder wires to the back of the board where the gate contacts were. This would make it possible to place a mechanical switch anywhere on the housing. Figure 13, below, shows the installed paper switch and the soldered circuit board wires. After the wires were connected to the circuit board, several options were conceived for dealing with the switch inputs.

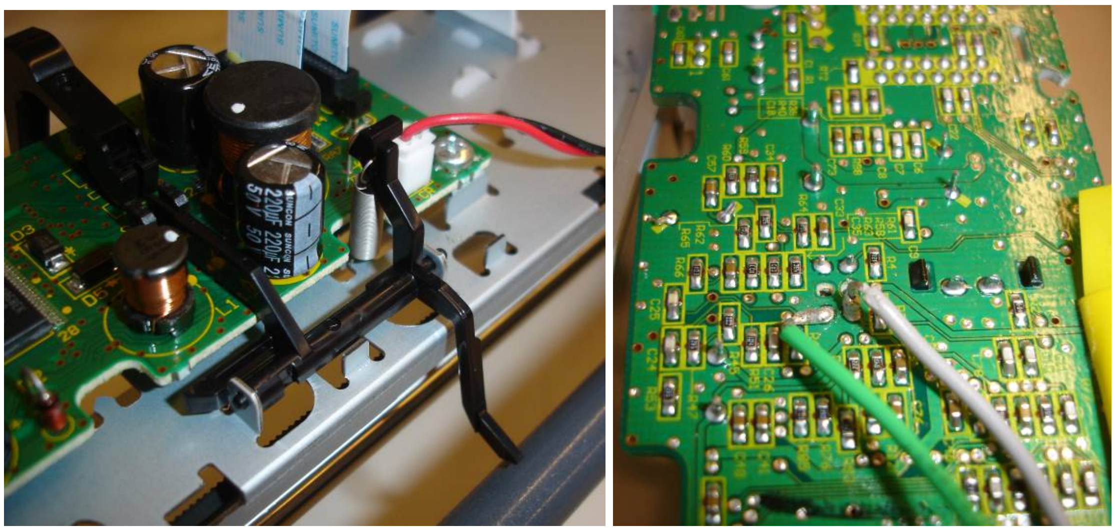


Figure 13 Photos of Paper Switch (left) and Soldered Circuit Board Wires (right)

It was known that the print carriage would move in reverse direction until it detected paper, at which point it would immediately start to move forward and print. It was also known that the printer would have a paper jam error if the paper switch was not released soon after printing was complete.

The first option to solve this problem was to use two switches in parallel. The first would be a momentary contact switch that would be mounted so the printer would push the switch when it started to move backwards. Soon after printing was started, a second switch would be actuated and stay in the “on” position until printing was finished. The exact mechanism that would engage and disengage the second switch had not been determined.

Testing soon revealed that this solution would not work. If the first switch is released even for a short period of time during printing, the printer will think the paper has been ejected and will stop printing. This meant that only one switch could be used.

The final solution to this problem was to mount a slider switch underneath the gear train. Just before printing, the switch would be in the “off” position to represent no paper. As soon as the printer started to move backwards, the switch would be engaged by a stationary piece of plastic mounted beneath the rack at a specific location. This location was set so that printing would commence as soon as the print head was at the top of the build bed. The switch would then stay “on” until it reached the end of the rack. The rack was mounted so that after the printer passed the bottom edge of the feed bed the gear train would no longer be in contact with the rack. This was done to keep the printer from paper jamming if the gear train locked up (after the printer finishes printing the paper feed motor will run for a short period to eject the paper). As soon as the printer was off of the rack, another stationary piece of acrylic would disengage the switch to tell the printer that the paper had been ejected. Figure 14 below shows the switch and both plastic switch actuator pieces.

Figure 14 Photos of Paper Switch (left), Engage Piece (center), and Disengage Piece (right)

Frame Reinforcement

After the print carriage was mounted, it was determined that the frame was far too flexible. A large torque is applied when the printer moves, because the drive train was on one side of the carriage; this caused the rail mounts to bind up because of the large frame flex.

Because this problem was discovered so late in the project, there was not time to design and machine parts to fix the problem. In order to quickly solve the problem, some of the extra acrylic pieces were secured to the frame and then glued together. A piece was attached to the drive train side with three screws; another piece was attached to the opposite side, also with three screws. Both of these parts were attached so that a flat side of the plastic would be level with the top of the print carriage frame. A third piece was connected to the top of the frame using three screws, and then all of the parts were glued together to create a more rigid outer frame. Figure 15 below shows one view of the outer frame. This frame was able to reduce most of the flex and allowed the carriage to move on the rails.

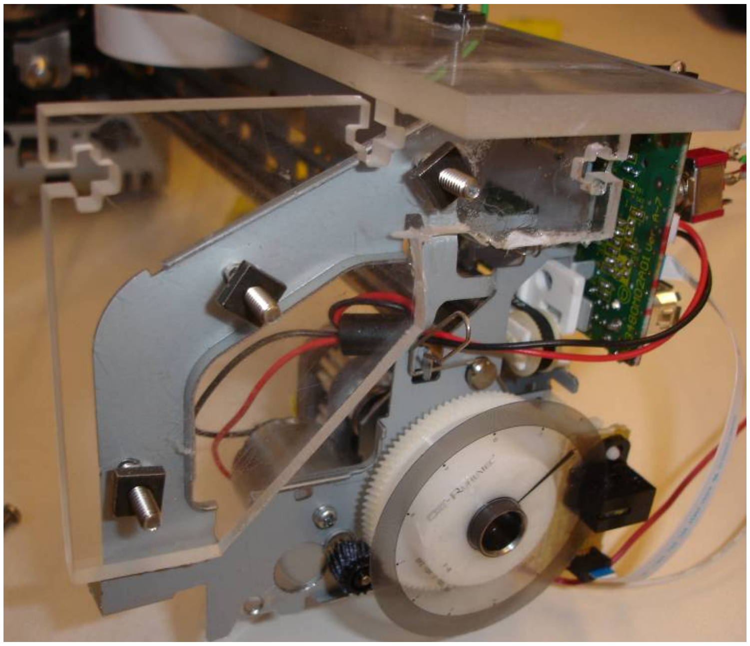


Figure 15 Photograph of Outer Frame

Control Team

Amplifier Board

In order to control the motors for the feed and part bed pistons, a control or amplifier board was necessary to provide power and step the motors. The initial requirements of this board were that it has at least 3 axes of control, allow for the use of limit switches, and be controllable through a computer or other interface. A Xylotex XS-3525/8S-4 Stepper Driver Board was used as the amplifier board as it met all the requirements with the added benefit of being immediately available for use.

Control of the motor signals was provided using a laptop running Win95 and DOS. Communication between the laptop and board was through the parallel port of the laptop using a DB25 – IDC26 ribbon cable to connect the 25 pins of the parallel port to the 26 pins on the Xylotex (see Figure 16 for a photo showing this cable connection). The computer was used to interpret limit switch information and control step commands to the motors through the Xylotex board.

Power for the motors was derived from an Agilent power supply set to 24V. This power supply was attached to the Xylotex board using the screw terminals with ground connected to GND and +24V connected to the V_{BB} connection (as shown in Figure 16). The Agilent power supply was chosen for it's convenience for testing and reliable voltage, however any 24 VDC power supply would be acceptable. Xylotex recommends using 24V (over 12V) for better performance [1], and motor tests indicated that 12V was not sufficient to run both stepper motors.

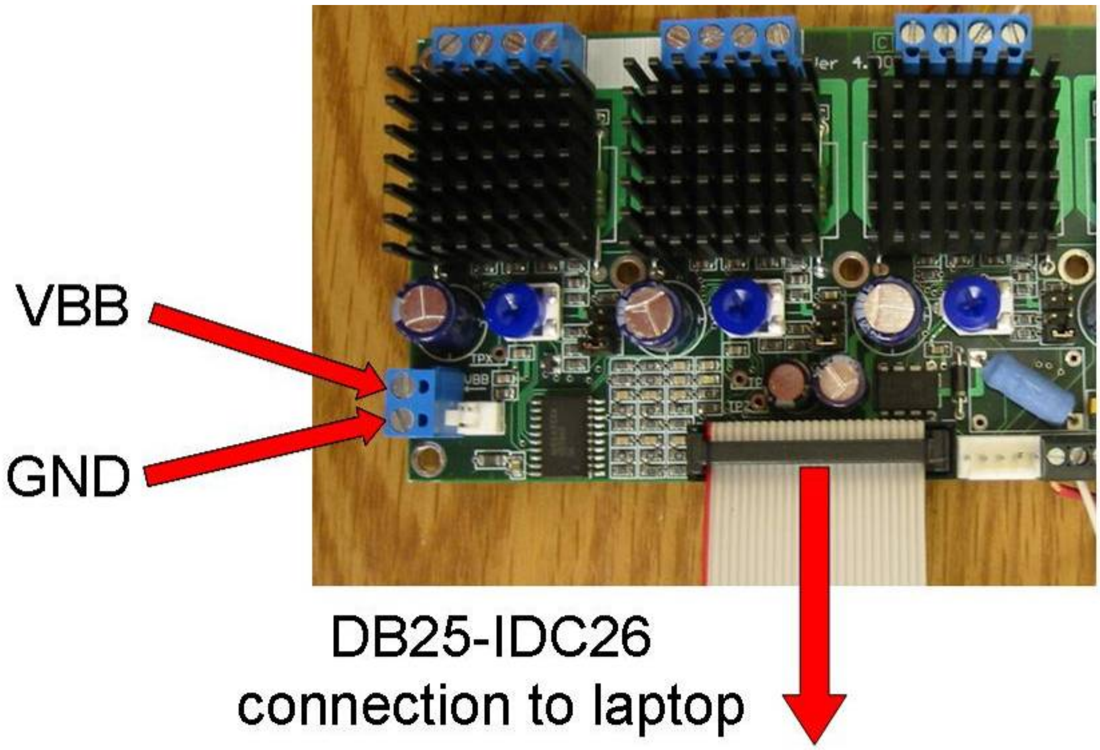


Figure 16 Connections for Power Supply and DB25-IDC26 Ribbon Cabel to Xylotex Board

The board had 3 functional axes, providing for the ability to control both pistons with the option of an additional step motor considered for previous design revisions. Motors could be connected using the screw terminals for the X, Y, and Z axes. As shown in Figure 17, each axis consists of four screw terminal connections labeled A, A#, B, and B# (a preceeding letter indicates the axis, for example, the X axis connections are XA, XA#, XB, and XB#). The HSI motors used come with four wires: red (R), red with white stripe (RW), green (G), and green with white stripe (GW). The part bed motor was connected to the X axis and the feed bed motor was connected to the Y axis using the following connections:

HSI wire color:	R	RW	G	GW
Xylotex connection:	A	A#	B	B#

Switching either R and RW or G and GW (but not both) would reverse the direction of the motors. The noted configuration works with the directions specified in the programming such that the motor turns in the correct direction.

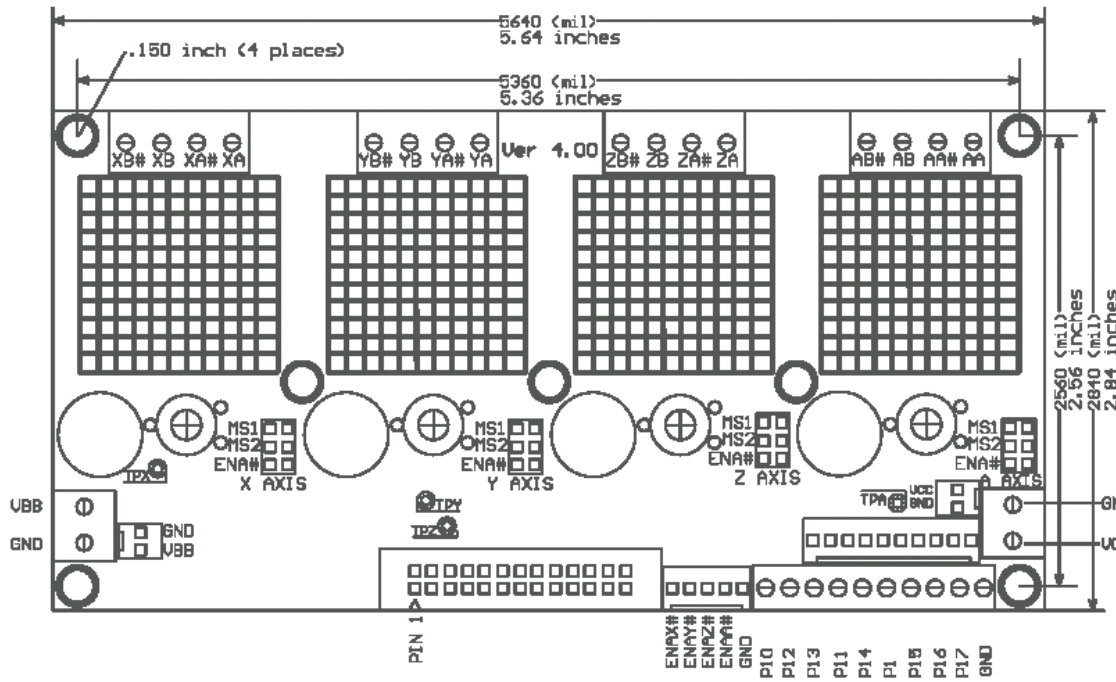


Figure 17 Xylotex Board Diagram (courtesy of Xylotex Inc. [1])

Limit switch input could be communicated through the board using the TB AUX connections (noted with numbering system in Figure 18). These connections allow for using the otherwise unused pins of the DB25 – IDC26 parallel port connection, thus allowing the connected computer to read the limit switch information. The V_{CC} terminal maintains 5 V for TTL logic. The xylotex board allowed for the inclusion of up to 8 direct switch inputs (TB AUX connections 2 through 9). TB AUX connections 1 and 10 are V_{CC} and GND, respectively. The mapping of the available TB AUX connections to their corresponding laptop registers are indicated in Appendix D. Of the 8 possible connections, 2 were used in the prototype for limit switches. Normally open (NO) switches were used in the design allowing the code to remain functional as switches were removed during design changes. One side of each switch was connected to GND while the other was connected to the desired TB AUX screw terminal.

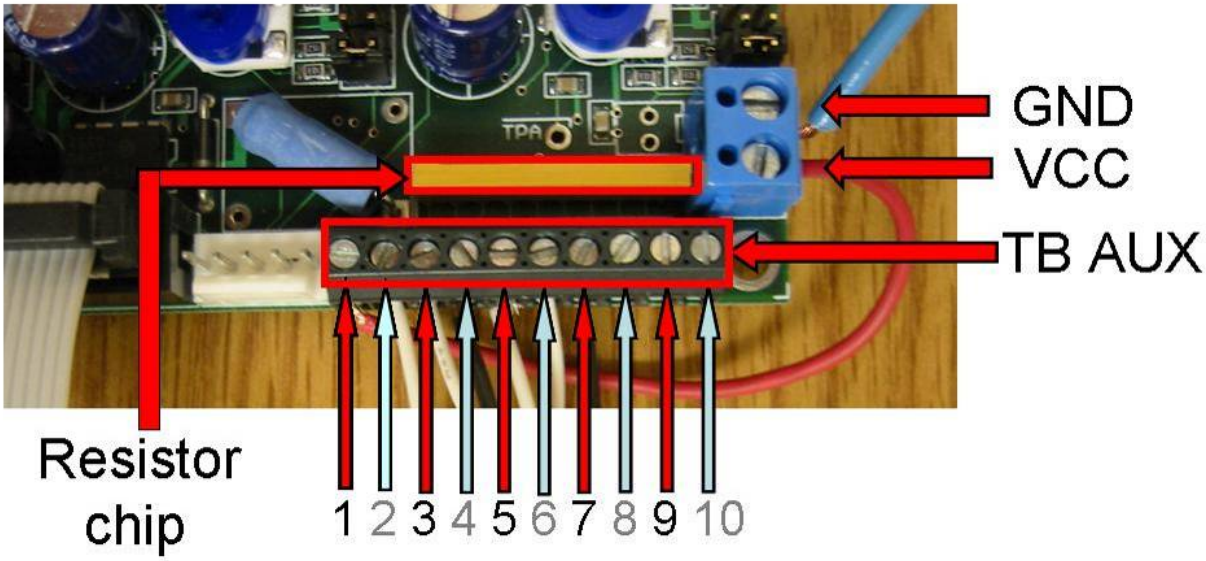


Figure 18 Diagram of Limit Switch Connections

The Xylotex board is not configured for limit switches as ordered. In order to use the TB AUX connections for limit switches two changes must be made to the board. Firstly, a wire must be added between the first screw terminal connection of the TB AUX board and V_{CC} (Figure 18 shows a red wire attached as described). Secondly, a 10 resistor pull-up chip should be soldered on in the location indicated in Figure 18 (pin holes for this chip shown in Figure 17).

