Multilayer Polymer Inkjet Printing

REPORT FOR A MAJOR QUALIFYING PROJECT

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Abstract

The goal of this project was to design and modify an inkjet printer to print multilayered images of a selected polymer. A standard inkjet printer was modified to create a dual axis printing system. A printable polymer solution was created containing polyvinylpyrrolidone. A printing material was also developed to provide a more compatible surface for adhering. With further modification, the printer could be used to print various polymer solutions onto a range of materials allowing for a variety of applications.

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1.0 Introduction

Inkjet printing has been widely used in the home and office for printing text and photographs onto various types of paper. This is mainly due to the fact that inkjet printing is reliable, is capable of printing full-resolution pictures as well as plain text, and it is a relatively inexpensive process. Recently it has been realized that inkjet printing technology could be applied to many more areas, especially to manufacturing processes. A few examples of this are utilizing the technology to 'print' medicines in pill or patch form, to produce light-emitting polymer (LEP) displays, creating printable circuits by printing particulate suspensions, as well as many other applications that could benefit many different industries. The possible areas in which this technology could be applied are growing rapidly, and the technology is currently being developed and improved.

Many of the possible applications of inkjet printing would require more than one layer to be printed on the same location, thus producing a three dimensional material. For this reason a traditional inkjet printer cannot be used, as the design allows just one layer of ink to be printed onto paper. This project will focus on modifying a traditional home and office inkjet printer to create one that is capable of printing multiple layers of a desired material onto the required medium. There are two fundamental ways to accomplish this. The first is a software approach, in which the programming of the printer could be altered so that printer would print in the desired manner. This project will use the other approach, which involves developing a mechanical solution to modify the printer resulting in an inkjet printer with the desired capabilities.

The objective of this project is to modify an inkjet printer to print multiple layers of polymer solutions on to various mediums, which would create a three-dimensional layered polymer product. In order to accomplish this, a final design that requires a Canon S750 inkjet printer to be modified to a dual axis design was chosen. The paper feed mechanism would be relocated so that it is oriented in a perpendicular position compared to the printing mechanism. The printing mechanism would be driven by the paper feeding mechanism so that the print head would move over the medium in both the x and y directions as it prints. A separate motor and circuit would be developed so that once the print head reaches the end of the page, it would return to its original starting position, ready for the next copy. This allows the medium to remain stationary while the printer movies over it, therefore the same design can be printed onto a medium as many times as desired. This would result in a sheet of the desired design, with the thickness depending on the number of layers printed.

2.0 Background Research

2.1 Inkjet Printing History

There are many different types of printers, but the most commonly used in households today is the inkjet printer. Although there is not one clear person who was given credit for the invention of the inkjet printer, it is clear that it was invented in 1976. It was not until 1988, though, that they became commercially available. The first company to offer an inkjet printer to the public was Hewlett-Packard (HP), at a cost of $1000. This cost was very high, which meant that the inkjet printer was not very popular when it was first released. Since then costs have drastically decreased, and ink jet printers have become very common.[1]

2.2 Inkjet Printing Technologies

An inkjet printer works essentially by propelling drops of ink of the desired size onto a desired type of medium, usually paper. There are two main methods of accomplishing this used today, thermal bubble and piezoelectric printing. In thermal bubble printing many tiny resistors are used in the print head. By passing current through the resistors heat is generated, which causes bubbles to form in the ink. When the bubbles pop a tiny droplet of ink is deposited on the medium. The vacuum that is formed when the bubble pops pulls new ink into the print head. There can be up to 600 of these resistors in the print head and all can be used at once. This technology is sometimes called bubble jet printing because of how it works.[2] This technology is currently used by manufacturers such as Canon and Hewlett Packard. To see an image showing thermal bubble inkjet print head structure, see Figure 1 below.

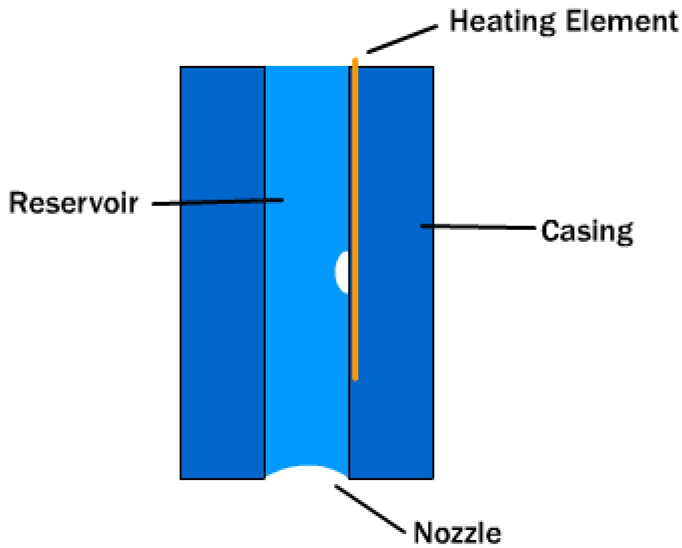

Figure 1: Thermal Bubble Inkjet Printing Technology[2]

Piezoelectric inkjet printing technology is fundamentally different than thermal bubble technology. This technology was developed by Epson, and it utilizes a piezo crystal located at the back of the print head. When a small amount of current is passed through the crystal, it vibrates. As the crystal vibrates forward it pushes a small amount of ink out of the print head. As it vibrates backward, it pulls a small amount of ink into the print head, to be used in the next cycle. To see an image showing the piezoelectric ink head structure, see Figure 2 below.

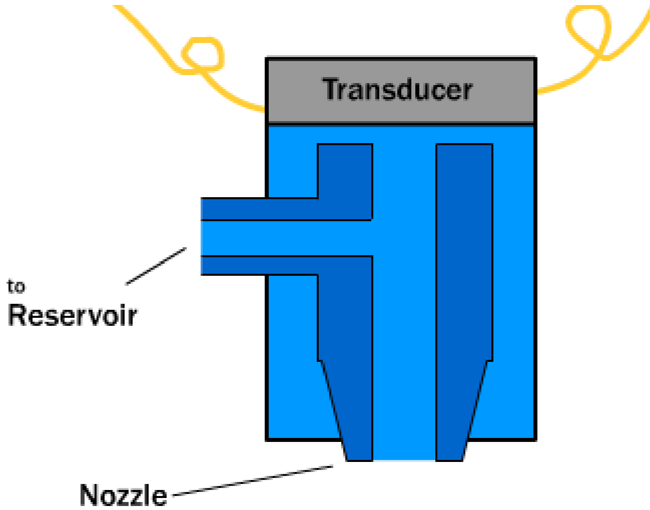

Figure 2: Piezoelectric Inkjet Printing Technology[2]

2.3 Current Research

Recently researchers have begun to develop methods of using traditional inkjet technology to produce functional materials. Inkjet technology will be useful when small amounts of a material need to be deposited in very specific areas on a desired substrate. Inkjet technology will allow this type manufacturing, as it has already been demonstrate that the technology is capable of doing so in graphic arts. By modifying the technology it could be applied to create functional materials such as medical patches or pills, printing LEP displays, light and thin solar cells, electrical and mechanical components, and thin-film transistor circuits.

Research has been completed by an MQP team at WPI in which they were able to develop a suitable polymer solution that is able to be printed by an inkjet printer. They used information found from Hewlett Packard's website to find the ingredients used in the ink of their cartridges. The polymer being used in the cartridges is Polyvinylpyrrolidone, or PVP. After testing, the team had successfully developed a polymer solution that could be printed onto paper. The other accomplishment the group had was beginning to develop a paper feeding system that could feed the paper back and forth for multiple layer printing capabilities. A paper tray was fabricated that was mounted on rollers. After a layer was printed, a separate circuit would then push the tray back to be printed again in the same location. This process would be repeated until the desired amount of layers had been printed.[3]

Another example of work being done in the printing field has been completed by Professor Michael J. Cima of the Massachusetts Institute of Technology. Cima has developed a new method of producing pills, by essentially printing them using technology very similar to that of inkjet printing technology. Three-dimensional printing in this application works by dropping precise drug doses onto thin layers of fine powder as the tablet is formed. Pharmaceutical-grade powder which forms the structural matrix of the pill is then spread to form the next layer, usually around 100-150 micrometers thick. Next, the continuous-jet print head sprays pharmaceutical-grade binder to prepare for the next layer. 30-50 layers are bound to complete the building process. Hundreds or thousands of pills can be produced at once, which allows for mass production of the medications. The drop-on-demand technology can place dots of one drug, or multiple drugs, very precisely throughout the layers for the most effective release. This new technology means that the dosage of medications can be much more precise, and easily changed to meet the needs of a specific patient. Also, it will allow for the dosage to be delivered in a specific amount of time because depending upon the solvent that the drug is dissolved in for the printing process, the pill will degrade and release the drug a different rates. This means that medications could be custom ordered to carry different precise dosages which can be delivered at any time, up to hours after the pill is taken.[4]

Also, light emitting polymer (LEP) displays are being developed. In order to produce these displays piezoelectric inkjet printing technology can be used. The first step was to develop a solvent for the ink that could satisfy the required characteristics when being printed by the piezoelectric print head. These characteristics include the ability to be formed into droplets having a constant volume that can be ejected from a nozzle with no bending of their trajectory in flight, and also no change in inkjetting characteristics after a pause in printing. For these displays a water based ink was used, with PEDOT being the conducting polymer. PEDOT cannot be dispersed on its own, so PSS was added resulting in PEDOT:PSS which can be suspended in water. This polymer does not absorb visible light, so Polyalkyflourene and its derivatives were used for the actual LEPs. To produce circular pixels, a PEDOT:PSS/water ink is first deposited via inkjet printer, followed by the Polyalkyflourene ink with organic solvents. The research team printed the LEP displays onto polysilicon thin-film transistors as a back plate, forming a functional display that could produce various types of images. For a schematic of a pixel of the LEP, see Figure 3 below.