One benefit to using the Xylotex board was that it had the capability to enable or disable the motors to prevent overheating and eventual burn-out. The ENA# jumpers (see Figure 17) when closed enable the motors. These may also be accessed through the ENAX#, ENAY#, and ENAZ# connections left of the TB AUX connections (also shown in Figure 17). A switch was used to allow manual enabling and disabling of the two motors. This was done by first removing the jumpers from the ENA# pins for the X and Y axis. Next one side of a SPDT switch was connected to both ENAX# and ENAY#, while the other was connected to GND. Using this arrangement the switch may be used to manually enable and disable the motors and also act as an emergency kill switch. The wiring for including the Z axis to the switch if another motor was added was included in the design.

Programming

Coding for motor control was done on a Win95 laptop using TurboC. The prototype made use of v2.01 of the Borland Turbo C compiler which was downloaded from <http://www.pitt.edu/~stephenp/misc/downloadTC.html>. Instructions for downloading and installing this program are included in the website [2]. The code used during testing and demonstration of the prototype has been included in Appendix C.

The parallel port used for the Xylotex board was port 378. Included in this port are the data register (address 0x378), the status register (address 0x379) and the control register (address 0x37A). The motor signals use the data register with two bits for each axis – one to step the motor (axis) and a second to indicate the direction of the step (direction). Axis and direction values are indicated in Table 3. By sending a square wave signal to specific axis and direction bits in the data register the motors may be stepped. Axis controls the stepping with the square wave, making the direction bit high moves the motor one way while using 0x00 (low) would reverse the direction.

Table 3 Summary of Axis and Direction Values for Each Axis

	Axis	Direction
X	0x01	0x02
Y	0x04	0x08
Z	0x10	0x20

Limit switches were interpreted using the laptop, since the Xylotex board has no ability to read or act on limit switch information. In order to map the limit switches a code was used to display the values of the status and control registers while closing switches connected to the various TB AUX connections. Code to display the status and control registers is included in the prototype code (Appendix C). A brief description of the mapping procedure and results of this mapping are included in Appendix D. Once the TB AUX connections were mapped, the status and data registers could be read by the laptop to determine if a switch had been triggered.

The prototype code allows for several distinct operations, as outlined in Table 4. For several of the items the addition of limit switches would be possible with minimal alterations to the code.

Table 4 Summary of Prototype Motor Controls

Key	Name	Function	Notes
ESC	escape	Stops the program	
M	menu	Displays the control options	
Q	query	Displays the values of the status and control registers	If switches are all open/not connected status register should be 0x78, control register should be 0xC
L	layer	Steps the part bed 1 layer thickness down, steps the feed bed 1.2 times the layerthickness up	Layer thickness is set at program start up. The entered value is the number of 1/8th steps desired at 0.000625"/step. A value of 64 corresponds to 0.005 inches.
B	base	Returns both the part and feed bed pistons to the base of the beds	Limit switches attached to base of beds stops motors automatically
X, Y, or Z	axis	Selects a motor axis	
U	up	Steps selected motor up 1 layer thickness	To move pistons large displacements consider closing the program and restarting using a larger layer thickness.
D	down	Steps selected motor down 1 layer thickness	Limit switches attached to base of beds will not allow either piston to move down if one is depressed.

Initial Testing

Operation

Two functional print tests were performed on the prototype machine. The first was a print of two rectangles, the second a print of the letters UW and two arrows. For the testing the general operating procedure outlined in the Operation Overview section was followed. The layer thickness used for initial testing was 0.01 inches per layer, and each layer was spread by dragging an extra printer paper roller across the top of the feed and print beds. Printer settings for the first and second test were photo quality on glossy paper and normal quality on plain paper, respectively.

Results

Printing occurred largely as expected. As the layers progressed the color of the binder appeared to change, as can be seen in Figure 19. This could be due to the fact that the cartridges were not cleaned out prior to the binder being added. The expected binder color was pink, similar to that visible in the top rectangle of the rightmost photo in Figure 19.

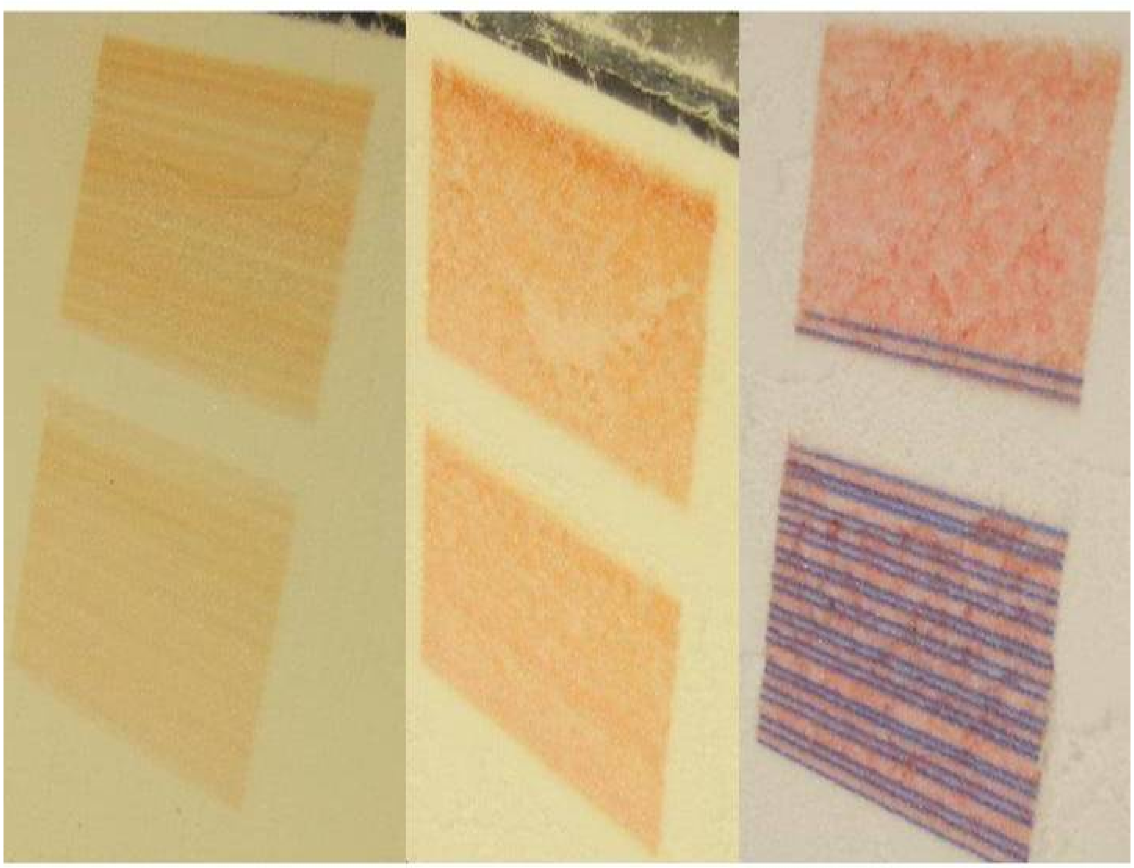


Figure 19 Photos of First Print Run Progression

Both print runs printed 25 layers at 0.01 inches per layer for 0.25 inch test pieces. Parts were dried in the oven on low setting for at least 1 hour before removal from powder. The initial test run had very little strength, crumbling easily. The second test run, also lacked structural integrity. As can be seen in Figure 20, the arrow lost shape completely when it was removed from the plate.

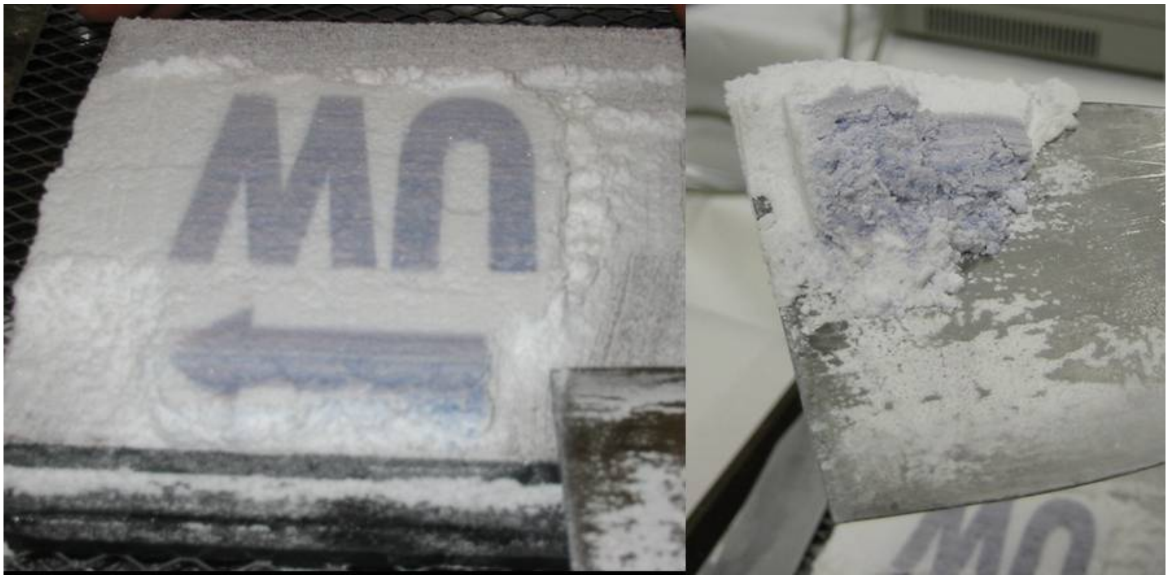


Figure 20 Photos of Second Print Run Removal of Arrow from Print Plate

Optimal layer thickness for the powder used would probably be between approximately 0.005 and 0.008 inches per layer. Given that 0.01 inches per layer was used, it is not surprising that the parts lacked cohesion, as layers were probably unable to bind properly to the previous layer. Additional testing must be performed to determine the idea layer thickness and printer settings to achieve the best results.

Economic Evaluation

An economic evaluation of the final selected concept or a comparison of the economic feasibility of the various generated concepts should be included. It should contain an estimated list of the costs encountered in developing the design and producing a prototype. Include the cost for the time you spent working on this project at $50/person-hour. Explain any unusual cost items (items which cost either significantly less or significantly more than would be expected).

A summary of the expenses associated with this project have been included in Table 5. Shaded items indicate costs for items that were used during the design process, but which would not be included in a second build. Items using the Estimated Cost column were those which were either fabricated or available without requiring purchase. For example, the Xylotex board was given to the project team for use, but would normally cost $155 if ordered directly from Xylotex.

Table 5 Summary of Associated Project Costs

Item	Unit Cost ($ or $/hr)	Estimated Cost ($ or $/hr)	Total Cost ($)		Puchaser
Printers					
Lexmark P315	34.52		34.52		Tri
Lexmark Z735	26.33		26.33		Erik
Lexmark Z735	29		29		Nathaniel
HP A310	35.84		35.84		Erik
P315 Cartridge	27.24		27.24		Erik
Frame Materials					
Acrylic	90.43		90.43		Tri
Fasteners	5.09		5.09		Erik
Fasteners and Rods	70.57		70.57		Tri
Print Carriage					
Drive Gears	12		59		Kory
Xtra Gears		3	3		
Rack	22.9		56.8		Kory
Rail Mounts		35	175		
Gear Bracket		35	61.25		
Print Buckets					
Polycarbonate	10.9		10.9		Tri
Stepper Motor	117		234		Nathaniel
Switches	3.44		13.75		Tri
Switches	7.28		7.28		Nathaniel
Switches	3.1		3.1		Kristina
3-Axis Xylotex board		155	155		
24V Power Source					
Insulated Wire		5	5		
Sandpaper	4.27		4.27		Erik
Foam	4.27		4.27		Erik
Adhesive	5		5		Nathaniel
Labor					
Waterjet Cutting		105	630		
Manual Machining		50	1500		
Eletrical Wiring		50	500		
Assembly		50	50		

Several printers were purchased during the initial stages of the project and evaluated for feasibility for use as the base printer carriage. The various printers evaluated and their associated advantages and disadvantages have been listed in Table 2 of the Printer Selection section. The listed printers in Table 2 which have not been shown in Table 5 are those which were donated for project use.

Most of the labor costs associated with the project are not considered as contributing to the overall project cost. The manual machining time was largely a result of time pressure during the design process: the feed and part chambers were machined by hand out of polycarbonate using adhesive, and this time would not be necessary if the chamber machining had been incorporated into the water jet cutting of the rest of the printer frame. Additionally, the time for assembling the frame and hooking up the components is not considered as contributing to the overall cost as it is assumed to be absorbed by the end user. The personal printer is expected to appeal to educators and hobbyists – who may in fact consider the ability to self-assemble to be a benefit and not a cost. Self-assembly allows the end user to know how all parts of the printer work together, aiding maintenance and modification and, specifically in the case of educators, assembly could be used as a way to involve students on another level.

The overall costs associated with both the prototype and the expected cost to an end user have been included in Table 6. This table also includes a comparison to the target maximum costs decided on during the initial stage of the development. The actual cost paid for the prototype by team members was determined through addition of various receipts and includes cost of shipping items. The estimated cost for an end user was determined by including the cost of all non-shaded items in Table 5.

Table 6 Overall Cost of Prototype and Estimated End User Cost Compared to Design Targets

	Estimate	Target
Cost to Develop Prototype	$720	$1,250
Estimated Cost to End User	$1,600	$2,000

One way that overall costs may be reduced would be to use polycarbonate for the printer frame. Initially acrylic was used for greater stiffness, however it was discovered that acrylic is more difficult to machine using waterjet cutting, and thus more expensive. It is believed that the polycarbonate would provide sufficient structural support while at the same time taking approximately 1/3 the time (and thus 1/3 the cost) to machine. Additionally it could be possible to reduce the cost for the gear bracket and rail mounts by redesigning them so that they could be made out of polycarbonate and included in the waterjet cut rather than being printed on a rapid prototyping machine (Stratesys).

Future Work

Powder Team

Housing

There are several improvements that may be implemented with future iterations of the p3p housing that will increase the productivity and decrease the costs of the fabricating and assembling the housing.

Slimmer Design

As built, the large right side wall is used only for aesthetics since the Xylotex was fastened directly below the waste container (036). The right side wall can be removed and the right side brace (029) could be replaced by a member similar to the left side rail brace (031) attached to front and rear panels (015). The slimmer housing may be less rigid than the current design and there may be a risking of tipping due to the required height of the print surface. Extending the right side wall (022) to the ground may maintain desired rigidity.