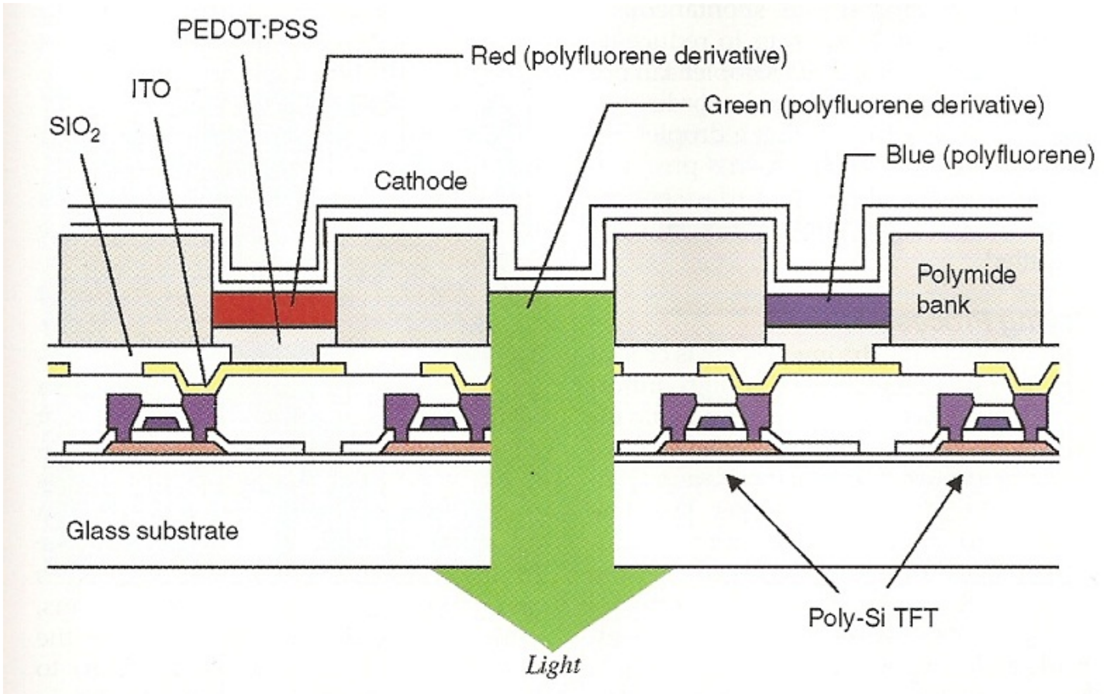

Figure 3: Schematic of a LEP Pixel[5]

After printing, the drying process is very important to ensure uniformity. The droplets of ink are so small, ~20µm, that they do not dry in the same manner as large amounts of the same liquid. The drying times of the ink are only 1 minute, meaning the drying processes is not to difficult to complete appropriately. The team reported results of a printed LEP screen that can produce vivid images, and lifetime of the green diodes to be up to 25,00h, 40,000h for the green diodes, and even up to 8,000h for the blue diodes which are the most difficult to extend because of its wide band gap.[5] For an image of the completed printed LEP screen, see Figure 4 below.

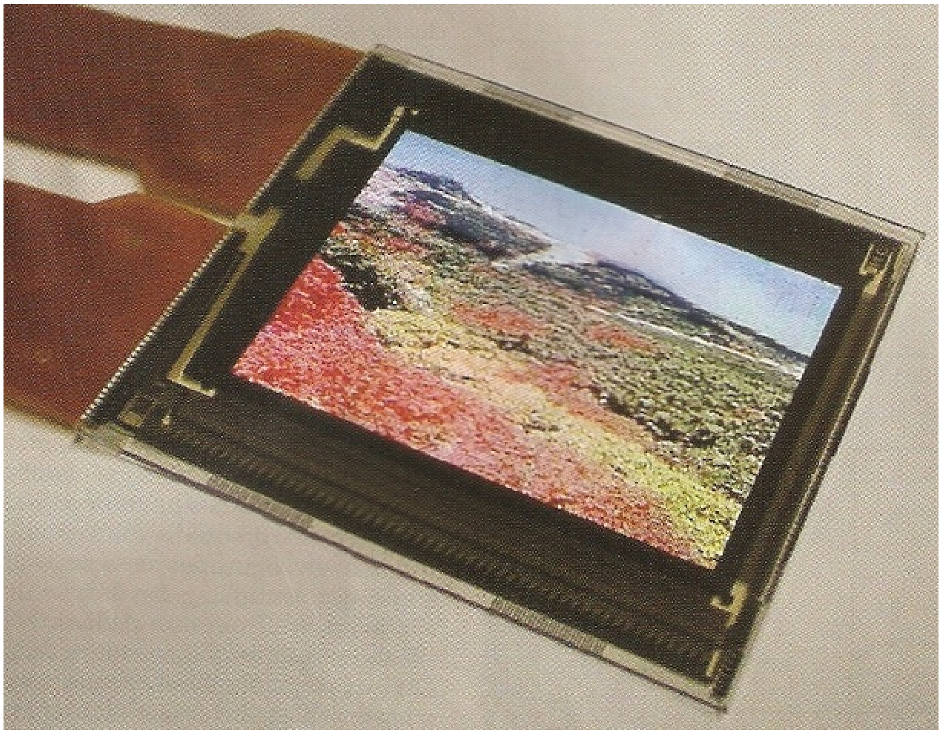

Figure 4: Complete LEP Screen Produced With Inkjet Printing[5]

The potential possibilities of inkjet printing prove to be growing rapidly, as the technology has also been shown recently that it is possible to print solar cells with the technology. The research team started with a thin layer of indium tin oxide (ITO) as the basis for the solar cell. Next, a thin layer of the chosen ink was printing using inkjet printing technology onto the ITO. The team used four different inks, composed of a conducting polymer PEDOT:PSS, along with glycerol and ethylene glycol butyl ether (EGBE) to alter the properties of the ink solution. To see a chart of the four inks contents, see Table 1 below.

Inks	PEDOT:PSS (g)	Glycerol		EGBE	
		g	wt.%	g	wt.%
1	7.194	–	–	–	–
2	7.194	0.431	6	–	–
3	7.194	0.431	6	0.014	0.2
4	7.194	0.431	6	0.028	0.4

Table 1: Inks Used for Printing Solar Cells[6]

Next an active layer of P3HT:PCBM is coated onto the printed conducting polymer via spin coating. Finally, LiF was evaporated on the active layer to about 0.7 nm thicknesses, and then Al evaporated to about 150 nm thicknesses under a vacuum of 10^{-6} torr. This results in a very thin and flexible solar cell that can be used in a wide variety of applications. Due to the inkjet printing manufacturing methods these cells can be fabricated rapidly with relatively low cost.

The research team then tested four solar cells, on produced with one of the four formulated inks in order to determine the best performing ink. The results can be seen below in Figure 5.

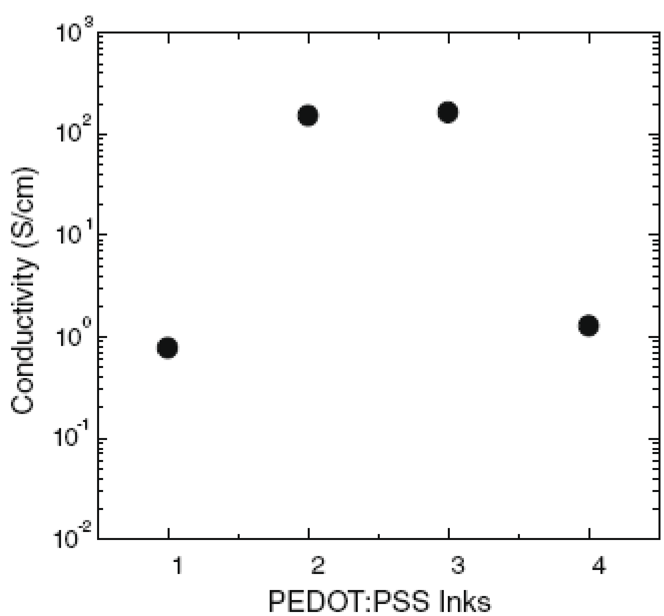

Figure 5: Conductivity of Printed Solar Cells Using Four Different Inks[6]

As can be seen, the formulation of the ink, specifically the additives used to affect the properties of the ink solution are extremely important. In this case, inks two and three are very similar, with ink three being the best. This is because the properties of these inks yielded the most uniform polymer layer with the smoothest surface, making it able to conduct more efficiently. After testing, the team showed an overall efficiency of the solar cell to be 3.61%. While there is still more work to be done with these cells, their lightweight, flexibility, and relatively low cost mean they have potential to be a very valuable commercial product utilizing inkjet printing technology.[6]

It is also possible to print highly loaded particulate suspensions in order to manufacture small components for electrical or even mechanical applications. There are two main ways to accomplish producing parts by inkjet printing. The first involves depositing a liquid binder material onto the desired flat bed material in powder form. The binder material is then deposited in the desired location on the power to solidify the powder where desired. Finally, the excess powder is removed and the remainder is heat treated to complete the solidification. This method wastes a significant amount of material however, and is not as versatile as directly printing the component with a particulate suspension already containing the desired material. This method yields higher quality printing, and allows for more complex components to be manufactured. The limiting factor with this type of printing is the fluid properties of the suspension, however Al_2O_3 alumina powders suspended in a paraffin wax has been successfully printed using a simple piezoelectric inkjet print head. Using suspensions such as these, it is possible to print a three-dimensional object from a computer-aided design file.[7] An example of a three-dimensional object manufactured can be seen below in Figure 6.

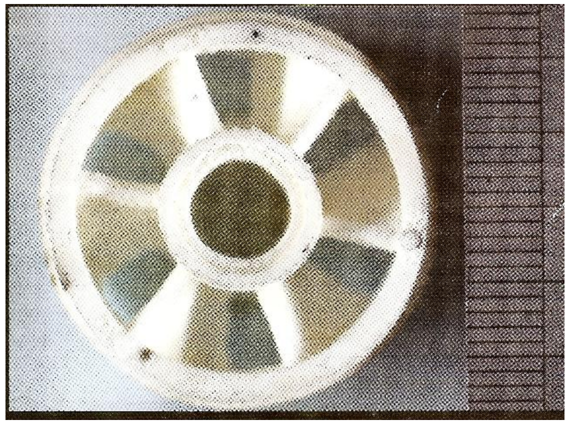

Figure 6: Mechanical Component Manufactured Using Inkjet Printing Technology[7]

Traditionally thin film electronics have relied on either photolithographic patterning or vacuum deposition manufacturing techniques to produce transistor circuits. It is not currently possible to produce these types of circuits onto flexible substrates using these types of manufacturing processes, however, research has been conducted that shows that inkjet printing of conducting polymers onto flexible substrates can result in a relatively low cost and environmentally friendly manufacturing process to produce flexible thin-film transistor circuits. Traditional photolithographic methods result in a large amount of wasted photo resist, and vacuum deposition results in only a portion of material actually be used, meaning that inkjet printing is much more efficient and has lower cost. Also, inkjet printing methods mean large flexible poster-sized displays or even intelligent labels to replace optical barcodes can be produced. This process is challenging though, as there are very small tolerances for drop placement, as low as ±5 μm, which is a much smaller tolerance than typical graphic arts applications for inkjet printing.

Similar to other polymer applications to produce electronics, PEDOT:PSS was used as a conducting polymer. This polymer was used as the drain, source, and gate of the transistors, but it is not conductive enough for gate and data interconnect lines due to conductivity of 100 S/cm. For these connection lines inkjet printable suspensions of nanoparticles of inorganic metals were used. The result is a functional thin-film transistor circuit that can be applied to various electronics.[8] Figure 7 shows the process of printing these transistors as well as a completed transistor created by inkjet printing.

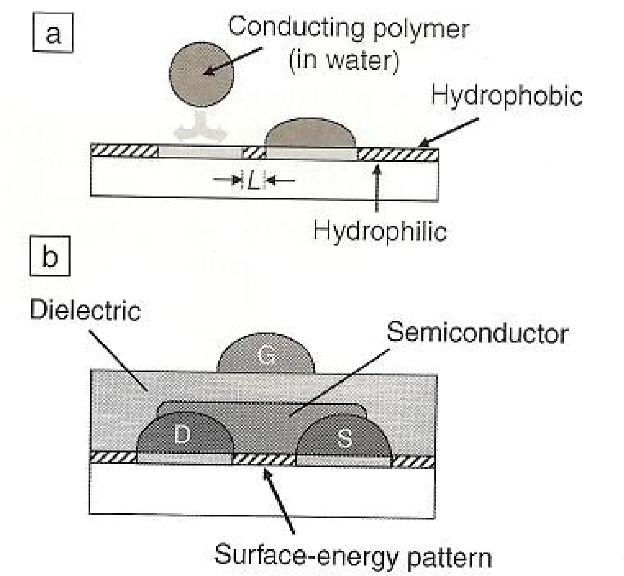

Figure 7: Transistor Manufactured Using Inkjet Printing Technology[8]

In most applications it is necessary to design specific ink cartridges that will be able to print the desired print design. Different ink solutions will require different print head designs. These changes represent the main modifications research teams have been doing to apply this technology to produce functional materials. The properties of the solution to be printed can vary greatly depending on what materials it contains, and the amount of the materials in the solution. Aspects that need to be addressed when designing a print head are as follows: the number of jets, drop volume, drop placement accuracy, and consistency of performance. All of these parameters can be influenced in various ways, and are heavily dependent on the type of ink solution to be printed. This process can take years to complete, but can provide reliable methods for inkjet printing of many functional materials.[9]

2.4 Summary of Findings

Inkjet printing technology has been shown to be an alternative means of manufacturing functional materials, such as medical patches or pills, LEP screens, solar cells, mechanical components, and thin-film transistor circuits. This technology can provide quicker and more efficient manufacturing process in some cases, and the ability to manufacture materials that are not currently able to be produced in others. In many cases, this processes required redesigned print head specific to solution or suspension to be printed which could take long periods of time. More research needs to be done to perfect these manufacturing processes; however, there are many potential applications of inkjet printing of functional materials.

3.0 Purpose and Goals

The purpose of this MQP is to design a Multilayer Polymer Inkjet Printer to create a three-dimensional, layered, polymer product. The final goal for the project is to produce a printed polymer configuration with a height of at least one millimeter. The team will design the printer and polymer solution(s) with the intention of versatility for many applications in mind.

Objective: To modify a commercial inkjet printer to print multiple layers of polymer solutions on to various mediums, to create a three-dimensional layered polymer product.

Goals:

- Develop a two-dimensional coordinate feeding mechanism to allow an inkjet printer to accurately print multiple layers of a desired configuration on a medium.
- Derive a polymer solution(s) suitable for particular applications and compatible with inkjet printer technology.
- Create a three-dimensional, layered, polymer product that may be applied for various uses such as medicines, electronics, consumables, or plastics manufacturing.

4.0 Methods and Materials

The goal is to construct a polymer solution printer that can accurately reprint multiple times allowing the multiple printings to be layered thus created three dimensional polymer structures. This involves three major steps, first is to construct the mechanical printer that will allow the team to accurately print the polymer solution. The second step is to create a polymer solution that contains the desired attributes for the final product while also possessing the properties necessary for it to be printable in an inkjet process. The third step is to create a substrate that the polymer solution is printed on. This is a very specific material because it can't be rough or porous which will allow the solution to permeate the substrate, however it must still have some adhesion with the polymer solution to allow it to settle and dry correctly without beading or wandering.

1. A careful study of the progress from the previous 3D polymer printing MQP Team provides further knowledge as well as creates a starting point for the present MQP Team to work from. A printer design was developed for which to reach the goals most effectively, the design was modeled in SolidWorks 3D CAD software (See Figure 8 below) to create an easy-to-change version of the design as well as to help reveal any unanticipated flaws with the design. The design was finalized based on the materials, budget, and machining techniques available to the MQP Team. A two-dimensional coordinate feed design was chosen to provide the best printing accuracy as well as the most versatile option for various print mediums.

2. The final design was constructed using elements from modern ink printers, common electrical components available, as well as custom fabricated parts by the MQP team. All fabricated parts were built from the materials listed below in the WPI

Washburn Machine Labs. Once completed, the multilayer polymer printer was tested in various ways for any remaining flaws. The printer was then modified accordingly and final changes were completed so that the printer operates in a way to best achieve the MQP goal in a reliable manner.

3. Various polymer solutions, mainly derived with polyvinylpyrrolidone, were created and tested under multiple conditions in order to find the best polymer solution to meet the requirements of the printer. Research and development in water and alcohol soluble polymers provided the team with the best polymer solution to accomplish the project goal. The team best matched the characteristics of the commercial ink designed for the printer head to achieve the best results. Factors such as viscosity, drying time, density, and solubility are considered.

4. Multiple substrates were developed using a wide variety of materials from various types of commercially available papers to foils coated in a thin layer of polyvinyl chloride. The purpose of these substrates is to hold the liquid polymer solution upon printing, allowing it to solidify and polymerize properly. Some of the substrates used during testing and creation of the final product had to be created by the team in different ways, while others were readily available.

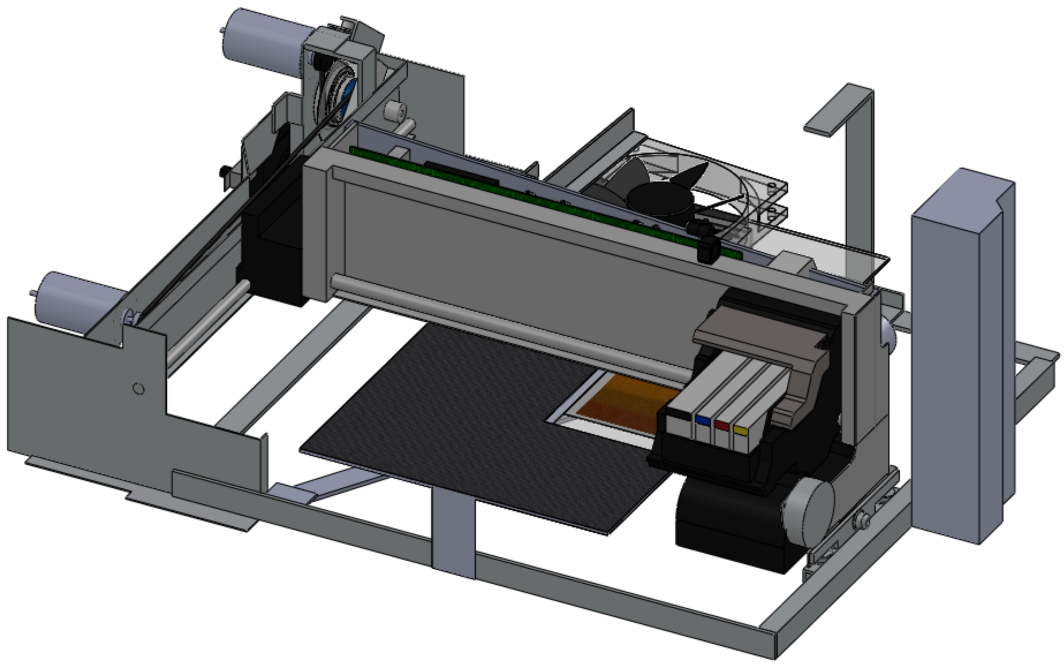

Figure 8: SolidWorks CAD Rendering of Printer Design

4.1 Construction of the Printer

The overall proposal developed for the multilayer polymer printer was to take an existing inkjet printer, and modify it in a way so that it travels in two axes, and retracts automatically after every print to the origin location. This design enables the printer to print on any flat material that is aligned under the print head, and to make multiple, accurate print passes over the same region so that a multilayered printed result can be achieved. The printer that was chosen to be used was a Canon S750 Bubble Jet printer because it offers four separate ink containers and on this model the ink containers are separate from the print head which allows for more consistent results.

Initially, an aluminum frame was constructed to support the main printer assembly which includes the print head, purge unit, and main circuitry; and to allow the printer to travel in the lengthwise direction, which we have deemed the y-axis. The existing travel axis already incorporated into the printer, (the axis that allows the print head to move back and forth across a piece of paper), would be used for the transverse axis which we have deemed the x-axis. This frame was built mainly from aluminum metal stock of sizes $\frac{1}{2}$”× $\frac{1}{8}$”, $\frac{3}{4}$”× $\frac{1}{8}$”, 1” × $\frac{1}{8}$” and with a travel axis assembly from another inkjet printer. This new travel axis would facilitate the travel of the print head along the y-axis. All parts of the frame were bolted together rather than welded or riveted to make for an easier and more accessible disassembly as utilized in many prototypes, which may be useful in the future for any design changes. Below, Figure 9 is rendering of the completed frame.

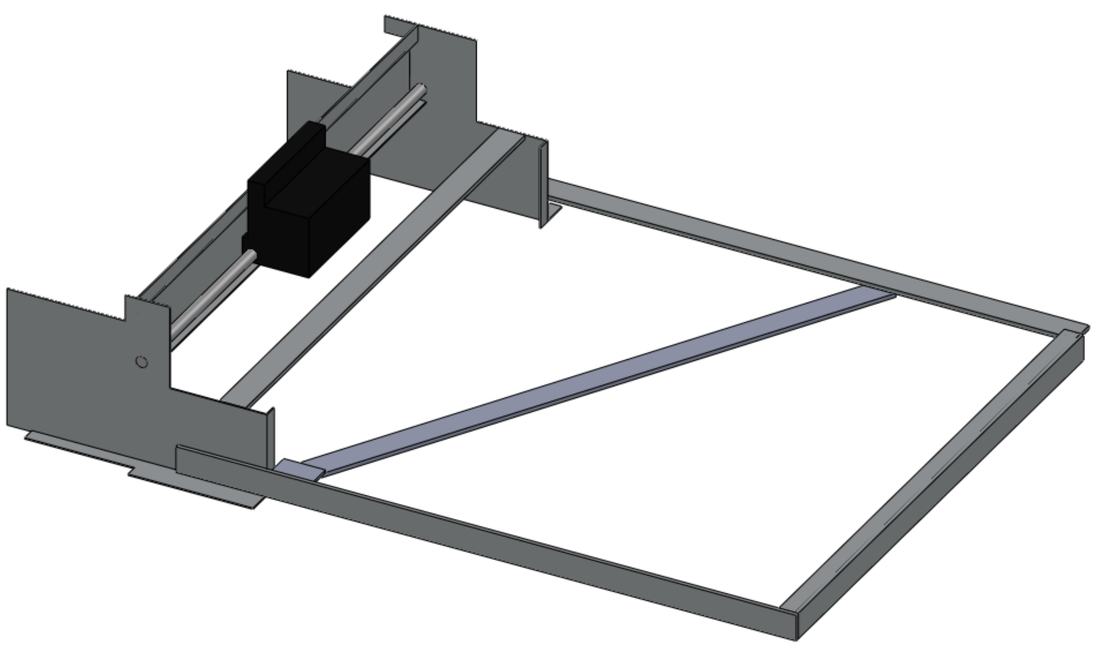

Figure 9: Completed Aluminum Frame

The paper feed drive system from the Canon S750 was removed and modified so that it could be attached to the new travel axis on the aluminum frame. This drive system is a belt driven system that uses a rotary position sensor as a guide for its movement down the printing substrate. Now the system that previously fed the paper through the printer and under the print head would now move the entire printer assembly down the length of the material on which to be printed. Below, Figure 10 is a 3D rendering of the frame with drive system of the left.