Housing Material

Although acrylic is cheaper approximately 20% cheaper than the polycarbonate, it takes three times as long to fabricate the acrylic panels using the water jet cutter. Considering an hour of water jet use costs more than all of the acrylic material, using polycarbonate instead of acrylic would be beneficial.

Adjustable Rail Supports

Ideally, the mounted rails should be straight and level to print surface. If the rails were skewed, the risk of the rail mounts binding during travel was increased. Determining the positioning of the rail holes on each rail support (029 & 031) proved to be difficult tasks. It was assumed that the brace was perfectly symmetrical between the front and rear panel. In reality, they were not symmetric which caused several binding issues. To increase the precision of the rails, they must be adjustable within the rail supports. One idea is to use a series of set screws that were installed through each side of the support that would reach the rail opening. One would then be able to adjust the rails within a predefined area of clearance.

Handles

The p3p unit was designed to be a personal unit that could be small and relatively portable. Handles slots should be cut into the front and rear panels (015) so the housing can be held and carried more easily.

Printer Team

Return Mechanism

There are many modifications that would need to be added to the printer side of the project in order to make the device more automated. The first suggestion would be to create a return mechanism for the print carriage. A mechanical device may be able to return the carriage but there are many problems that would need to be overcome.

One solution would be to use a control board wired to the printer’s motor so that when it finishes printing the carriage will be returned to the other side. There are several issues with this:

- What happens to the printer circuit board when an external device applies a current to the motor?
- How would the carriage be positioned close to the starting position for the next layer?

- The motor will have to stay on the rack in order to move itself back, how will paper jams be avoided after a layer has been printed?

Another solution would be to use a secondary motor or stepper motor to control the reverse movement, but this solution also has issues:

- How will each motor be disengaged while the other motor is running? Or are the motors powerful enough to move the carriage while the other motor is in contact with the rack?
- Will it require a second rack? Possibly one on each side.

In its current configuration the printer does not like to move itself in the reverse direction, how will this be solved?

A second more elegant solution to this problem would be to modify the printer drivers. If the drivers are able to be modified, the printer could automatically move itself back to the start when done printing. The drivers could also be modified so that paper jamming is no longer an issue.

Binding Problem

The printer was not able to move very well in the forward direction, and had a lot of problems moving in the reverse direction. There are several options that could be employed to solve this problem:

- Combine gear train part and gear train side rail mount into one piece. This would make the rail mount much more rigid (this part was one of the most flexible). The way the new combined part is attached would have to be different than the way the current two parts are attached.
- The rail mounts on both sides could be more securely attached to reduce the flex.
- Precision pillow blocks and flange mount shaft supports should be used for the rail mounts instead of acrylic and ABS mounts.
- Another option for mounts might be to use wheels that run along the rail instead of a fully enclosed mount. It might be a good option to use a pillow block for the gear train side and use the wheel mount for the side that has a higher chance of binding.
- Building a new frame would allow the designers to mount parts with greater flexibility on their location while reducing the frame flex. If a new frame is built it would be necessary to mount the print head parts and optical encoder parts very precisely.

Powder Spreader

Because of the time constraint and printer movement limitations, mounting a spreader onto the print carriage was not an option. If a spreader is mounted to the carriage, it should be mounted so that it will pass the build bed before the print head while printing. This is necessary so that the spreader is not dragged over the layer that is just printed.

Spring tensioners may be needed to keep the spreader in contact with the build and feed beds. The start and stop position of the printer carriage will need to be modified so that the spreader is able to move from the far edge of the feed bed to the waste bin.

A counter rotating spreader could also be beneficial.

Gear Train Simplification

Two gears were used to ensure that the printer moved in the correct position. An early solution was to reverse the polarity on the printer's DC motor; this did not work because the optical encoder is able to detect its rotational direction. It might be possible to mount the encoder upside-down so that only one gear is needed.

Ink Leak

The binder in the ink cartridge is able to slowly leak out of the cartridge. There is not currently a sponge or reservoir mounted below the cartridge home position to catch the leaking binder.

Potential Use of Lexmark Z35

The only printer that was examined that may be better than the Z735 was the Z35. This printer only had one optical encoder and seemed to have a more accommodating frame. It was not chosen because the frame mounting parts had already been designed for the Z735 by the time the Z35 was examined and also because the Z35 used a stepper motor instead of a DC motor and optical encoder to drive the carriage (another issue that had already been taken care of). A stepper motor may be a better option if it will also be used to return the carriage, but because they require a large force to move them, it would not be a good option if another motor will be used to return the carriage (unless it can be disengaged).

Control Team

Layer Stepping

The prototype requires manual input each layer to step the part and feed beds. Ideally this step would be completely automated. A switch could be attached to the one of the currently unused TB AUX connections (such as TB AUX 8), and used to trigger the layer step. This switch would be triggered by the motion of the printer carriage – being pressed when the carriage reached the end of its print run. The challenges of this include finding and mounting a switch which would work for this purpose as well as coding issues. The computer must be able to read that the switch has been flipped, but only step the powder beds a single time, even though the switch may remain depressed.

Limit Switches

The motor control program was initially written to accommodate 6 limit switches, two for each motor in the initial design. The prototype uses only 2 of these switches, those to stop the downward motion of the pistons. Due to mounting issues, the limit switches for the upward motion of the switches was not included in the prototype. These switches could be easily accommodated by the controls if appropriate switches and mounting could be accomplished. One possible solution would be magnetic proximity switches mounted in the side of the piston and chamber.

Single Computer Operation

Currently two computers are necessary to run the prototype. One computer is used solely for the motor operation. This is because there are some difficulties with controlling the parallel port (if such a port exists) for newer computers running operating systems of Win98 and later. At the same time, a computer is necessary for printing as no drivers could be found for operating systems earlier than Win98. Ideally the code could be fully automated and loaded onto a small control board similar to how the Fab@Home is operated. Alternatively, it may be possible to alter the code to run using a newer operating system, thus allowing for both the motor control and printer programs to run on the same computer.

Automated Motor Enable/Disable

There is a risk that the motors may burn out if left powered for an extended period of time. The manual enable switch was added to allow motors to be disabled when not in use, however it is possible that a user would forget to disable the motors after operating them. Automated control would prevent motor burn out due to this kind of error. This could be possible through attachment to a control board (as is done on the Fab@Home) or possibly through some kind of switch arrangement with the TB AUX connections using the control register. If the enable pins (ENAX# and ENAY#) could be grounded using a control board or computer, then the motors could be automatically enabled for use and automatically disabled after use.

Amplifier Board Location

The current location of the Xylotex amplifier board places the board underneath one side of the waste bin. In this arrangement powder can fall from the space between the waste bin and frame and directly onto the Xylotex board. In order to prevent this from occurring the amplifier board could be moved to a different location on the frame – for example: centered under the waste bin so that there are no direct lines for powder to fall onto the board.

User Interface

One goal for the motor controls would be that they would be intelligible and easy to operate for someone without programming experience or familiarity with the printer functions. This could include a more user friendly interface, with more clear instructions. Another possible improvement would be to allow the user to input layer thicknesses in inches, which would be more intuitive for most users. Additionally, trouble shooting functions to try to determine why a printer is not working as expected could be useful for finding shorts or wires with loose connections.

Project Experience

At the beginning of the project cycle, there was only a vague concept of what the p3p would eventually become. As the project progressed, there was a realization that the project would take longer than the proposed schedule and the many of the originally planned features would be scrapped. This was due to the conflict in the team schedules and the long lead times for parts. Also, the project was designed and fabricated on a component by component basis, instead of having the project fully designed before proceeding with fabrication. There were several additions to the printer that were not as elegantly designed as its counterparts. Though irregardless of these constraints, we were able to reach our goal of being able to print on powder while also actuate the print chamber pistons.

References

[1] (2004) “XS-3525/8S-4 Preliminary DataSheet Verson 4.00.” Xylotex Inc. < http://www.xylotex.com/XS3525V400.pdf> (12 June 2008).

[2] <http://www.pitt.edu/~stephenp/misc/downloadTC.html> (14 May 2008).

[3] “Sugar Engineer’s Library.” <http://www.sugartech.co.za/density/index.php>

[4] Sachs, Emanuel M., et al. “Three-Dimensional Printing Techniques.” US Patent 5204055. 8 December 1989.

[5] Z Corporation (2008). “3D Printers,” < http://Z Corp.com/Products/3D-Printers/spage.aspx>

Appendices

Appendix A	**Parts List**
Appendix B	**P3P Assembly Instructions**
Appendix C	**Motor Control Code**
Appendix D	**TB AUX Mapping for Limit Switches**

Appendix A – Parts List

Table A 1 Parts List of Items Used for P3P

Part Name	Quantity
LOW HEAD SOCKET CAP SCREW, 6-32 THREAD, 5/8" LENGTH	67
MACHINE SCREW SQUARE NUT, PLAIN STEEL, 6-32 SCREW SIZE, 5/16" W, 7/64" H	67
SOCKET CAP SCREW, 6-32 THREAD, 1" LENGTH	12
METRIC BRASS THREADED INSERT FOR THERMOPLASTC, TAPERED, M4-.7 INTERNAL	2
HARDENED PRECISION STEEL SHAFT, 1/2" OD, 24" LENGTH	2
ALUMINUM SET SCREW SHAFT COLLAR, 1/2" BORE, 1" OUTSIDE DIAMETER, 7/16" WIDTH	4
CIRCUIT BOARD STAND WITH 4-40 HEAD AND INSERT	4
4/40 SMALL PATTERN NUTS	4
SOCKET CAP SCREW, 4/40 THREAD, 1/2" LENGTH	4
THE ORIGINAL SUPER GLUE CORPORATION QUICK SET EPOXY	1
CRAFTICS #33 THICKENED CEMENT	1
LEXMARK Z735 W/ CARTRIDGE	1
MISUMI 500mm RACK [PARTNO. RGEA1.0-500-N]	1
MISUMI K SPUR GEAR [PARTNO. GEAHB1.0-12-12-8]	1
HSI 3500 SERIES HYBRID LINEAR ACTUATOR [PARTNO. 35F4B-05-012ENG]	1
ALL THREAD, B CLASS THREAD, 7.5” LENGTH	2
XYLOTEX BOARD	1
24V POWER SUPPLY	1
2’ X 4’, 0.25” THICK ACRYLIC	2
2’ X 4’, 0.25” THICK POLYCARBONATE	1
SINGLE PULL DOUBLE THROW SWITCH	1
SINGLE PULL SINGLE THROW MOMENTARY SWITCH	2
40’ 22 GAUGE INSULATED COPPER WIRING	1
ELECTRICAL TAPE	1
M3 x 9mm LENGTH SOCKET HEAD CAP SCREW	8

Appendix B – P3P Assembly Instructions

Lexmark Z735 Disassembly

1. Remove Z735 from box. Remove packaging and tape.

Figure B 1 Unpackaged Z735

2. Remove two cover screws located under the case lid (See Figure B 1).
3. Remove two cover screws located on the backside of the printer (See Figure B 2).

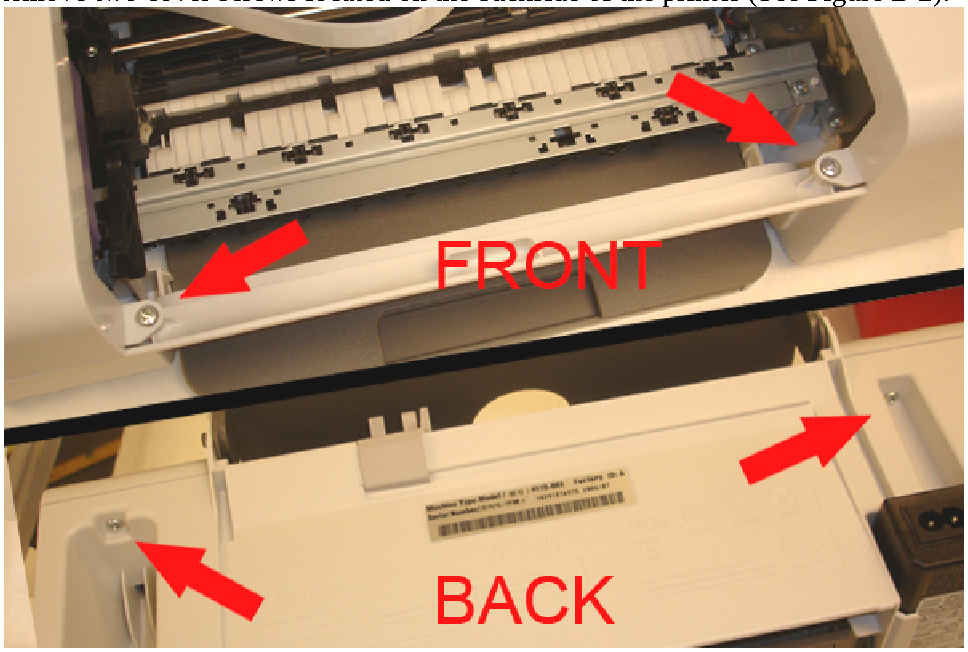


Figure B 2 Cover Screw Locations

4. Now lift top cover off of printer assembly.
5. Remove four screws holding front paper guide and remove paper guide.
6. Remove two front (Figure B 3) and two right (Figure B 4) screws that secure print carriage to case.