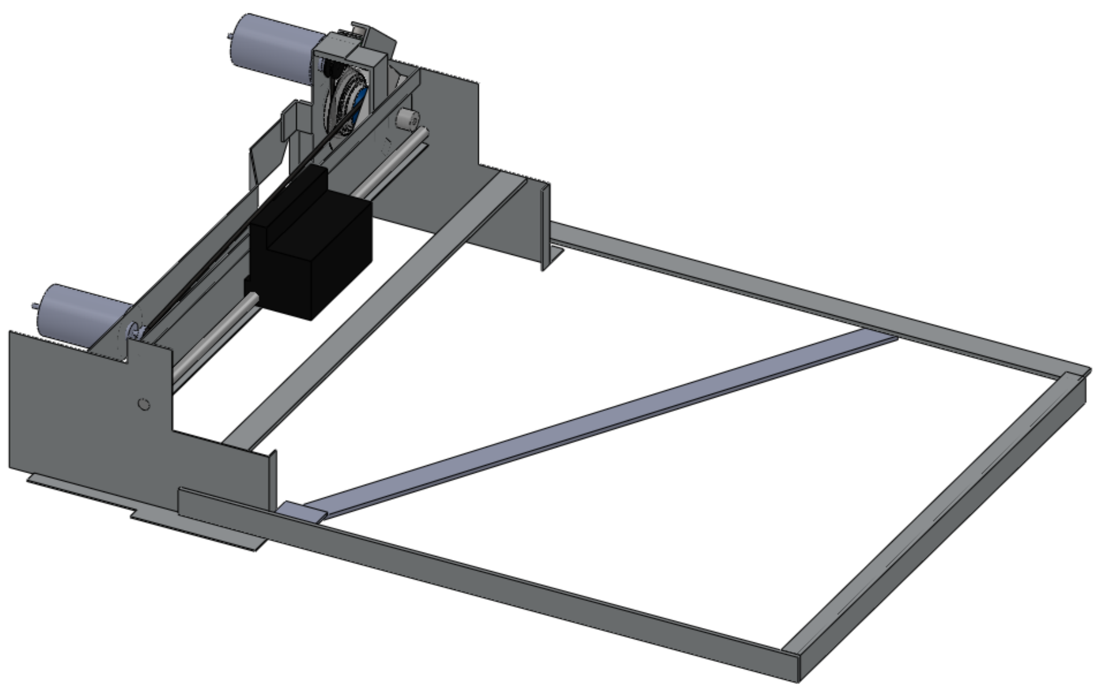

Figure 10: Aluminum Frame with S750 Drive System

Next, a reverse feed motor and drive system was added to the frame to automatically recall the main printer assembly back to the origin point after each print. The same type of motor is used to power this system as the forward feed system. This system is a belt drive system very similar to the forward drive system taken from the Canon S750. The parts needed to create this reverse feed were gathered from various similar inkjet printers that were obtained just for building components. With the addition of the reverse feed system, a clutch needed to be added between the forward and reverse systems to ensure that they could operate independently of each other while still driving the main printer assembly at the correct time. For this purpose, a slipper clutch from an HPI RS4 model radio controlled car was adapted to work with the printer feed drive systems. Below, Figure 11 is a rendering of the forward and reverse drive systems with the integrated HPI RS4 clutch.

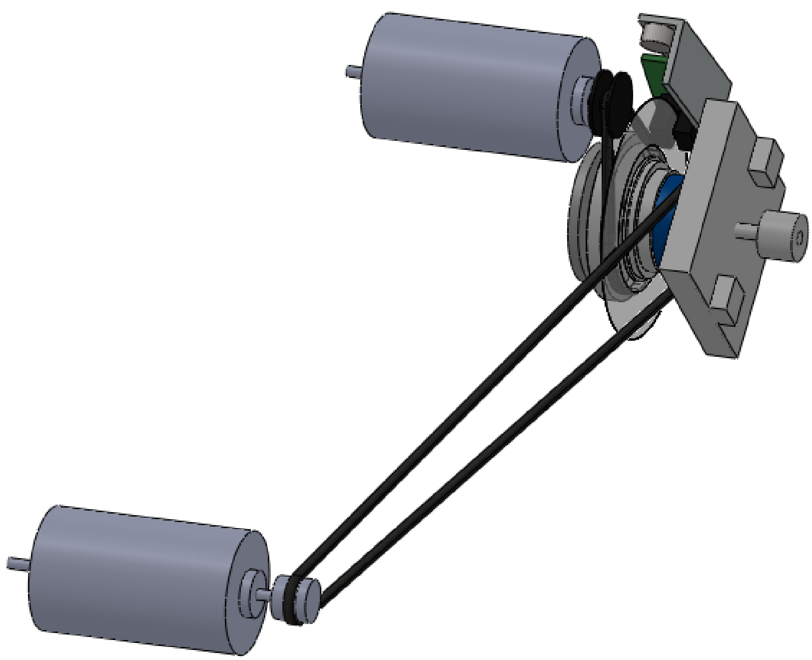

Figure 11: Forward and Reverse Drive Systems

For the reverse feed system, a simple custom circuit was made and powered from an existing power source from the printer power supply. The system includes a simple switch with endpoint stops which turn the system on when the printer reaches the end of its y-axis, and off when it reaches its origin point. Below in Figure 12 a diagram of the circuit constructed for the reverse feed system.

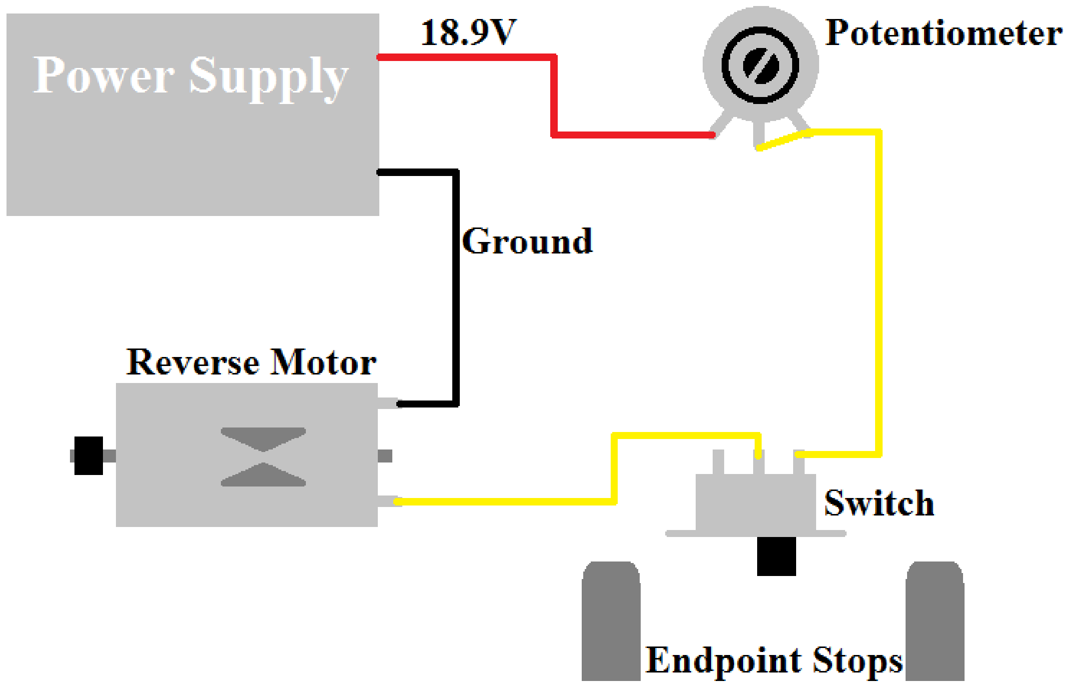

Figure 12: Reverse Drive Motor Circuit

Another endpoint stop was added to the rear of the frame to trigger the paper feed sensor on the main circuitry. A mechanical approach was chosen to trigger this sensor instead of an electrical option in the interest of time. This sensor used to detect when a piece of paper was traveling through the printer in order to detect a paper jam; this sensor now must be triggered after each individual print pass, and therefore is now used to detect if the y-axis feed gets jammed. If this sensor is not triggered correctly, all printer functions are paused until the error is resolved. Below, Figure 13 is a rendering of the frame with the reverse feed system and the sensor endpoint stop.

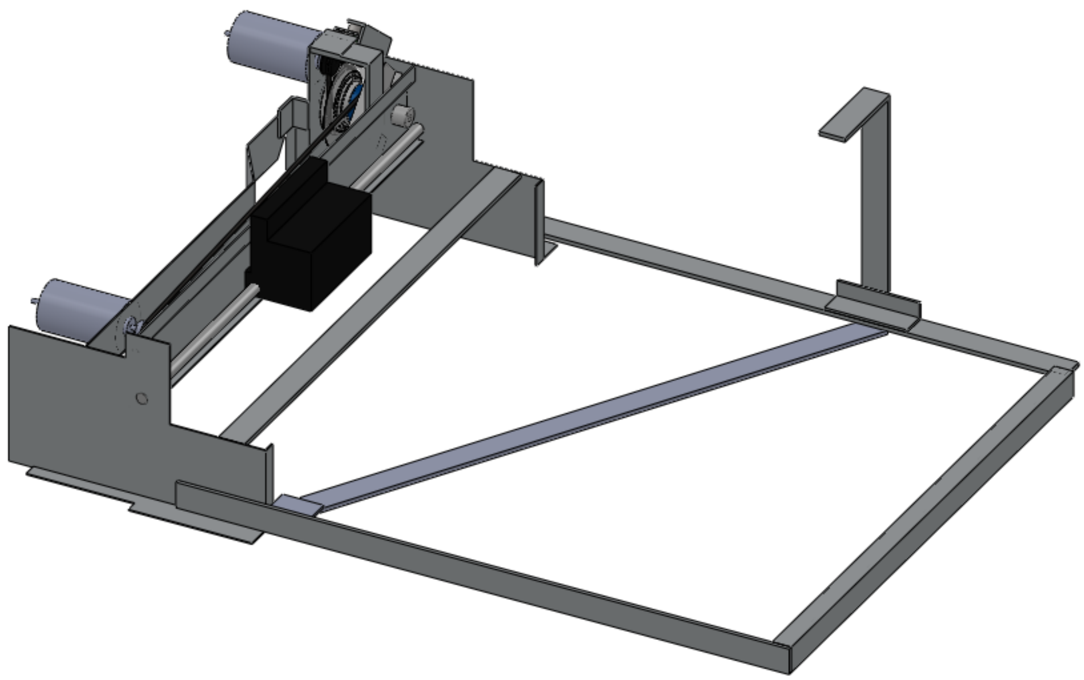

Figure 13: Aluminum Frame with Drive Systems and Sensor Endpoint Stop

One end of the main printer assembly is attached to and supported by the y-axis feed system and moves along the y-axis feed rod on brass bushings. The other end is supported by a bearing system built by the team that rides along a track on the edge of the frame on the right side as seen in the renderings. This bearing system originally only contained two bearings; however two more were added later in the construction process for more support. This bearing system provides a very low friction option for the main printer assembly to travel on and provides stable support in both the vertical and horizontal directions. The bearing system consists of an aluminum sub frame which holds four 4mmx11mmx3mm ball bearings. One bearing rides above the track, another rides below it, and the other two ride along the inside of the track, one being at the front and one at the rear of the bearing system sub frame. This is similar in construction to a rollercoaster car and track and is where the inspiration for the design came from. Below in Figure 14 is a rendering of the bearing system.