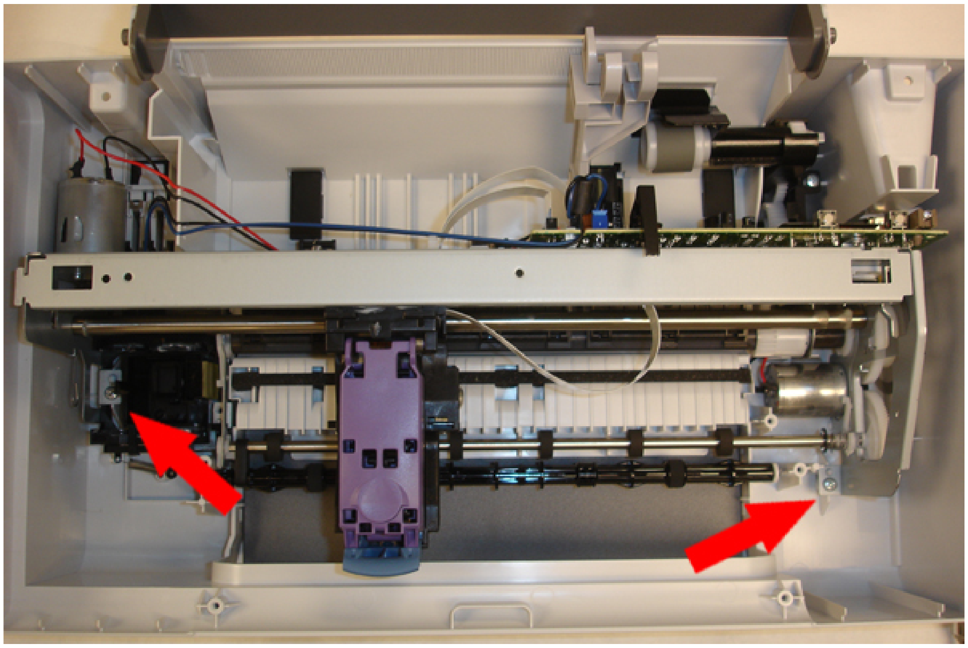


Figure B 3 Front Screws that Secure Printer Carriage to Case

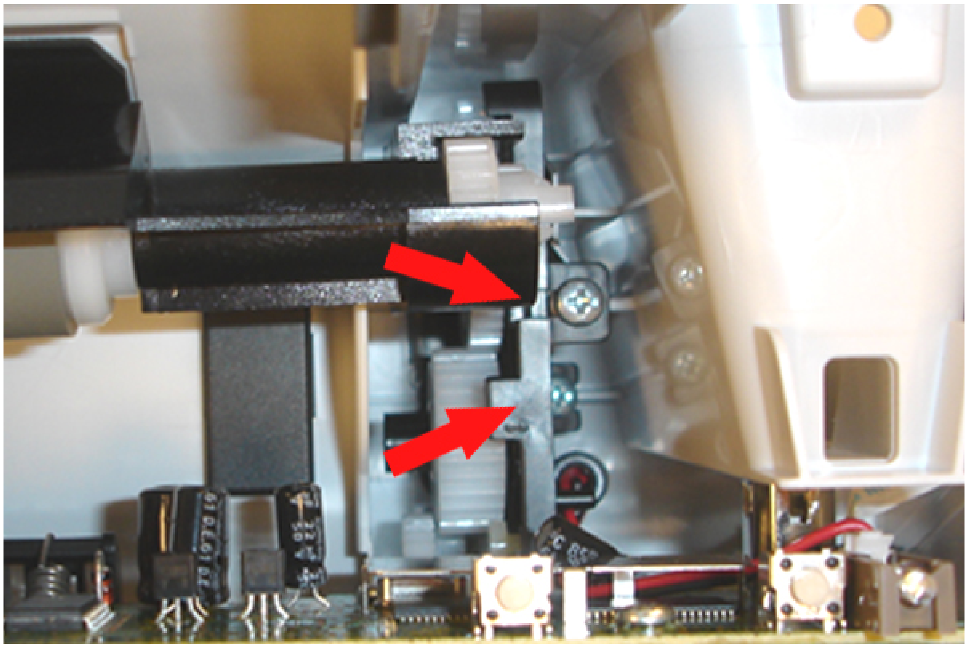


Figure B 4 Right Screws that Secure Printer Carriage to Case

7. Remove black plastic paper-feed roller by flexing rod.
8. Unplug power plug from controller board
9. Remove any obstructing wires and lift print carriage out of case

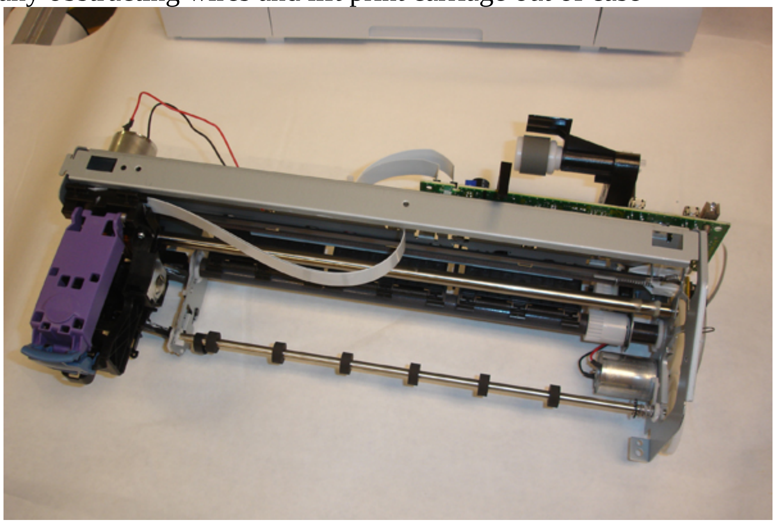


Figure B 5 Printer Carriage Removed from Case

10. Remove two screws securing paper feed assembly (Figure B 6)

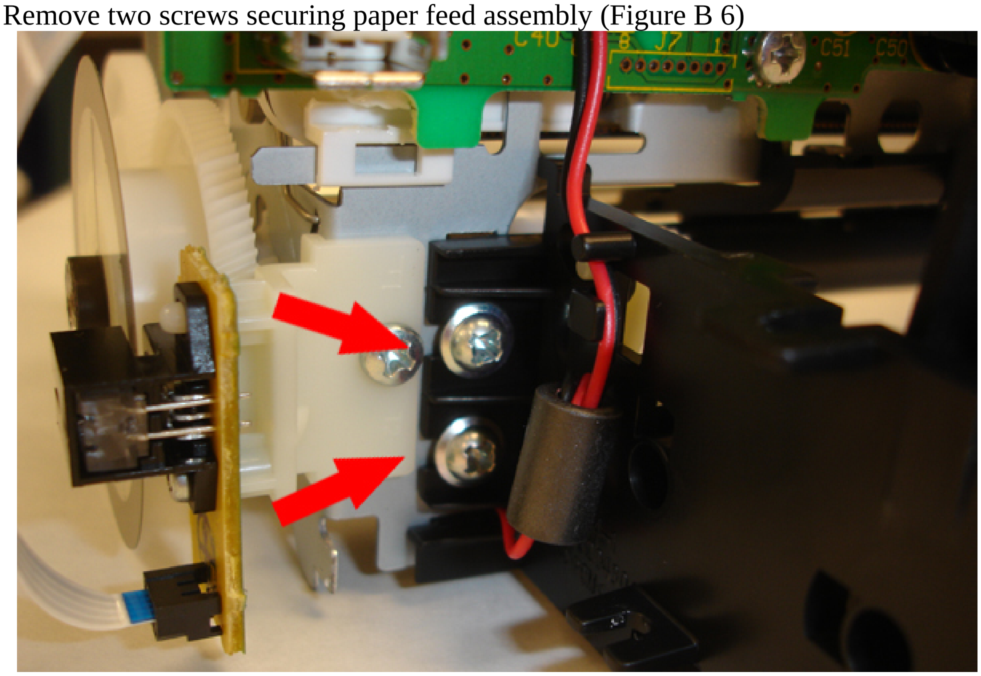


Figure B 6 Two Screws Securing Paper Feed Assembly

11. Remove three overhead paper guide springs (Figure B 7). (Be careful not to damage Optical Encoder Strip)

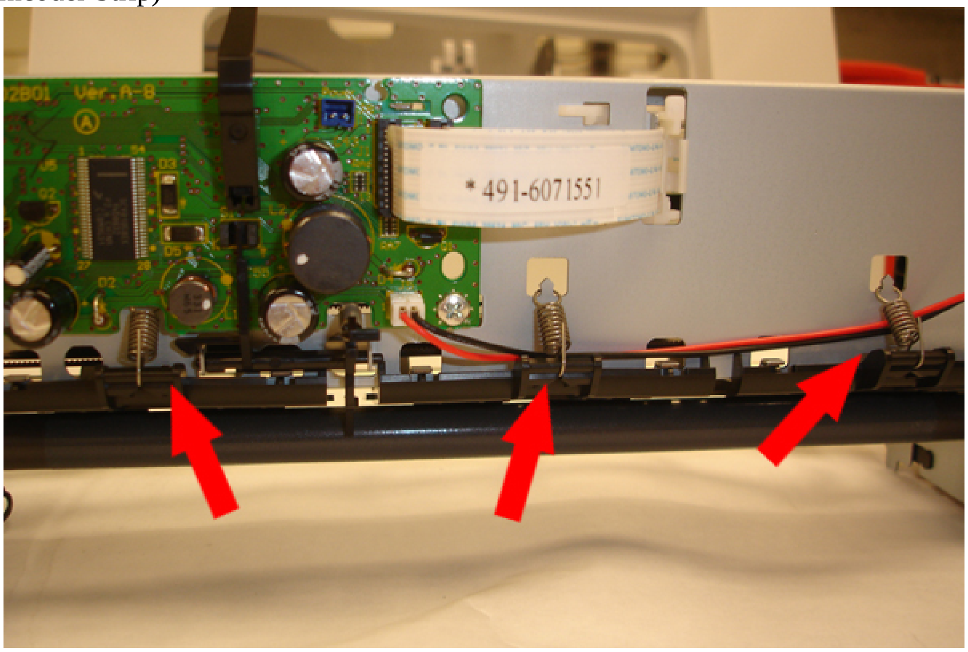


Figure B 7 Overhead Paper Guide Springs

12. Remove three overhead paper guide pieces (Figure B 8).

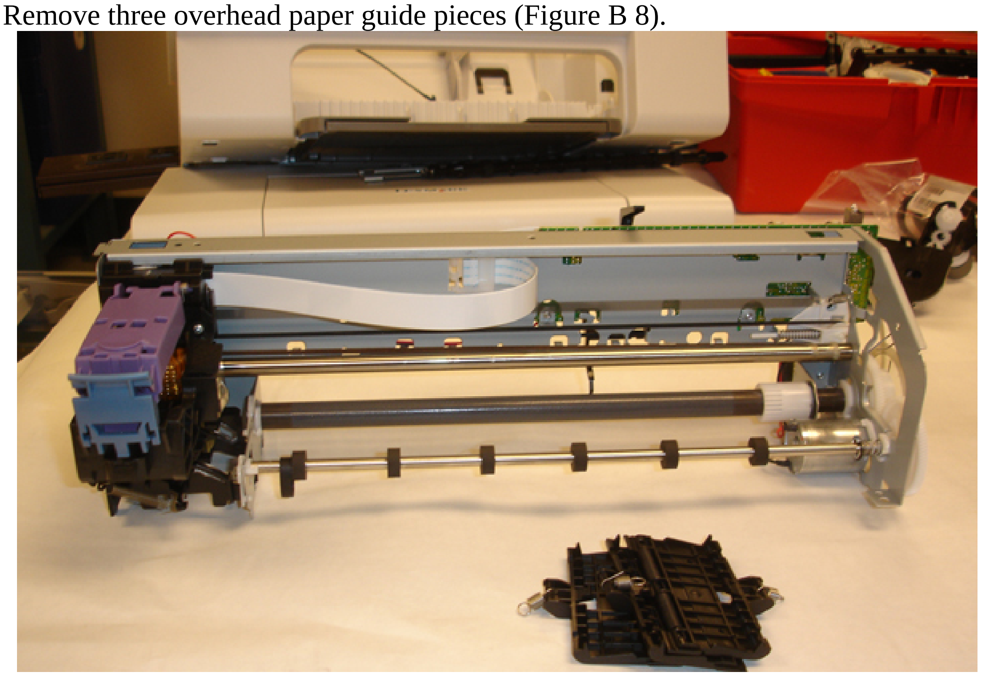


Figure B 8 Overhead Paper Guide Pieces Removed

13. Disengage tabs on two shaft collars shown in Figure B 9.

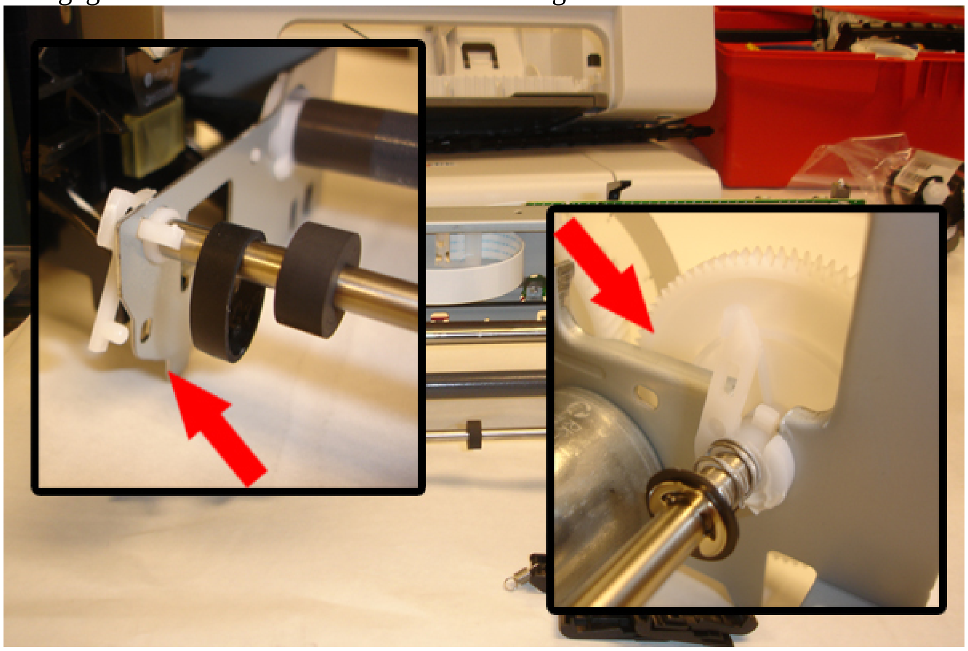


Figure B 9 Two Shaft Collars with Plastic Tabs

14. Remove shaft collar on left side of assembly (Figure B 9, left).
15. Lift right-side shaft collar (Figure B 9, right) upward and slide out bar. (Be careful not to damage optical encoder wheel)
16. Remove AC adapter from back of case (Figure B 10).

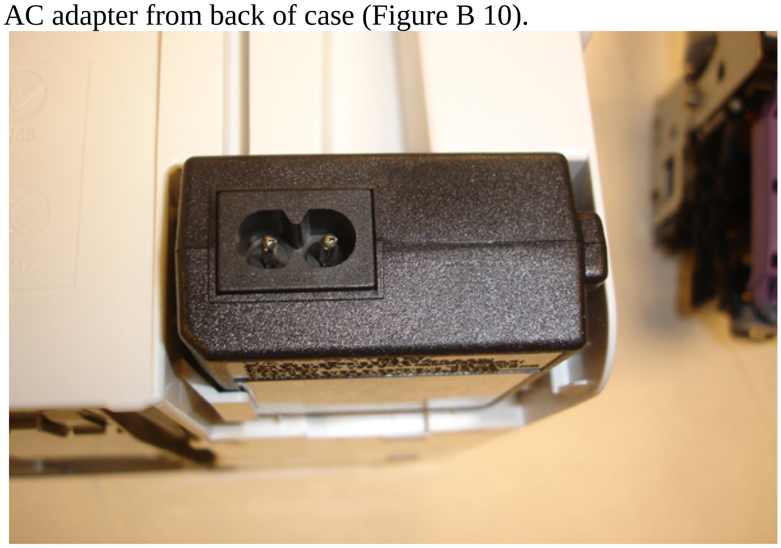


Figure B 10 AC Adapter Unit

17. Remove power contacts from printer case (Figure B 11). Use a flathead screwdriver to pry tabs and remove contacts. These will need to be connected to the power supply. In the first design electrical tape was used, a more robust solution would be better.