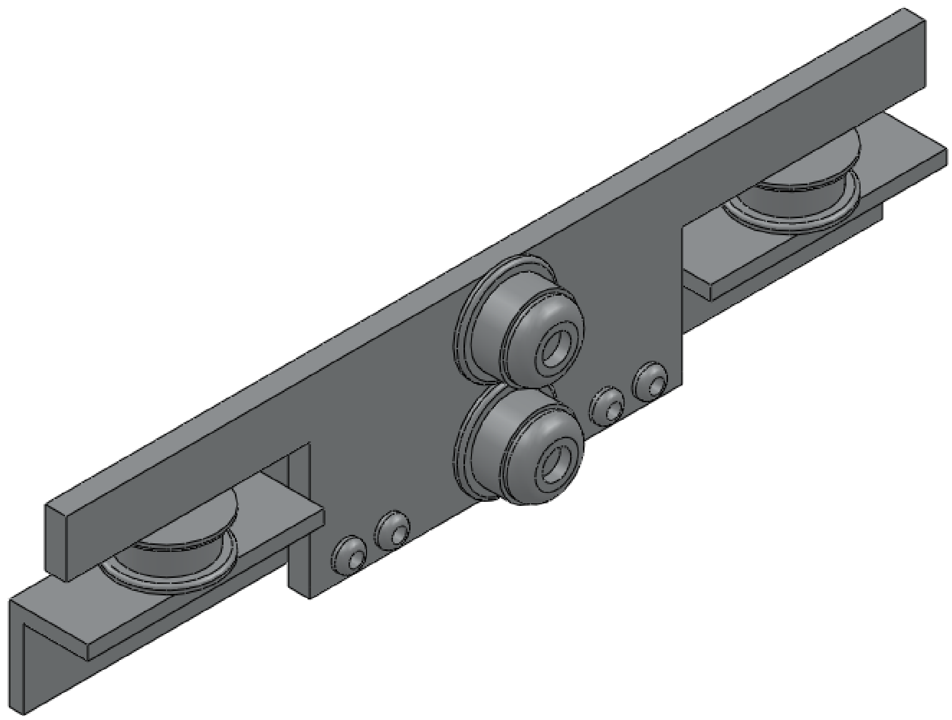

Figure 14: Printer Bearing System

The last steps in the construction of the printer included building the substrate table, mounting the power supply, final wiring, and the addition of cooling and drying fans. The substrate table was built with piece of 20 gauge steel stock that was shaped to form the table frame, and a rectangular section of $\frac{1}{8}$" thick polycarbonate that was attached with epoxy to the frame to create the substrate mounting surface. The power supply was attached upright to the right side of the aluminum frame which allowed the power supply wires to be routed to the main printer assembly from above and travel with the movement of the print head. Below in Figure 15, a rendering of the substrate table is shown with a partial felt covering used as a printing failsafe to absorb polymer solution in case of a malfunction with the print head.

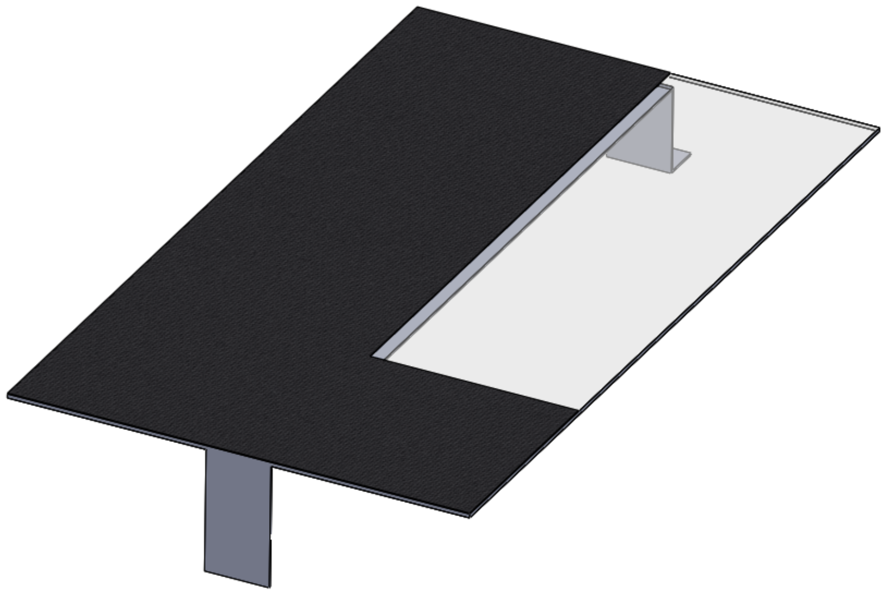

Figure 15: Polycarbonate Substrate Table

After initial testing with the completed printer, it became evident that a cooling fan would have to be added to cool the y-axis feed motors. The additional work required to move the main printer assembly as opposed to a piece of paper, resulted in excess heat emitted from the feed motors which would have to be removed to prevent the motors from overheating. A standard computer cooling fan designed for use in laptop computers was chosen for its efficiency and cost. This fan is powered from a simple circuit separate from the rest of the printer by a 12V power source, so that the fan could be controlled independently of all other printer functions. Later while actively testing with a polymer solution developed for the project, it was decided that a low speed drying fan that hovered over the print substrate would aid in solidifying the printed polymer more quickly. A larger computer fan designed for desktop computers was chosen because of its large surface area and integrated speed controller. This fan is also powered by the same separate circuit and 12V power source. This drying fan allows for quicker printing times and better quality results. Below in Figure 16 and Figure 17 respectively, renderings of the feed motors cooling fan and the low speed polymer drying fan are shown.

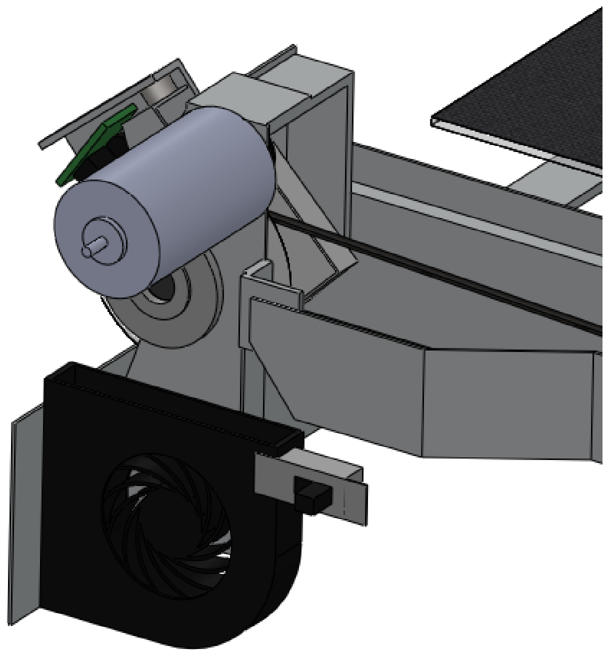

Figure 16: Feed Motors Cooling Fan

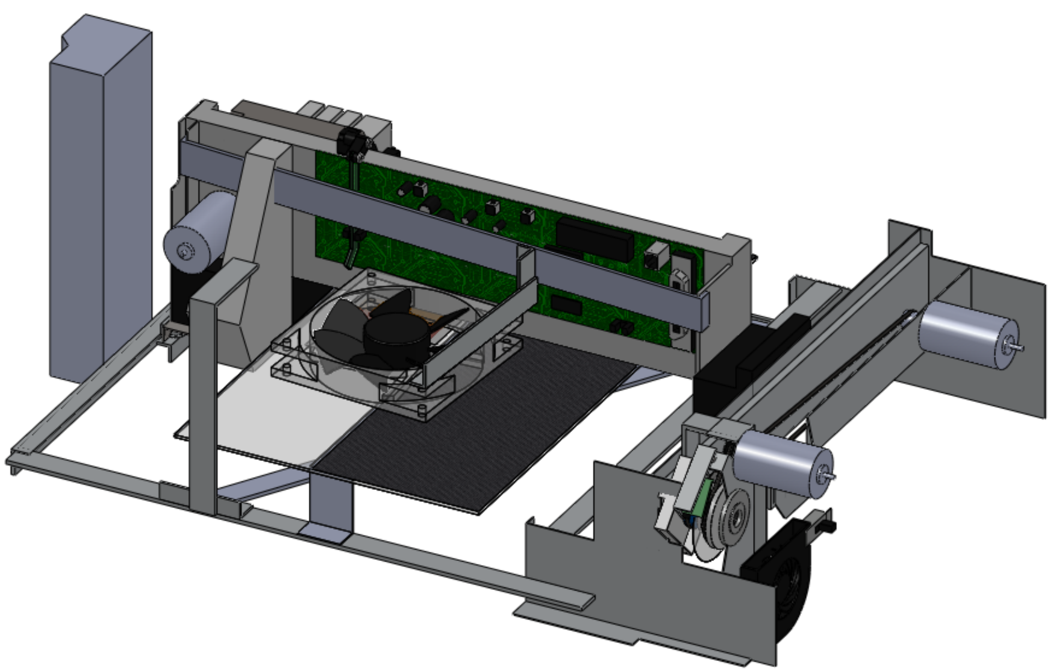

Figure 17: Reverse View of Completed Printer Displaying Drying Fan

4.2 Multilayer Printer Overview

The frame of the design is comprised mainly of aluminum stock, but also consists of some steel parts that came from the original Canon S750 printer and small amounts of steel stock. It is designed to allow a conventional inkjet printer to be configured in a dual axis feed formation, meaning the printer can move over a stationary medium while printing instead of moving the medium itself. On one side, the frame holds the track and motor for the feeding mechanism which feeds the print head over the medium during the printing process. Also on this side, a separate motor is mounted that when activated sends the printer back to its beginning location. The opposite side of the frame provides support and a bearing track for that side of the print head to roll on during the printing process, and on the outer edge of the track the power supply is mounted. Along the rear of the frame a device is mounted that closes the paper feed sensor, which we now utilize as the y-axis sensor which allows for the printer to be fully automated. The print head itself is largely unmodified, other than changes that needed to be made allowing it to be mounted in the dual axis feed configuration. An aluminum stabilizing brace was added to strengthen the printer to reduce unwanted movement of the print head which can cause distortions in the printing. Mounted in the middle of the frame, under the print head, is a polycarbonate table that holds the medium at the desired height during printing. Two fans were added to the printer last, one to cool the feed motors and another to aid in polymer solution drying. See Figure 18 below for a picture of the completed assembly, which includes a felt cover on the polycarbonate table used during testing.