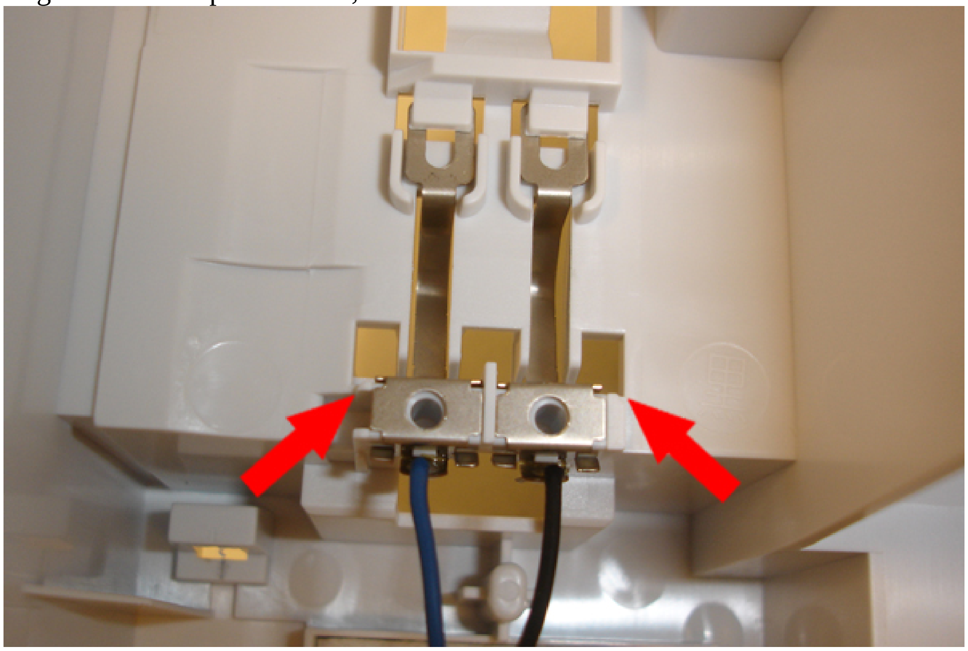


Figure B 11 Power Contacts in Printer Case

18. Extraction of Lexmark Z735 printer carriage is now complete.

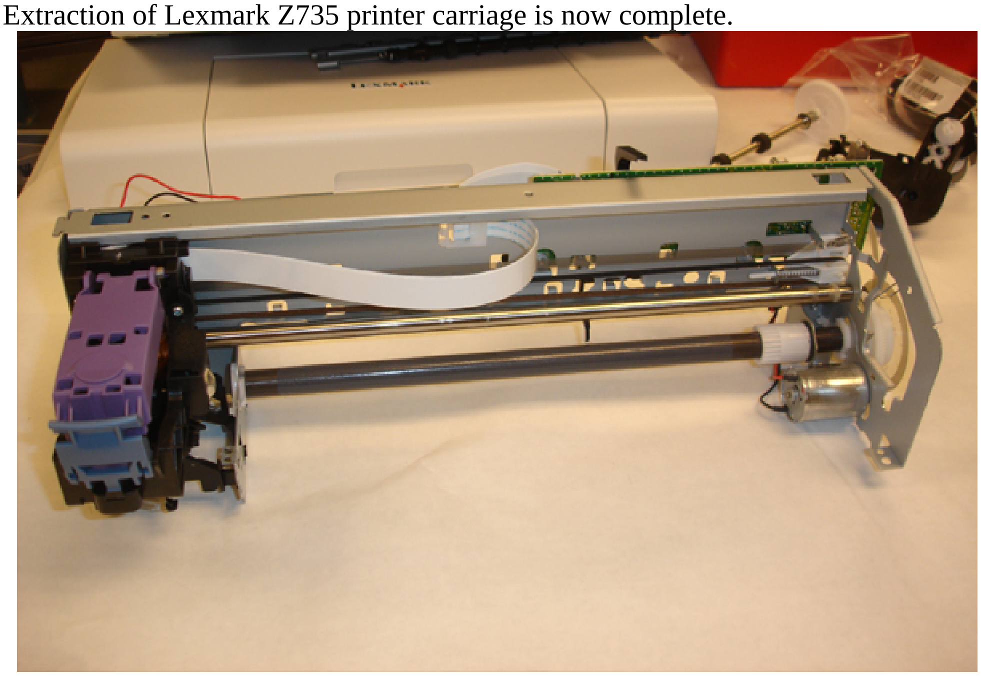


Figure B 12 Extracted Lexmark Z735 Printer Carriage

Printer Modifications

Paper Trip Wires

The first modification to the print carriage was the addition of two wires connected to the back of the circuit board. These wires will later be connected to a slider switch in order to simulate paper entering the print area. Figure B 13 shows the back of the circuit board before removal.

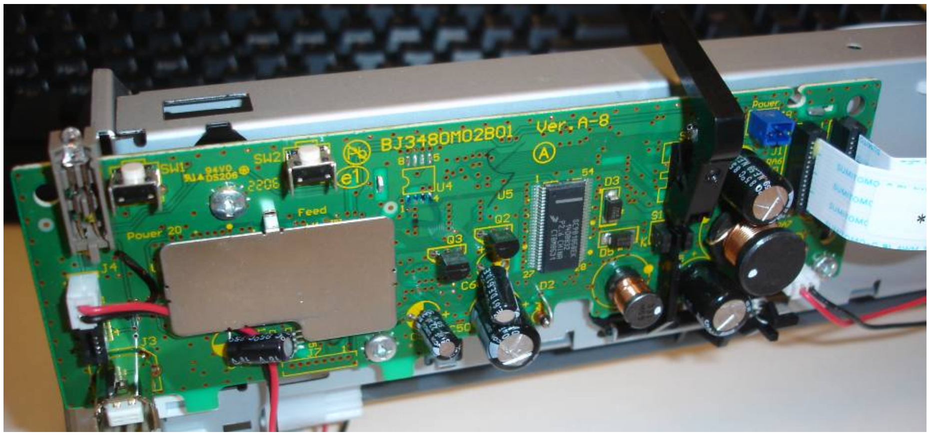


Figure B 13 Circuit Board Screws

The three screws were removed in order to access the back of the circuit board. The two wires that connect to the photo gate were found by inspection on the front of the board and two wires were soldered to it on the back of the board. This is shown below in Figure B 14.

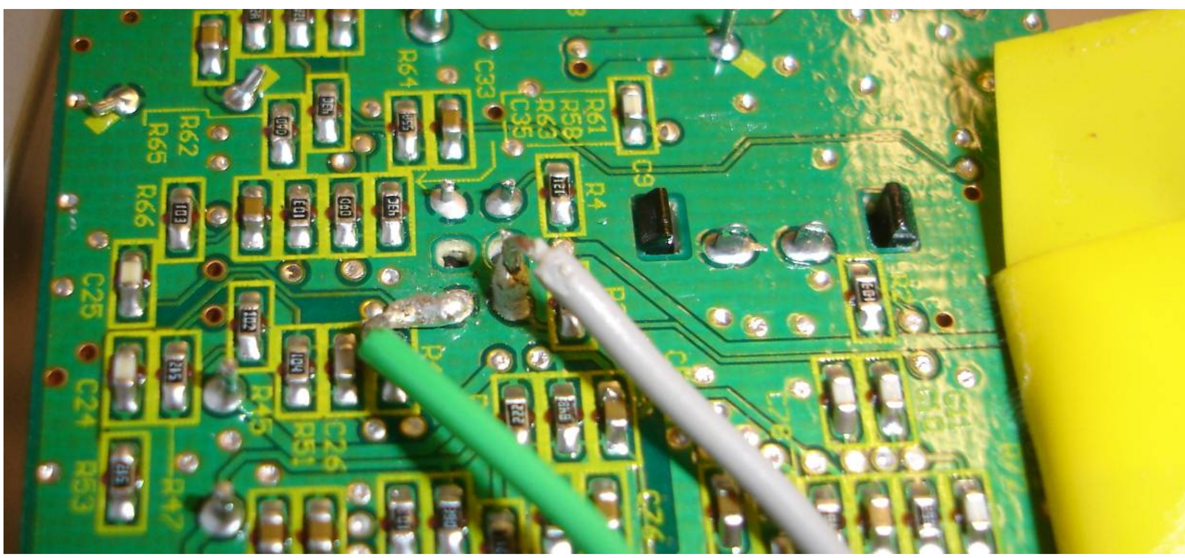


Figure B 14 Wire Solder Location

In order for the switch that will be connected to work, the plastic part that is blocking the gate must be left in place. Because of the size and location of the part, it must be cut in order to not interfere with the print bed. Figure B 15 shows the before and after pictures of the plastic part.

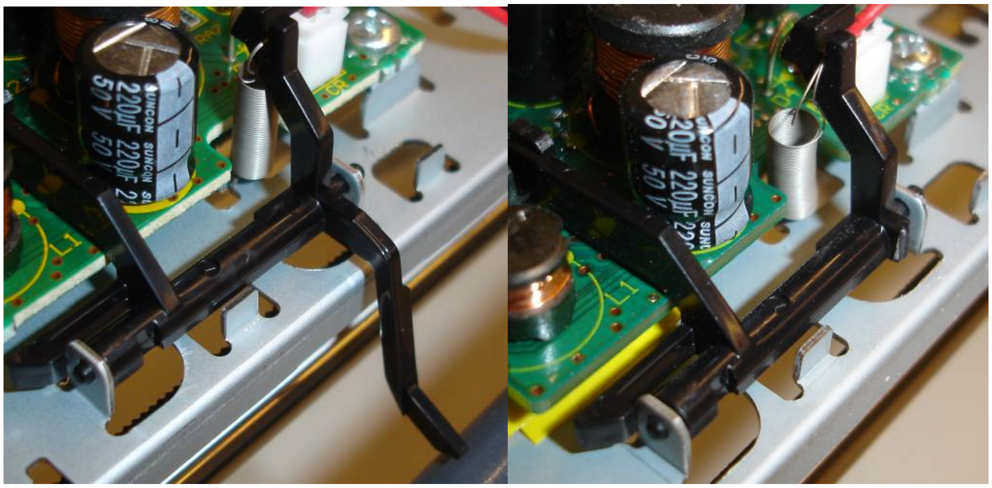


Figure B 15 Paper Trip Part Before and After

These wires will later be attached to the new trip switch.

Gear Train

The plastic gear train piece that was designed will be slid onto the metal frame and secured with two screws.

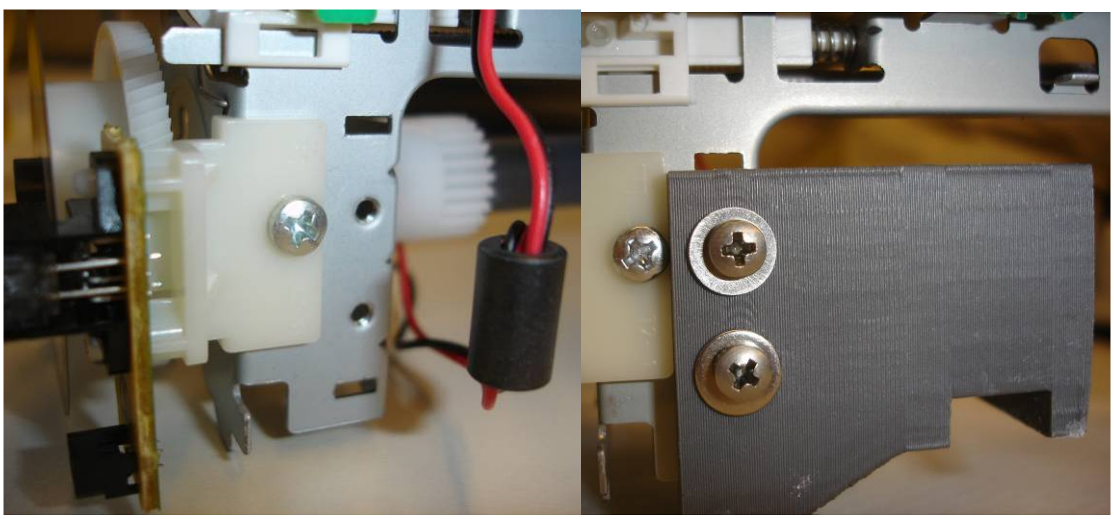


Figure B 16 Gear Train Attachment

Before this can happen the paper feed rod first had to be cut. Figure B 17 below shows the rod attached to the printer before it is modified.

Figure B 17 Paper Feed Rod

The rod was removed from the print carriage similar to how the guide rods were removed earlier (the motor must first be removed). During the removal care must be taken to not damage the optical encoder disk. Once removed the rod was cut near the center of the white plastic gear. The accuracy of this cut is not a big concern, as long as the bar is cut with enough clearance for the new gear. It should also be noted that there is a spring in the center of the white plastic gear used for tension, this spring will be needed. After the rod was cut, a solid metal rod with a diameter equal to the inner diameter of the new gear was glued into the center of the paper feed rod. One of the new gears was then glued onto the end of that rod in the right position so it would fit in the gear train part. Figure B 18 below shows the final gear train assembly.

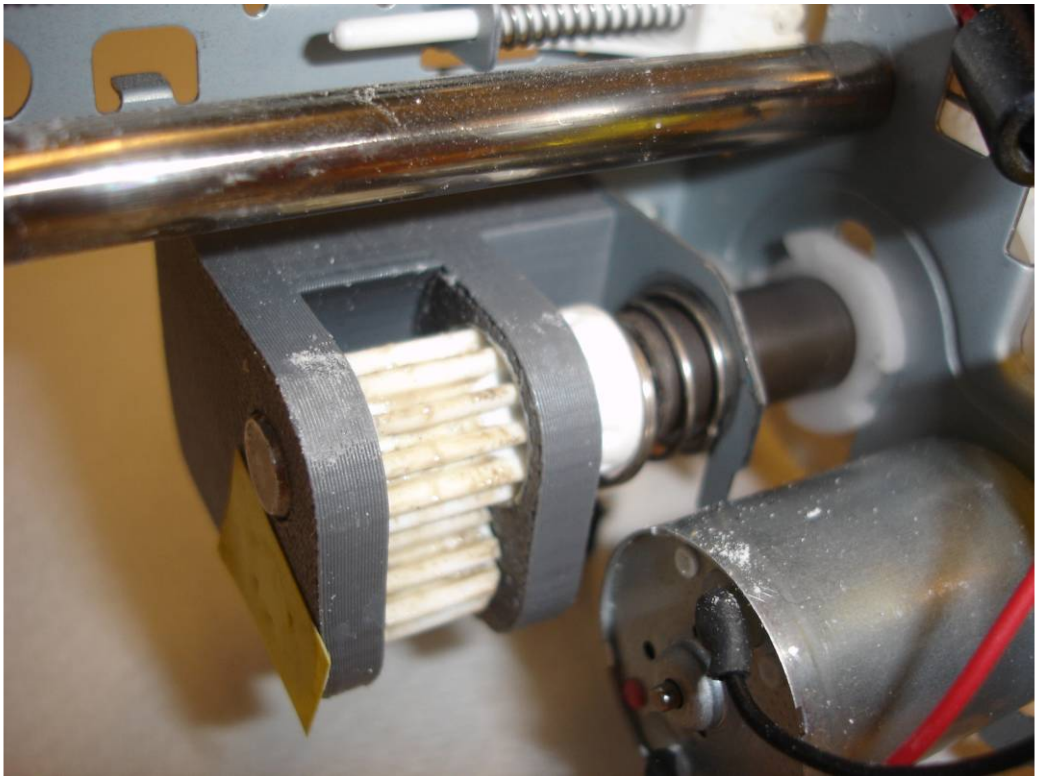


Figure B 18 Gear Train Assembly

The solid metal rod was cut to be nearly flush with the outside of the plastic gear assembly piece. The entire assembly was slid onto the printer and then the screws were inserted to keep it in place. The second gear shown has a small piece of metal rod keeping it in place. In this image the second gear is not secured by anything but a piece of tape

Rail Mounts

The rail mounts that were designed for the print carriage were made to be easily slid on to the metal frame. In order to attach these two parts, three holes had to be drilled into the frame. The mount near the drive train was attached in front of the motor; a hole was drilled in the position. Figure B 19 shows this the frame before and after this hole was drilled.

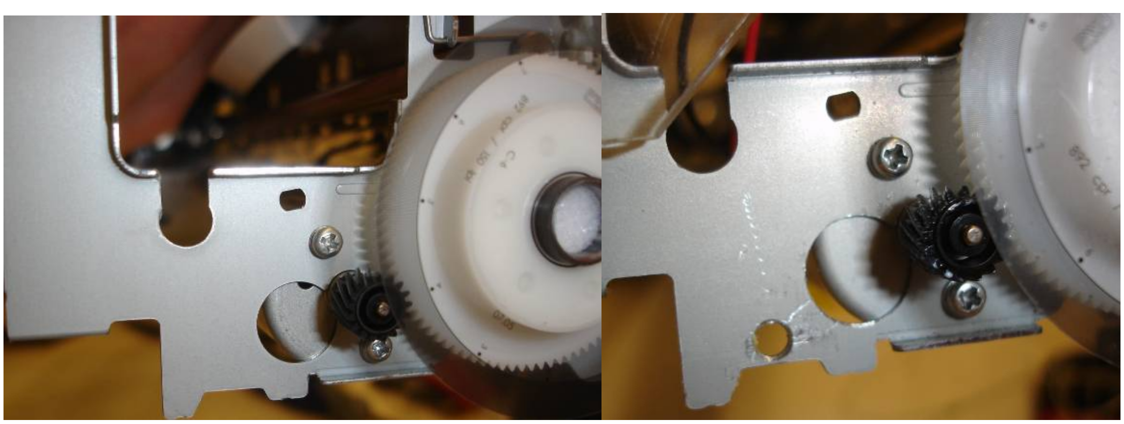


Figure B 19 Drive Train Side Rail Mount Hole

The position of the hole was determined by sliding the part over the frame and then marking the position. Figure B 20 below shows two angles of the mount secured in place

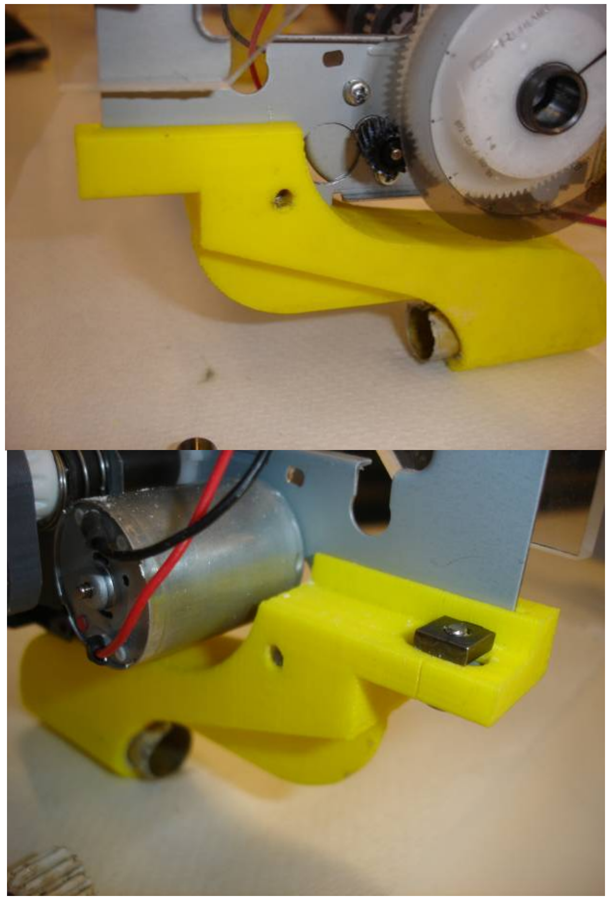


Figure B 20 Drive Train Side Mount

The left side shows the hole where a screw will be inserted. The right side shows a second screw and nut that are put in place. It should be noted that the hole for the rails on both mounts needed to be drilled out using a drill press before they would accommodate the rails. For the drive train side only a shim was put in place to increase the accuracy of the printer movement. If a shim is put on the other side, the printer tends to bind up during movement. Grease was also spread over the rail to reduce friction. The second rail mount was also placed on in order to mark where the two holes had to be drilled. This was then done using a hand drill. Figure B 21 shows the metal frame before and after the two holes were drilled.

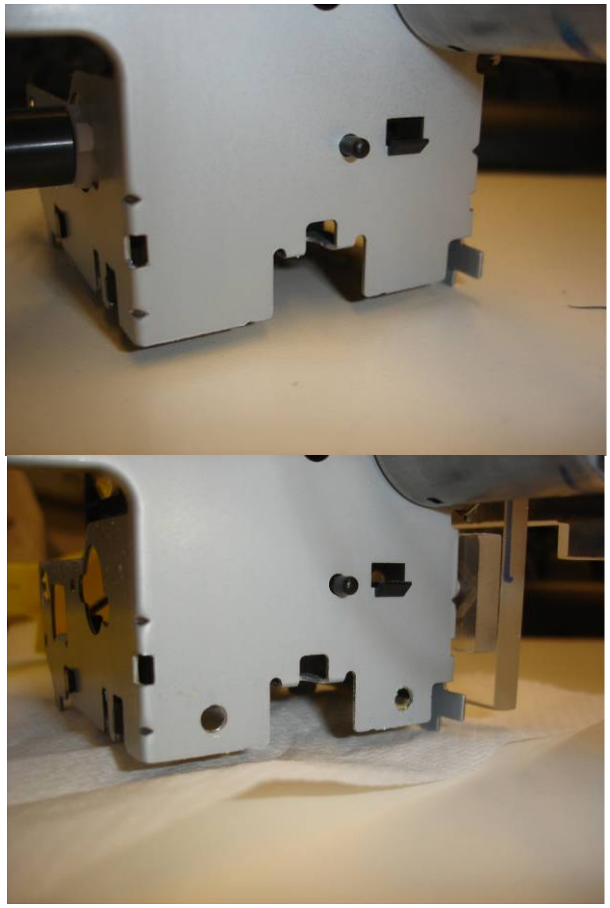


Figure B 21 Second Rail Mount Holes

The mount was then slid into place and two screws and nuts were used to secure the mount. This is shown below in Figure B 22.

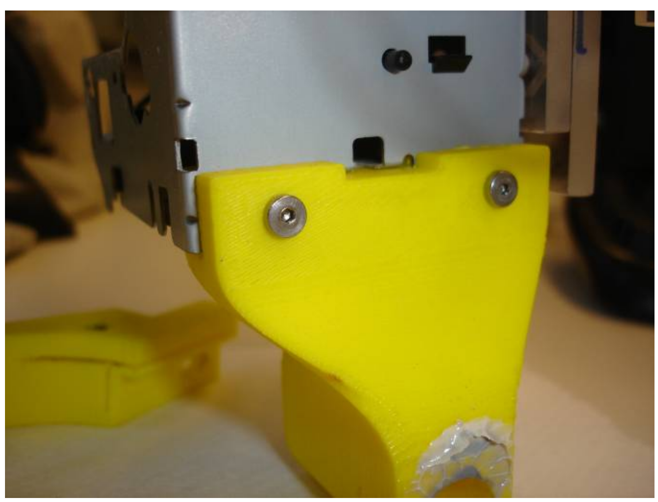


Figure B 22 Second Rail Mount

Slider Switch

The slider switch that was described earlier was attached to the bottom of the gear train assembly just above the rail mount on that side. This is shown below in Figure B 23.

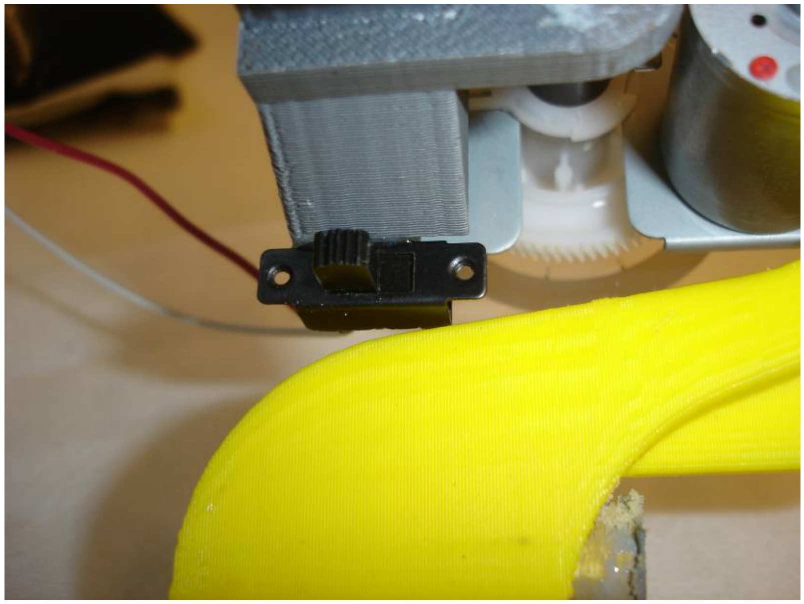


Figure B 23 Slider Switch Attachment

The switch was attached using epoxy and the two wires from the circuit board earlier were soldered to the switch. The switch should be “on” in the position shown above.

Frame Reinforcement

The torque that the drive train applies to the frame causes it to flex during printing. In order to solve this, the frame had to be reinforced. This problem was solved by using extra acrylic pieces. The pieces were positioned over three sides of the frame and holes were drilled through both the piece and the frame. The two side pieces were positioned so the top edge would be flat against the top piece. After all of the parts were attached using screws and nuts, the three parts were glued together to be perpendicular to each other. This will keep the frame in the position it should be. Figure B 24 shows the drive train side piece.

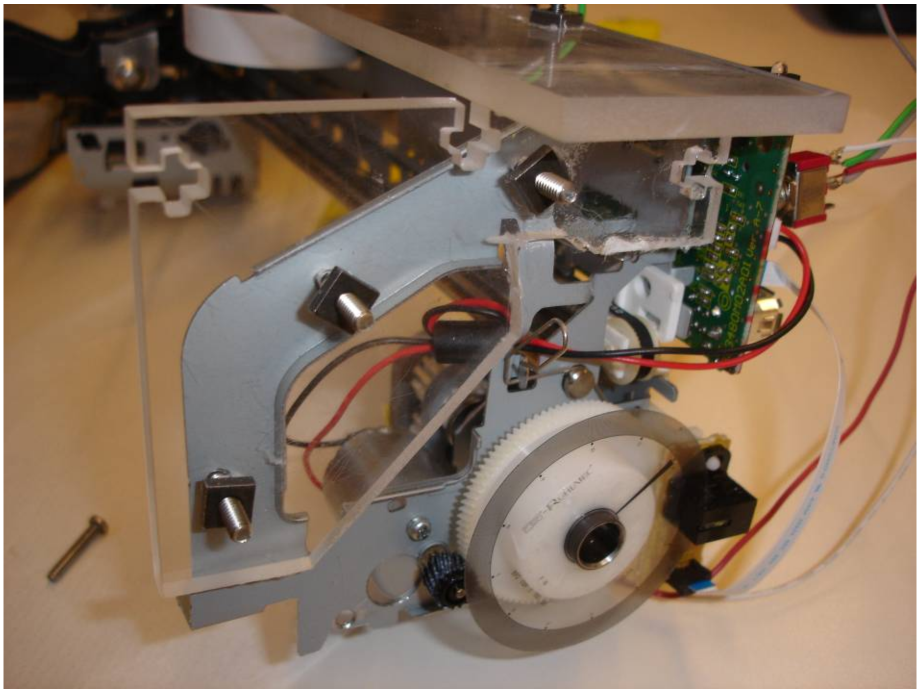


Figure B 24 Drive Train Side Reinforcement

This part was secured using three screws. A small section had to be cut out of the acrylic in order to avoid the rod tensioner. Figure B 25 shows the second side reinforcement piece.

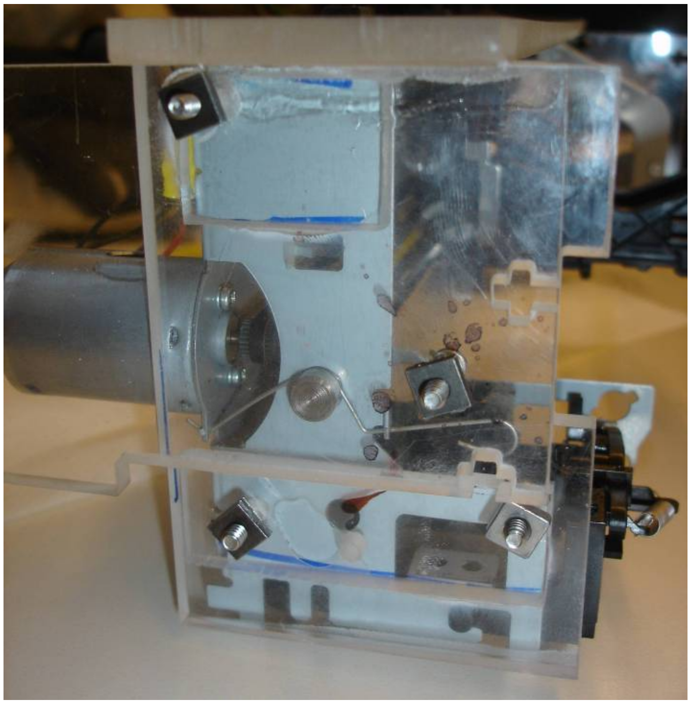


Figure B 25 Second Side Reinforcement

For this side two pieces of acrylic had to be placed underneath the main part. This is to keep the main piece ¼ inch away from the frame in order to avoid protruding parts. These parts were glued to the main part and holes were drilled in a similar manner to the first side. The part was then attached using three screws and nuts. In all three pieces the low profile screw head was placed towards the inside of the carriage to ensure that the print head would not hit them. Figure B 26 below shows the final top piece.

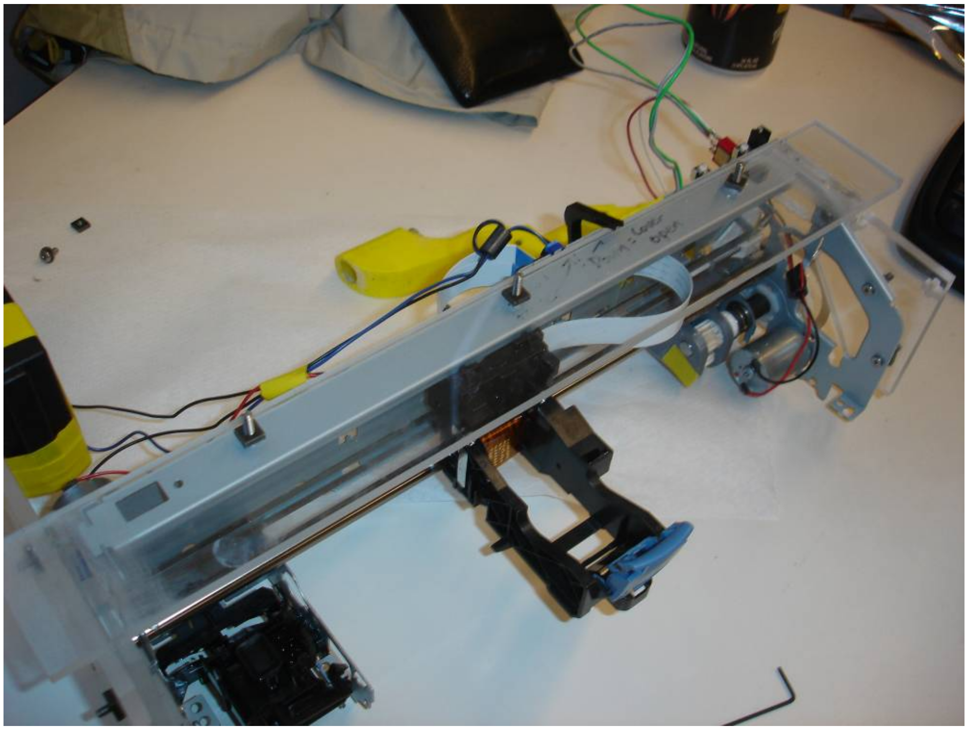


Figure B 26 Top Reinforcement

The top piece was also secured using three screws and nuts. The parts were then glued together. Figure B 27, below, shows another piece of acrylic that was attached to the second side piece.