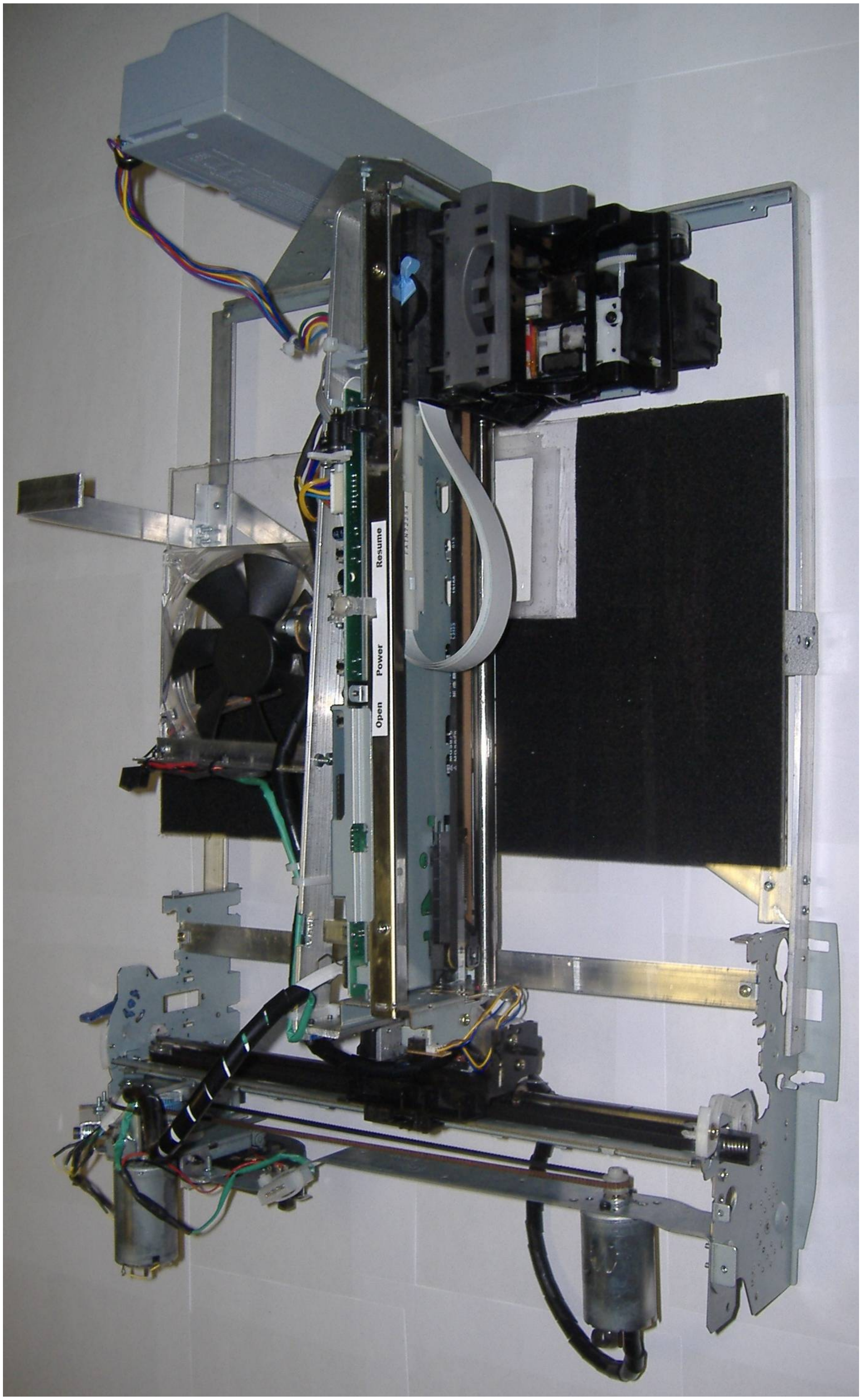

Figure 18: Completed Printer Assembly

4.3 Design Issues

During the design process of the printer, many issues have come up. The first major issue was to figure how out to drive the printer deck so that the print medium could be stationary. Originally, printers have a drive motor that feed the paper through as ink is deposited on the sheet. To overcome this issue, the team modified the existing set up to turn the printer into a dual-axis device. The modifications used the existing drive motor to move the printing deck back and forth just as it did with the paper in the commercial design.

Once the printer was capable of moving down the length of the printing region, another issue was encountered. While making a few initial test runs, the text was observed to move out of line at the end of the rows, but remain level in the middle sections. These variations were concluded to be from the lack of stability in the printer deck. An aluminum brace was attached to both ends to eliminate some of the back and forth motion (See Figure 19 below). Still, that was not enough, and the design team decided to add two additional bearings to the y-axis bearing system oriented horizontally against the inside edge of the printer frame to prevent further front to back motions that interfere with the print quality. See Figure 20 below for before and after renderings of the bearing system.

Additional issues began to arise as the design team continued to make the printer more automated. There are two sensors onboard that determine paper feed direction and detect paper jams. For the paper jam sensor, trial and error showed that it had to be triggered at very precise times, otherwise the printer would error. The sensor uses light to determine whether the paper is feeding through or not. The light is emitted from one side, passes through a small gap where the “switch” is positioned, and is converted back to an electrical signal on the other side of the sensor if nothing is blocking it. The final solution to this issue used a plastic arm to block the sensor; and attached to a remaining paper feed component, a small plastic tab that moved the arm out of the way at the proper time. At the end of the print run, the sensor had to be blocked off again, so an aluminum arm was mounted to the rear of the printer to reset the sensor to avoid any errors.

When trying to feed the printer deck back to the original position, several issues came into play. The first attempt was to switch the polarities of the drive motor at the end of the run, and feed the deck all the way back to the start. However, the paper feed direction sensor caused an error almost immediately. It became clear that a second drive motor would be needed, as the first had to be completely powered off prior to feeding the deck back in the other direction. A second motor was mounted, but there was a short time where both were running, and they were fighting one another which resulted in additional errors. A slipper clutch was put into place, which allowed the initial drive motor to slip once the other motor was switched on, thus stopping any additional errors.

The final major design issue the team encountered was one that was long overlooked. Paper in the original printer was fed back to front; therefore the printer deck was designed to move in the same direction. However, this was a mistake because this meant that the paper was now being printed over front to back, opposite of the printer’s intended design. The design team noticed this while printing a circle, and seeing that the curves were being positioned backwards, curving up away from the center of the circle, rather than down towards the center. This particular issue was very discouraging, as it seemed likely that a complete redesign stage for the printer would be required. However upon investigation it was found that a permanent polarity reversal of the power sent to the two feed motors as well as a simple backwards positioning of the drive sensor allowed the printer to print in the correct direction without flaw.

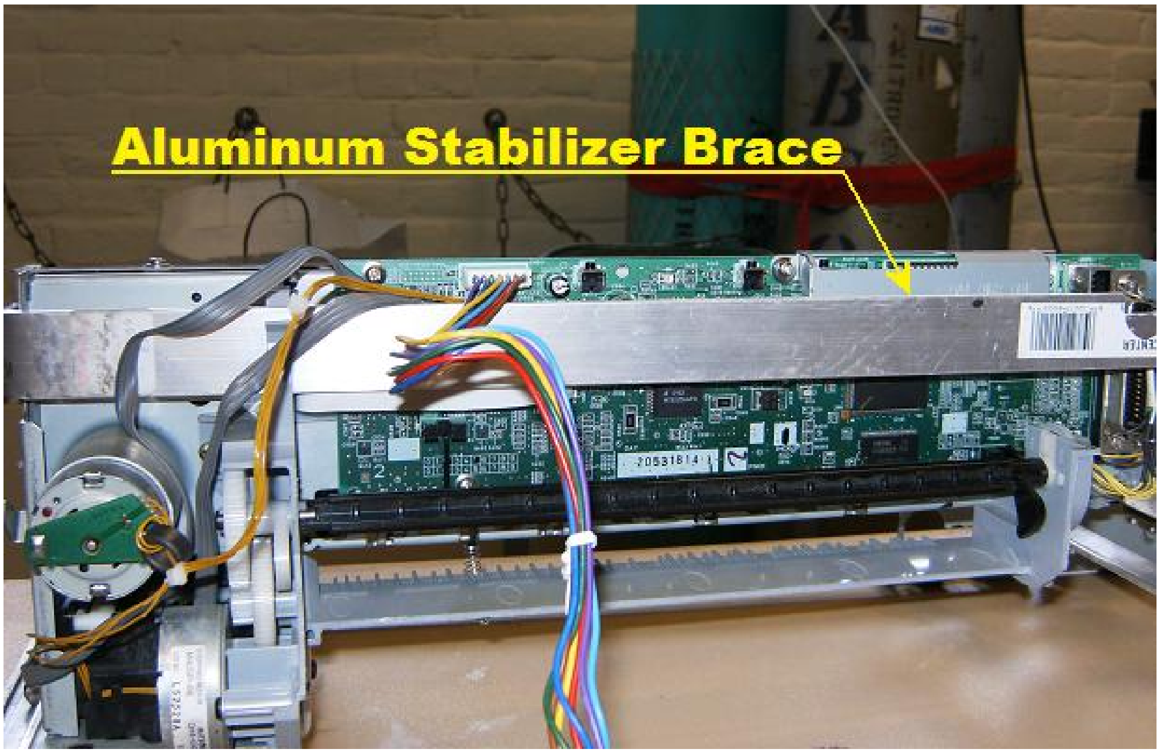

Figure 19: Aluminum Stabilizer Brace

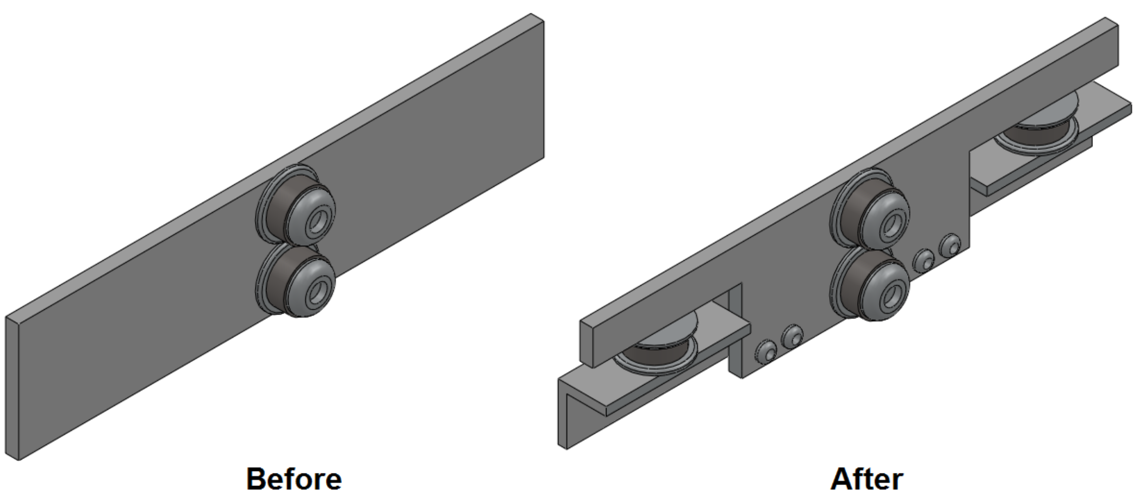

Figure 20: Y-axis Bearing System Redesign

4.4 Polymer Background

The polymer chosen by the team for the ink solution was polyvinylpyrrolidone, or PVP for short. This particular polymer possesses a couple of properties that make it well suited for the applications this project was intended for. It is very soluble in water, making preparation of the polymer solutions much easier, as PVP will break down fairly quickly in water, and no sediment remains. PVP also forms films easily, which is useful in printing because it spreads evenly on the printing surface. These two properties made PVP a very good choice for the project, as it can print smoothly, and solutions can be prepared quickly, cutting down on the amount of time spent developing the inks.

In the polymer printing MQP last year, they too used PVP, and by using the same polymer in this project, it gave the team a good idea where to start with the polymer solution ratios between the three components: PVP, isopropyl alcohol, and distilled water. The solution offered in their report had the following constituents: Water (83% by weight), PVP (13% by weight), and Isopropyl alcohol (4% by weight). The current MQP team used the same water to alcohol ratio (~20.75 to 1) as a base solution for all polymer test solutions. Varying amounts of PVP were added to this base, systematically increased to narrow in on the solution that provided the best print quality for the Canon S750.