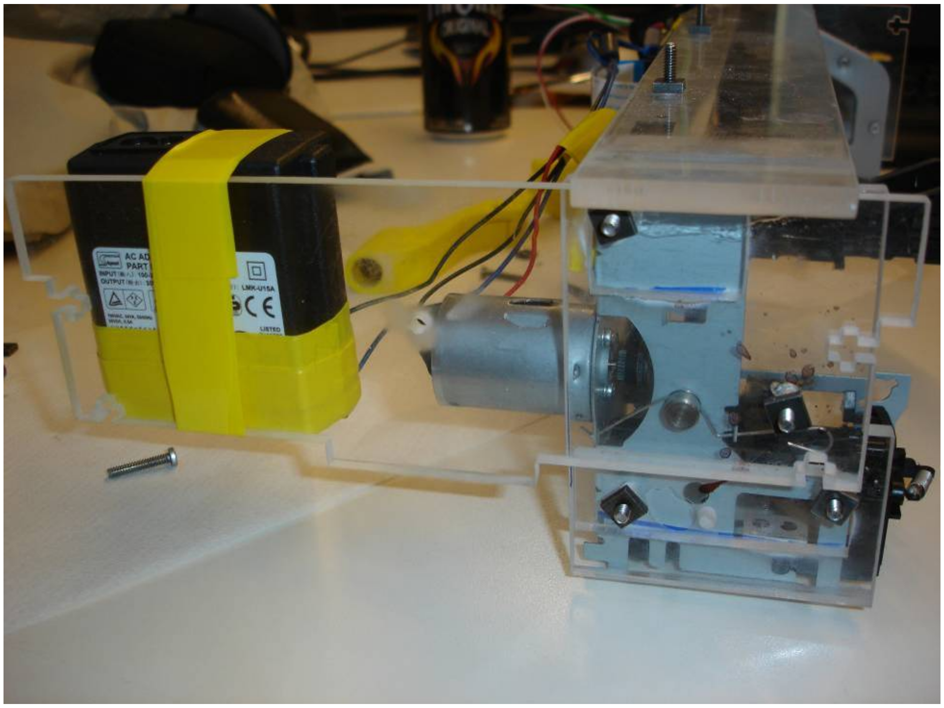


Figure B 27 AC Adapter Part

This piece was attached so that the AC adapter could be secured to it. The adapter also served as a counter weight as the printer seemed to move more easily with weight torquing it in that direction.

Ink Cartridge

The stock ink cartridge was cut open and the ink sponges were removed. Ideally the cartridge would have been flushed with deionized water or rubbing alcohol. Figure B 28, below, shows the ink cartridge cut open.

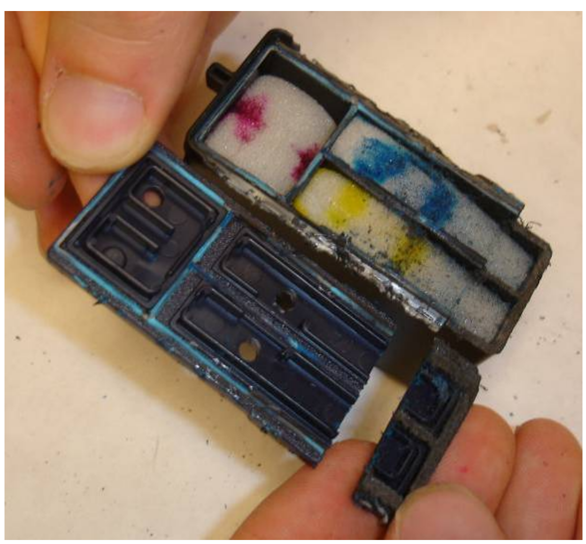


Figure B 28 Open Ink Cartridge

Once the sponges and ink were removed, the top was glued back on. The small piece of plastic was replaced with a small piece of acrylic to act as a viewing window. This is shown below in Figure B 29.

Figure B 29 Modified Ink Cartridge

The cartridge was filled with binder using the top ports and a piece of tape was placed over them. It should be noted that in order to change the ink cartridge, the purple plastic piece must be removed because of the frame reinforcement piece.

Housing Assembly

General instructions to assemble the housing for designed P3P housing. All part numbers are labeled within the parentheses.

NOTE: A. To fasten the components together using the square slots, slide the square nut into the appropriate desired fastener hole and place the screw through the corresponding hole on the piece being attached. Screw until the fasteners until tight. Unless stated otherwise, assume the screws used for fastening are 6-32 thread, 5/8” length screws.

B. The rack, rack spacers, print carriage, rails, rail mounts, limit switch blocks, circuit board and collars are not included in this instruction set.

1. Insert braces (024) into the appropriate slots on the print sides (022). Fasten.

2. Slide in the front and rear end panels (015) at the ends of the print sides (022). Fasten.

3. Slide the main right side wall (030) to the right side of the front and rear end panels (015). Fasten.

4. Slide the side brace (028) into the place at the bottom right area of the housing. Fasten.

5. Place the appropriate chamber braces (002 and 003) on to the appropriate locations at the tope of the housing.

6. Line the top panel (001) up with the holes of the print sides (022) and the chamber braces (002 and 003).

7. Fasten the right rail braces (029) between the ends of the right side wall (030) and the front and rear end pieces (015)

8. Fasten the left rail braces at the appropriate locations on the front and rear panels (015). [There is not drawing for the left brace since they were later designed.]

9. Build the waste container support outside of the house (017, 018, and 019).

10. Slip the waste container support through the left side opening and fasten it to the front end (015) and the top panel (001).

11. Slide in the waste container (036) and chambers (035).

12. Fasten the HIS 3500 series linear actuator to the bottom of the motor using M3x0.5 fasteners.

13. Thread the B-class thread 7.5" length shafts through the linear actuators, making sure the M4 head (smaller end) is pointed upwards.

14. Screw pistons (037) onto the shafts.

Piston Assembly

Build and Feed Chambers

1. Construct brace system to hold chamber panels vertical during adhesion.
2. Apply thickened cement to one vertical edge of first panel.
3. Repeat Step 3 for remaining four panels, forming butt joint between edge of previous panel and inside face of current panel. Brace, clamp, and allow setting for approximately fifteen minutes.
4. Apply thickened cement to bottom edges of panels and join to bottom plate. Let set for fifteen minutes.
5. Apply thickened cement to long edge of chamber flange and clamp to chamber, repeat. Let set for fifteen minutes, and then cure all parts for twenty four hours.
6. Mount HSI stepper motor to bottom of chamber using four 3X0.7 mm, 9 mm long screws.

Waste Chamber

1. Perform Steps 1 through 4 from "Build and Feed Chambers" using panels from (036). Let sit for fifteen minutes, and then cure for twenty four hours.

Piston

1. Insert threaded insert into center pocket of piston plate 5, then stack plates in order, as shown in (037) and join with four 6-32X1” screws.
2. Cut 4.75” square piece of low grit (60 or 80) sandpaper, apply spray adhesive to back side, and apply to top face of piston. Allow adhesive to set for duration specified on container.
3. Cut four 5.25” lengths of 3/8” diameter sealant foam. Chamfer ends of foam at roughly 45 degrees, fit ends together around piston and check for snug fit, trim as necessary.
4. Slice foam down middle leaving a small web, apply thickened cement to inside and end faces, and apply over center plate of piston assembly. Clamp and let sit for fifteen minutes, and then cure for twenty four hours.
5. Thread lead screw into insert and hand tighten, and then thread lead screw into stepper motor.

Integration

Several parts for the housing were not fully machined until the printer was ready to go on. This was necessary to make sure the print head was the correct height above the powder bed. Figure B 30, below, shows two of the four rail brackets mounted on the housing.

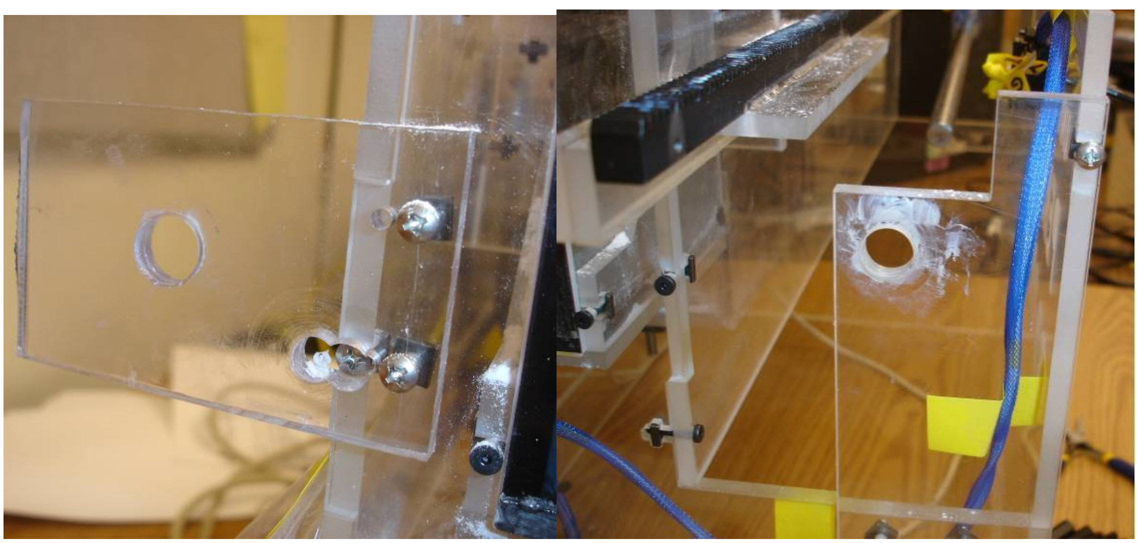


Figure B 30 Rail Mounting Brackets

As shown above, the left bracket was modified to include a place for the housing screw to fit through the acrylic. The rail holes were drilled to ensure that the bottom of the print head would be between one and two millimeters above the powder. Figure B 31 shows the rails part way inserted with collars on one end.

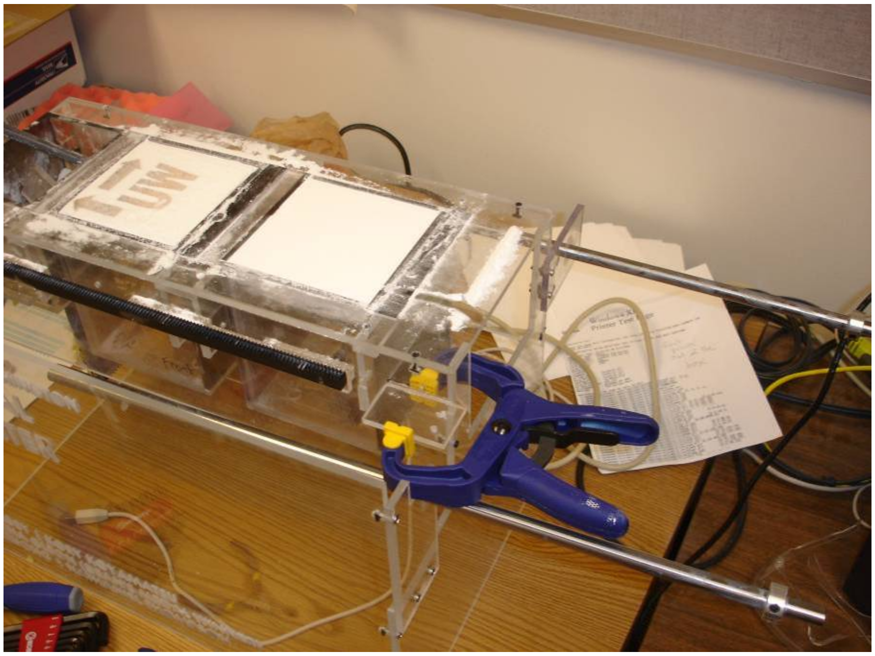


Figure B 31 Rails Partially Inserted

Once the rails were part way in, they could be slid through the printer rail mounts. Figure B 32, below, shows the printer sitting on the rails.

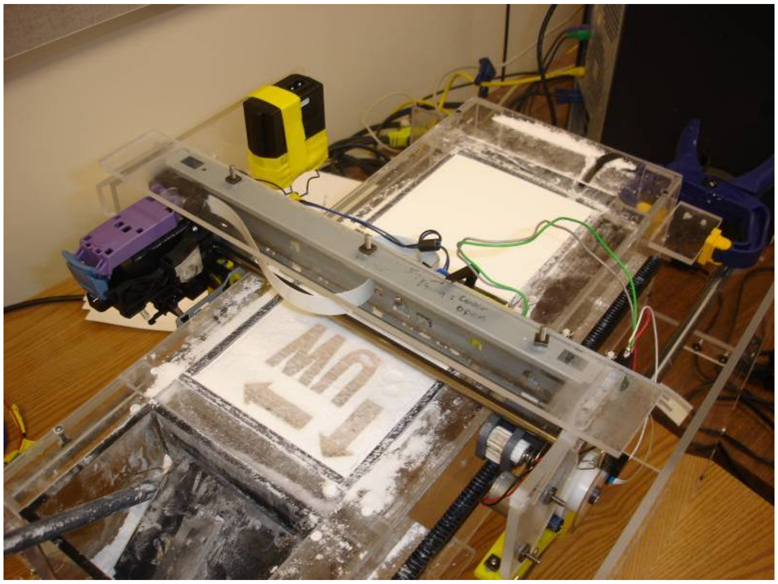


Figure B 32 Printer on Rails

After the printer was on and the rails had been slid through the other pair of rail brackets, collars were connected to the final end. This is shown below in Figure B 33.

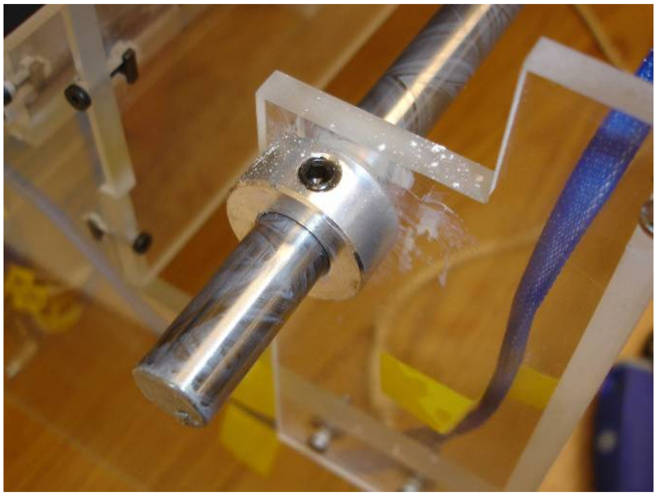


Figure B 33 Rail Collar

After the rails were fully assembled, the rack had to be put on. The location where the rack needed to be in order to contact the gear train was determined and the acrylic plate where it would be mounted was taken off and holes were drilled. Holes were also drilled into the rack and were then tapped. Several extra acrylic pieces were used as spacers to move the rack to the correct distance away from the main part of the housing so that it would contact the bottom gear of the gear train. Figure B 34 below shows the rack mounted on the housing.