Polyvinylpyrrolidone is already used in many printer ink solutions. It can also be used to coat printing substrates in a thin polymer film, allowing for strong bonding between the ink and the sheet. This stronger bonding is made possible by the polarity of PVP itself. Being a polar molecule, it will bond extremely well with other polar substances, so any polar substrate will greatly improve the bond strength of the printout.

PVP is also heavily used in medical applications. When ingested, PVP passes through the body without any absorption into the system, while still allowing the medication to be absorbed in the digestive tract. These PVP molecules are heavily used as binding agents in the pharmaceutical industry as they can pass freely through the system. By using the PVP as binders, the solubility of the medication can be improved. One reason for this increase in solubility is the fact that the medication in pill form without a binder is a single chunk of the compound. This compound is fairly insoluble, and very little of the medication is actually exposed for absorption into the body. By using a polar binding agent, these particle sizes can be greatly reduced. Once the PVP breaks away, these small particles have much more area exposed to the intestinal walls, and the amount of medication available for absorption is increased significantly.

4.5 Polymer Solution Testing

The creation of each polymer solution that is to be tested requires several steps to prepare it for a test print run. The current constituents of the polymer solutions are: 58,000 M.W. polyvinylpyrrolidone (PVP), distilled water, 91% isopropyl alcohol, and red food coloring. To begin the process of testing and determining which solution is best, the original ink was tested in a rheometer to determine the viscosity currently present in the printer. This value fluctuates depending on the testing conditions, i.e. temperature, age of ink cartridge, time of exposure to air, etc. but is usually within the 4-5 mPa-s range. After this base was established, the solution creation process began.

Every polymer solution starts off as a base mixture of 94.5% distilled water and 5.5% isopropyl alcohol (91% purity). These values were estimated from last year's project, in which a 20.75 to 1 mass ratio of water to isopropyl alcohol was used. Factoring in the densities of each substance, this becomes a 16.5 to 1 volume ratio. Based on a volume of 20mL, that equates to 18.9mL distilled water and 1.1mL isopropyl alcohol. The quantity is measured using a small graduated cylinder with a resolution of 0.1mL, and added to a 50mL beaker for mixing.

The PVP powder is weighed out using a micro spatula and an electronic scale, to the nearest 0.001g. The water-alcohol base from the previous step is placed on a hotplate, and allowed to heat up past 50º C, at which point the measured PVP is added and allowed to mix in until fully dissolved. Finally, 2 drops of food coloring is added to ensure that the solution is visible when printed on paper. After the solution has cooled to room temperature, viscosity measurements are taken, and the remainder of the solution is emptied into a clean ink cartridge for testing. Even if the viscosity measurement is outside of the anticipated range from the original ink, the solution is usually tested fully, as other properties can affect the printer's ability to print the polymer solution. Depending on the results of the print test, the concentration of PVP in the solution can be adjusted for the following print runs. Figure 21 shows the rheometer used to measure the viscosity of the polymer solutions.

Figure 21 - Brookfield DV-III Rheometer Used in Viscosity Testing

To gather viscosity readings, the Brookfield DV-III Rheometer was used. In order to achieve the most accurate readings possible, the same preliminary steps must be taken prior to using the device. Beyond simply turning on the machine, it must first be calibrated, to get the spindle to the same starting position before each reading. After the rheometer is corrected calibrated, the solution is prepared. Using a micropipette, 0.5 mL of the polymer solution was placed in the spindle. A thirty second timed average of ten readings was then conducted at 150 RPM.

The process of finding the ideal mixture started off using a 0.25g PVP solution. From there, small increments would continue to be added until the printing test failed. After the solution had been prepared, its viscosity was measured in the rheometer, and a test print was conducted. The polymer content was increased by 0.25g for each successive solution, and the steps from above were repeated. Several solutions later, the maximum polymer content was established at 1.75g, as the test print resulted in no visible solution on the paper. At that point, the measured viscosity had increased from <1.2 mPa-s in the water-alcohol base, to over 8.3 mPa-s in the 2.60g PVP solution from the previous MQP's polymer solution. Figure 22 shows the recorded viscosity measurements of the tested polymer solutions as well as Canon's ink.

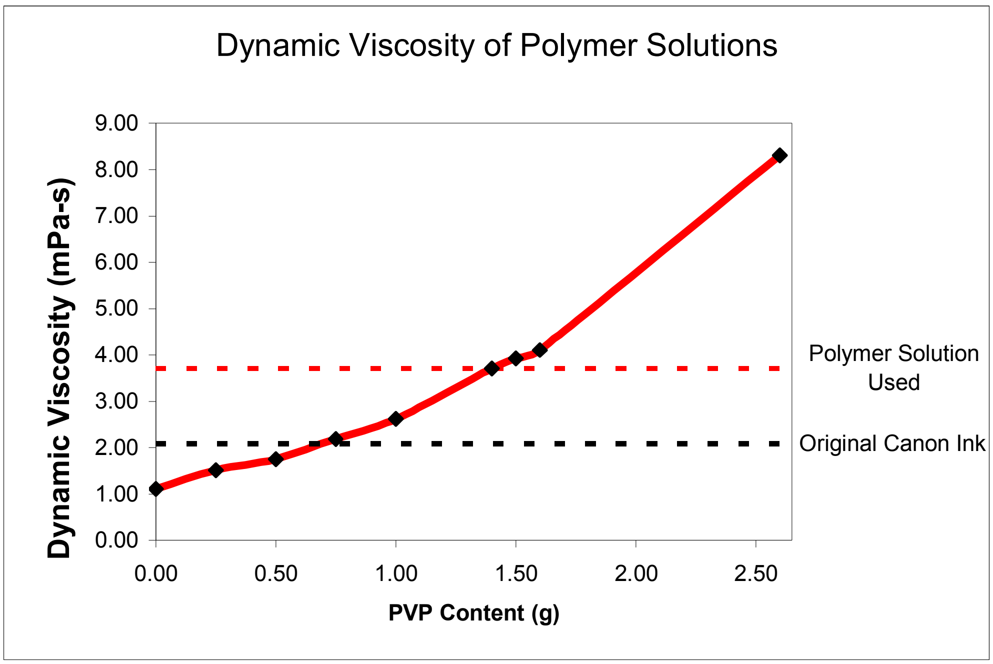

Figure 22 - Viscosity of Polymer Solutions

Of the solutions tested, 1.25g and 1.50g had performed the best, with 1.50g being a clearer, streak-free test print. However, at that 1.50g level, the print out was very faint, and this solution was used as the new maximum polymer content. To zero in on the best solution in this range, 0.05g steps were made, starting at 1.50g and working down. At 1.45g, the resulting test print was thicker and nearly streak-free, but not as much color was showing up as what was seen with the 1.25g solution. That led to another 0.05g decrease down to 1.40g. At this level, streaks were still very infrequent, and the color had become brighter, closer to that of the 1.25g solution. Finally, once the content had been decreased to 1.35g, streaks began to occur regularly, leaving 1.40g as the preferred polymer solution, representing a 6.61% PVP by weight solution and having a dynamic viscosity of 3.71 mPa-s.

While the original intent was to match up the viscosity of the polymer solution to that of the original Canon ink, that proved inadequate. Instead, the solution was tested to find which worked best as a printable solution. Other factors such as surface tension within the solution made it impractical to try and match up all of the properties of the ink with those of the tested polymer solutions.

4.6 Substrate Development

A substrate needs to be developed that will allow printing of a thin polymer film. A satisfactory substrate will be thin, light, and resist deformation when printed onto. Ordinary paper will not be appropriate as it is too porous, causing the polymer to soak into the paper to such an extent that the paper becomes significantly wrinkled, rendering the finished product useless. Materials must be developed that are semi-porous or non porous and strong enough to resist wrinkling.

In the interest of time, the proposed method was to use multiple types of paper with varying absorption properties, and varying types of aluminum foil as bases. These bases would be coated in various materials to form both a semi-porous substrate, and a non porous substrate. The types of paper include: normal copy paper, semi-gloss photo paper (also testing matte back side), and cardstock. The types of coating materials selected include: Polyvinyl Alcohol (PVA), PVP, oil, and starch. Each type of paper would be immersed in an aqueous solution of PVA and then PVP, and sprayed with spray type oil and starch and allowed to dry. Varying types of aluminum foil were used as the non porous substrate. These types include: normal, heavy duty, and non-stick. No added materials will be applied to the aluminum foil. A sample of the normal aluminum foil will also be coated in PVA.

In order to soak the various types of paper in the PVA and PVP, aqueous solutions of both polymers were made. These solutions were 5% by weight solution of PVA and PVP in water as a first test, with the possibility of adding more or less depending on test results. Heating the water was required to allow the polymers to dissolve into the water. Once completed each of the three types of paper were placed in the polymer solutions until completely saturated with the solution. The papers were then removed and allowed to fully dry.

For the oil, a spray type was chosen because it would allow for easy application to all types of paper. The oil used was canola oil, and was simply sprayed onto each type of paper on both sides. Due to the erratic behavior of the spraying, the oil was smoothed out until an even amount was covering the paper. The oil soaked into the various types of paper and made the papers slightly stiffer, with the most drastic changes occurring with the copying paper.

Similar to the oil, the easiest way to apply starch to the papers was to use a spray type starch. Each of the three papers was sprayed with the starch, which caused them all to start wrinkle upon contact. The card stock was effect the most by the starch, causing heavy wrinkling. All of the papers had to be flattened as much as possible before any testing could be done.

The aluminum foil substrates were very weak and were extremely susceptible to wrinkling which would not allow for high quality prints. To solve this problem, the samples were laid on top of a piece of photo paper and attached via double sided tape. This gave the aluminum foil structure, and the paper held the foil smooth meaning testing could be completed.

4.7 Substrate Testing

All of the produced substrates were tested by printing ten layers of the polymer solution of the WPI logo. The first substrate to be tested was the copy paper with PVA. Even after efforts to make this paper as flat as possible, it remained mildly wrinkled. During printing this paper began to wrinkle even more, causing the ink head to contact the paper, smudging the print.

Next the photo paper with PVA was tested. Similarly to the copy paper with PVA this paper wrinkled during the drying process, and was very difficult to flatten out. Once again, it wrinkled even more during printing, causing the same error of ink head contact, meaning this paper is also not useful. The same results occurred both on the semi-gloss side and matte back side of the paper

Card stock immersed in PVA was tested next. It wrinkled less than the copy paper and photo paper during the drying process, making it a better candidate. However, during printing it still wrinkled, although less so than the other types of paper. This small amount of wrinkling still lead to contact with the print head, meaning it would not be a suitable substrate for printing.

The aluminum foil with PVA solution was not a suitable substrate because during the drying process the PVA formed large beads on the surface of the aluminum foil. An uneven surface like this will not provide a good surface for printing, so this substrate was not tested.

After spraying the copy paper with starch it became very wrinkled, and was very difficult to flatten completely. When the printing process began this sample began to wrinkle even more severely, causing the ink head to once again contact the paper in some locations.

The photo paper sprayed with starch exhibited similar problems as the copy paper sprayed with starch did. This meant that on both the semi-gloss and matte sides of the photo paper, excessive amounts of wrinkling occurred. This type of paper will also not be useful for this application.

When the card stock was sprayed with starch, it curled severely. However, it was able to be flattened enough for testing. After testing, the added starch seemed to have little to no affect on the properties of the card stock. It acted similar to card stock with no additive, making it not useful for this application.