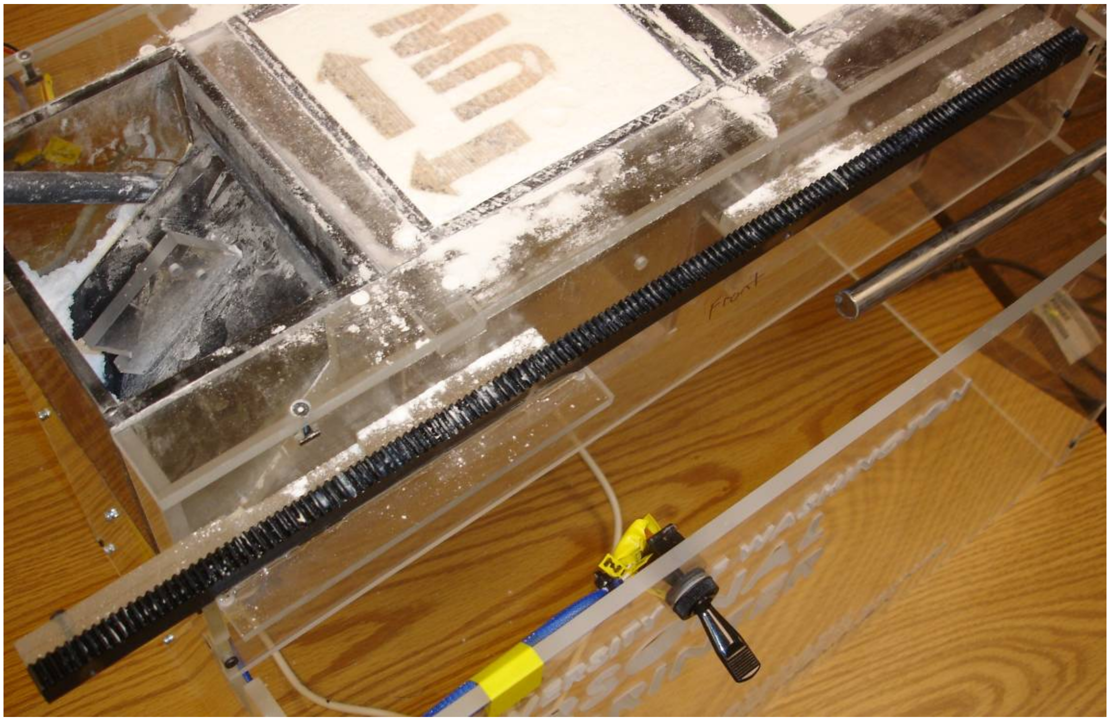


Figure B 34 Mounted Rack

The rack was mounted towards the left so that by the time the print carriage passed the feed bed it would be off of the rack. This was done to prevent the printer from paper jamming when the carriage reached the end of rail travel and the printer was still trying to "eject paper". Figure B 35, below, shows a closer view of the mounted rack.

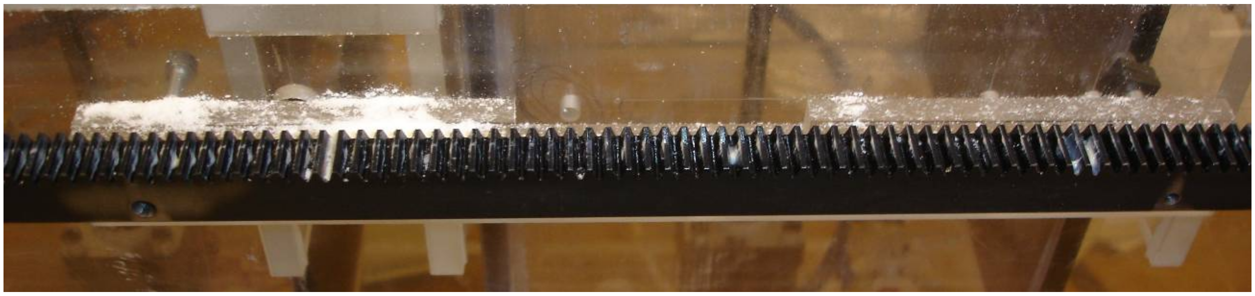


Figure B 35 Mounted Rack Close-up

After the rack was mounted, it was necessary to mount two pieces of acrylic to actuate the slider switch that was mounted on the print carriage. These two pieces are shown in the images below in Figure B 36.

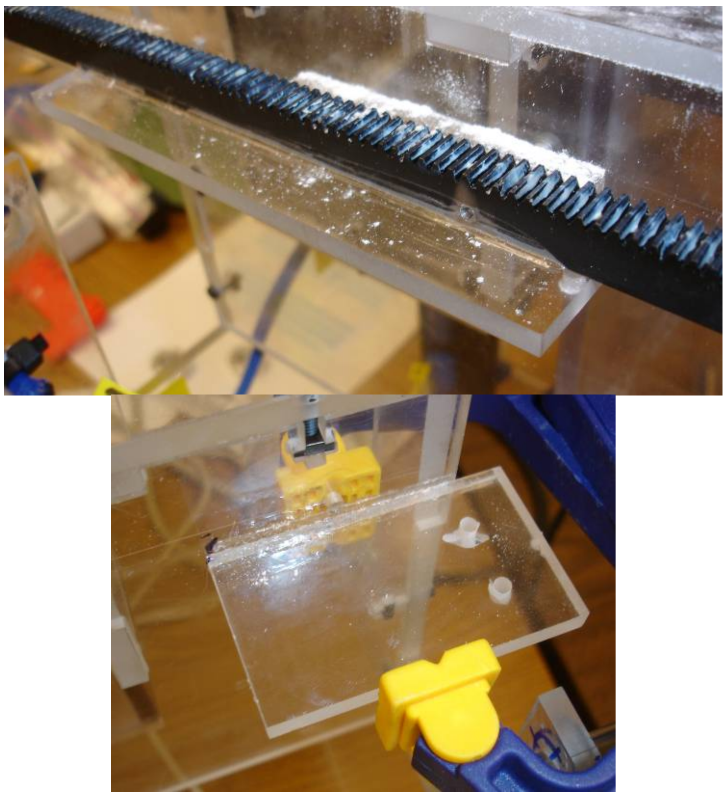


Figure B 36 Slider Switch Actuators

These two parts were mounted after inspection to check where the print carriage needed to start and stop. The part in the left image is positioned so that the print head will be positioned at the start of the build bed as soon as the switch is tripped (turned on). The part in the right image is positioned so that the switch will be pushed in the opposite direction (turned off) as soon as the carriage loses contact with the rack. As soon as the printer starts to print, it will move in the opposite direction until it actuates the switch (this is when the printer thinks it has loaded paper), then it will move in the correct direction to print and start printing. Once it reaches the end and comes off of the rack, it will receive the signal that the paper has passed through; it will continue to eject the paper for a short time, and then is ready to print again. The part on the left also ensures that it will start printing in almost the same position each time it prints. Figure B 37, below, shows an image of the spreader being used for the powder and also a plastic part used to compact the powder in the feed bed.

Figure B 37 Powder Spreader and Compactor

The compactor was made using extra plastic parts. The spreader is the other end of the paper feed rod that was cut off to create the gear train.

Appendix C – Motor Control Code

This program, called P3Pcode2, includes extraneous code which is not currently used but may aid future additions such as inclusion of limit switches. Coding for additional switches which are not used on the prototype has been included in several places.

```
#include <conio.h>

main()
{
int port;
int Sregister;
int Cregister;
char string[80];
char *ptr;
char ch;
unsigned char axis;
unsigned char dir, direction;
long x;
long count;
long layerthick;
int k;
ch = 0x00;
ptr = string;
port = 0x378;
Sregister = port+1;
Cregister = port+2;
dir = 0x00;
count = 5000;
k = 0;
clrscr();

printf("Press ESC to exit \n");
printf("Choose a layer thickness value: ");
gets(string);
layerthick = atoi(string);
printf("layer thickness number = %ld\n", layerthick);
printf("Press X, Y, or Z to choose axis\n");
printf("Current port = %x\n", port);
menu();
while (ch != 0x1b)
{
		if ( ((inportb(port+2) & 0x4) == 0) && k==0)
		{
			printf("Switch is FLIPPED\n");
			k = 1;
			for(x=0;x<10000;x++)
			{
			}
			printf("done\n");
		}
		if (kbhit())
		{
			ch = getch();
			if (ch == 0x1b)
			{
				exit(0);
			}
			if (ch=='q' || ch=='Q')
			{
```

```
                pincheck(Sregister);
            }
            if (ch=='m' || ch=='M')
            {
                menu();
            }
            if (ch=='l' || ch=='L')
            {
                layer(port, count, layerthick);
            }
            if (ch=='b' || ch=='B')
            {
                base(port, Sregister, count);
            }
            if (ch=='x' || ch=='X')
            {
                axis = 0x01;
                direction = 0x02;
                printf("Axis X: press (U) up or (D) down\n");
            }
            if (ch=='y' || ch=='Y')
            {
                axis = 0x04;
                direction = 0x08;
                printf("Axis Y: press (U) up or (D) down\n");
            }
            if (ch=='z' || ch=='Z')
            {
                axis = 0x10;
                direction = 0x20;
                printf("Axis Z: press (U) up or (D) down\n");
            }
            if (ch=='u' || ch=='U')
            {
                dir = 0x00;
                for(x=0; x<layerthick; x++)
                {
                    step(port, axis, dir, count);
                }
            }
            if (ch=='d' || ch=='D')
            {
                dir = direction;
                for(x=0; x<layerthick; x++)
                {
                    if(((inportb(port+1)&0x10)!=0) && ((inportb(port+2)&0x1)==0))
                    {
                        step(port, axis, dir, count);
                    }
                    else
                    {
                        printf("Part or feed bed not designed to move lower.\n");
                        printf("Move each piston up before trying again.\n");
                    }
                }
            }
            printf(".");
        }
        }
}

pincheck(int port)
```

```
{
        unsigned char regValues;
        regValues = inportb(port);
        printf("Status register status: %x\n", regValues);
        regValues = inportb((port+1));
        printf("Control register status:      %x\n", regValues);
        return;
}

layer(int port, long count, long layerthick)
{
        long i;
        int n;
        for (i=0; i<layerthick; i++)
        {
                if( (inportb(port+1) & 0x10) != 0)
                {
                        step(port, 0x01, 0x02, count);
                }
                else
                {
                        n = 1;
                }
        }
        for (i=0; i<(1.2*layerthick); i++)
        {
                if( (inportb(port+2) & 0x2) == 0)
                {
                        step(port, 0x04, 0x00, count);
                }
                else
                {
                        n = 1;
                }
        }
        if(n==1)
        {
                printf("Feed or part bed not designed to move any further.\n");
                n = 0;
        }
        return;
}

base(int port, int Sreg, long count)
{
        char affirm;
        printf("Printer is clear of print beds and turned OFF? Y/N \n");
        affirm = getch();
        if (affirm == 'y' || affirm == 'Y')
        {
          printf("Are you sure you want to return feed bed and part bed\n");
          printf("to lowest position (base of bed)? Y/N \n");
          affirm = getch();
          if(affirm == 'y' || affirm == 'Y')
          {
                while((inportb(Sreg) & 0x10) != 0)
                {
                        step(port, 0x01, 0x02, count);
                }
                while((inportb((Sreg+1)) & 0x1) == 0)
                {
                        step(port, 0x04, 0x08, count);
```

```
                }
                printf("Printbeds are now in their 'base' positions.\n");
                return;
            }
            return;
        }
        return;
}

menu()
{
        printf("\n");
        printf("OPTION MENU \n");
        printf("\n");
        printf("Press buttons for specific actions as follows: \n");
        printf("(ESC) - Exits the program. \n");
        printf("(Q)   - (question) reads the Status and Control registers.\n");
        printf("(L)   - Steps part and feed beds one LAYER thickness.\n");
        printf("(B)   - Returns part and feed beds to extreme BASE positions. \n");
        printf("(X) or (Y) or (Z) - selects a motor for manual adjustment. \n");
        printf("        X: part bed \n");
        printf("        Y: feed bed \n");
        printf("        Z: printer carriage \n");
        printf("(U)   - Moves selected motor (part or feed bed) UP. \n");
        printf("        or moves carriage right (toward waste bin)\n");
        printf("(D)   - Moves selected motor (part or feed bed) DOWN. \n");
        printf("        or moves carriage left (toward feed bed side)\n");
        printf("\n");
        printf("Press (M) to view these options again.\n");
        return;
}

step (int port, unsigned char axis, unsigned char dir, long count)
{
        long i;
        outportb(port, axis | dir);
        for (i=0; i<count; i++);
        outportb(port, 0x00 | dir);
        for (i=0; i<count; i++);
        return;
}
```

Appendix D - TB AUX Mapping for Limit Switches

The TB AUX connections were mapped to determine the bit in either the status or control register corresponding to the TB AUX connection. The numbering convention used for the TB AUX connections is shown in Figure C 1.

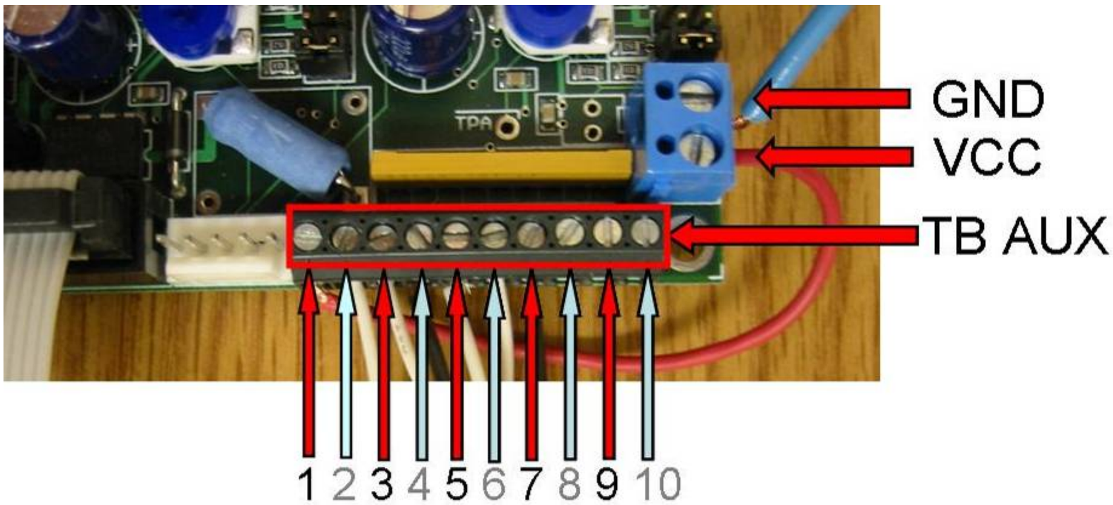


Figure C 1 Numbering Convection for TB AUX Screw Terminal Connections

The motor control program (attached in Appendix C) was run using the Q command to see the current values in the status and control registers. By closing a switch wired to each TB AUX connection one at a time it was possible to determine which bit was changed by using the switch, and thus how to read the switch. Table C 1shows the results of the mapping including which register and bit was affected.

Table C 1 Control Bit in Status/Control Registers for All TB AUX Connections

TB AUX number	Register	Control Bit*	Closed Result (Hex)	Closed Result** (bit values)	Alternate value
1					Vcc
2	status	2	58	01**0**1 1000	
3	status	3	68	011**0** 1000	
4	status	0	F8	**1**111 1000	
5	control	2	E	11 **1** 0	
6	control	3	D	110 **1**	
7	status	4	70	0111 **0**000	
8	control	1	8	1 **0** 00	
9					***see note
10					GND

*Control bit for status register may be between 0-7 (inclusive)
or for control register may be between 0-3 (inclusive)

**Open result for status register is 0x78 (0111 1000)
open result for control register is 0xC (1100)

**TB AUX 9 did not appear to change any of the bits in either
the status or control register

Based on the open circuit value and closed circuit value of the TB AUX ports, it was possible to create checks for each switch. This used the inportb() command of TurboC to read the registers and compare them to expected value. For example, the limit switch to prevent downward motion of the part bed piston was connected to TB AUX 3. The code determines that it is okay for the piston to move downward as long as the third bit of the status register is not zero (switch is still open), or in code form: if((inportb(0x379) & 0x10) != 0).