The copy paper sprayed with canola oil was a promising substrate during its development due to the effects the oil had on the paper. The oil made the paper exceptionally smooth, and slightly stiffer than original. This meant that the paper would lay extremely flat on the printing table. During printing, the WPI logo came out very clearly and the polymer solution was absorbed by the paper, and did not form any beads on the surface. However, the paper only wrinkled very slightly, much less than the other forms of the copy paper. After ten layers the produced paper with the WPI logo was of acceptable quality. Further testing is required for this substrate if no others are found to work even better.

The card stock sprayed with canola oil acted nearly the same as the copy paper sprayed with copy paper. It will also require further testing if no better substrates are found.

All types of aluminum foil are nonporous substrates, and acted as such. The printed polymer solution simply beaded up on the surface. They provided a result that could be useful when the printed polymer solution is dried, and then printed on once again. The initial ten printed layers yielded a clear WPI logo, however it consisted of many very small beads of the solution. When dried the tiny beads simply wiped off of the foil. This substrate requires further testing, but does show promise to produce an acceptable result.

The copy paper immersed in an aqueous PVP solution acted similarly to that of the PVA immersed paper, however it wrinkled slightly less. Also, the PVP immersed photo paper and card stock acted similar to the manner they did when soaked in PVA, except slightly less wrinkling. The card stock immersed in PVP was nearly completely smooth and appeared to have a layer of PVP on the surface. All of these types of substrates worked better than anything tested before them, with the card stock acting the best. During printing it exhibited nearly zero wrinkling, and little if any polymer solution appeared to soak into the substrate. This substrate was selected for further testing with significantly more layers.

4.8 Materials

Multilayer Printer Materials:

- Canon S750 Color Bubble Jet (Inkjet) Printer. This printer was selected because its thermal bubble printing technology allowed for the most flexibility when modifying the ink. Also, it utilizes 4 different ink cartridges for differing colors, allowing the highest potential for future applications as 4 different ink solutions could be loaded into the printer at once.
- Aluminum Metal Stock ($\frac{1}{2}$"× $\frac{1}{8}$", $\frac{3}{4}$"× $\frac{1}{8}$", 1" × $\frac{1}{8}$"). This aluminum was used to form the frame of the printer.
- Polycarbonate Sheet ($\frac{1}{8}$"Thick). The polycarbonate sheet forms the table that holds the substrate to be printed on.
- Steel Metal Stock. The sheet metal was used in some areas were metal is needed that is larger than the thin pieces of aluminum stock. For example, the mount for the printing table, and the mount for the power supply.
- Various Common Printer Components (Belts, Gears, Tracks). These extra components were used were required, most significantly when constructing the printer return mechanism and the track the printer slides on.
- Ball Bearings (4×11×3mm). These bearings were mounted onto the printer, so that it could roll on its track with very little friction, helping to ensure high quality prints and smooth operation.
- Various Fasteners
- 3W Rheostat. This was used to allow the team to be able to regulate the power going to the return mechanism. This needed to be adjustable as the power was

taken directly from the printer power supply, which is more than required for the operation.

- 18V Motor. This motor powers the return mechanism.
- Two Position Electrical Switch. This switch was mounted onto the printer, and allows power to be sent to the return mechanism when the printer reaches the end of the track. It completes this by physically hitting a bumper at the end of the track that flips the switch on, when the printer is fully returned it hits another bumper flipping the switch off.
- HPI Slipper Clutch. The drive motors for the printer feed mechanism and return mechanism are both turning opposing each other at the end of each print cycle for a brief moment. This causes the printer to sense an error. A slipper clutch was installed to allow both motors to spin against each other freely, eliminating the error.
- 12 x 21 x 5 mm Flanged Ball Bearing. This bearing was used so support the drive mechanism for the printer feed. It allowed for greatly reduced friction meaning much smoother and more reliable action of the printer.
- 4" Computer Fan. This fan was installed onto the printer, moving over the print during the printing process in order to speed up the drying process allowing for quicker printing capabilities.
- 2" Computer Fan. This fan was installed below the motor for the printer feeding mechanism to help cool the motor, allowing for longer durations of continuous printing.

Polymer Solution Materials (Anticipated):

- Water.
- Isopropyl Alcohol.
- PVP (Polyvinylpyrrolidone) 58,000 g/mol
- Coloring dye

Medium Materials:

- Inkjet Paper (20lb.)
- Inkjet Semi Gloss Photo Paper
- Card Stock
- Aluminum Foil (Standard, Non-Stick, Heavy Duty)
- Polyvinyl Alcohol
- PVP
- Starch
- Canola Oil
- Wax Paper

5.0 Results

5.1 Polymer Film

Once the PVP immersed card stock was found to be a suitable substrate for printing, the ability of the printer to produce a polymer film could be tested. In order to do this, 250 layers of the polymer solution were printed onto the substrate. In order to determine the built up thickness, 5 different color inks were made. Starting with red, 50 layers of each color were printed, with each successive layer printed onto a smaller area. This meant that the increasing thickness would easily be able to be measured, allowing an understanding of how quickly and uniformly the polymer film grew in thickness. Figure 23 shows the printed polymer film.

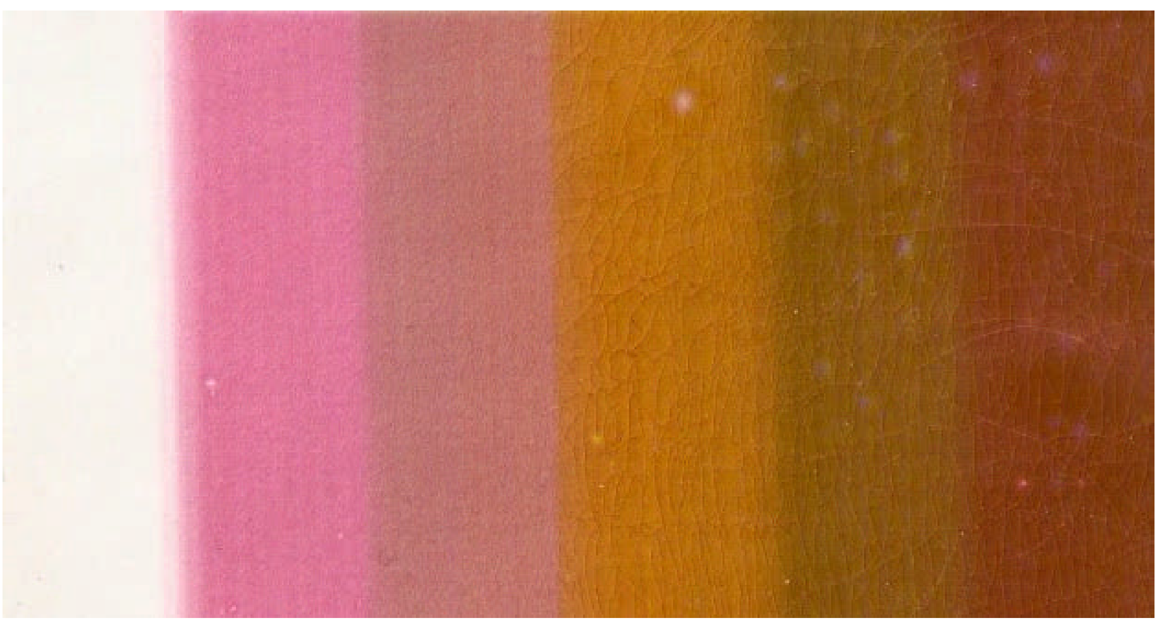

Figure 23: Printing Polymer Film with Increasing Thickness

The white area on the left has no layers of the polymer solution on it, and the pink layer to the right represents 50 more layers. Each color represents 50 more layers meaning a total of 250 layers were printed at the brown layer. The pink layer has a polymer thickness of 63 µm and the following layers have a polymer thickness of 114 µm, 165 µm, 216 µm, and 228 µm respectively. 63 µm of polymer were deposited in the first 50 prints, meaning that minimal amounts of polymer were soaking into the substrate. The increasing pattern of thickness shows that the polymer film increased in thickness relatively linearly, until the fifth layer. There could be many reasons for this, as the polymer solution's properties varied greatly with only minor changes in conditions. The results are summarized in Figure 24.

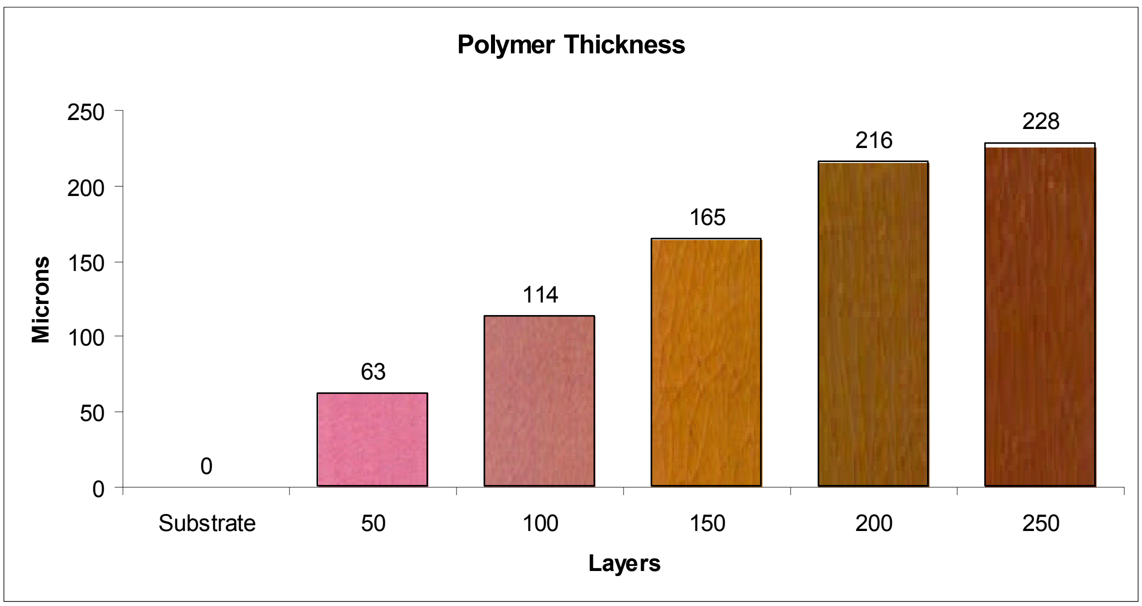

Figure 24: Polymer Film Thickness with Increasing Printed Layers

More testing is required to determine if the polymer film will continue to gain thickness with more layers. However, 228 µm thickness of polymer represents a useful thickness for various applications.

The Figure 25 below shows a highly magnified view of the printed polymer surface with a corresponding length scale in the lower right. From this image you can see the cracks that have formed in the surface of the polymer upon drying. These cracks as seen in comparison to the length scale range from 5µm and 10µm in width. This is about 1/10th the diameter of a human hair. Also seen are bubbles or voids in the solid polymer structure. For this printing process we did not have an accurate way of measuring the volume or amount of these voids in the structure, however from qualitative estimations it appears the porosity is about 0.4, or that about 40% of the structure is void space, meaning the remaining 60% is solidified polymer. Porosity affects the surface area of a structure in a directly proportional manner, and therefore alters its rate of dissolution. Changing this dissolution rate with changes to the porosity could aid in regulating the rate of drug delivery, if the polymer film were used in a medical application such as a medication pill or patch.

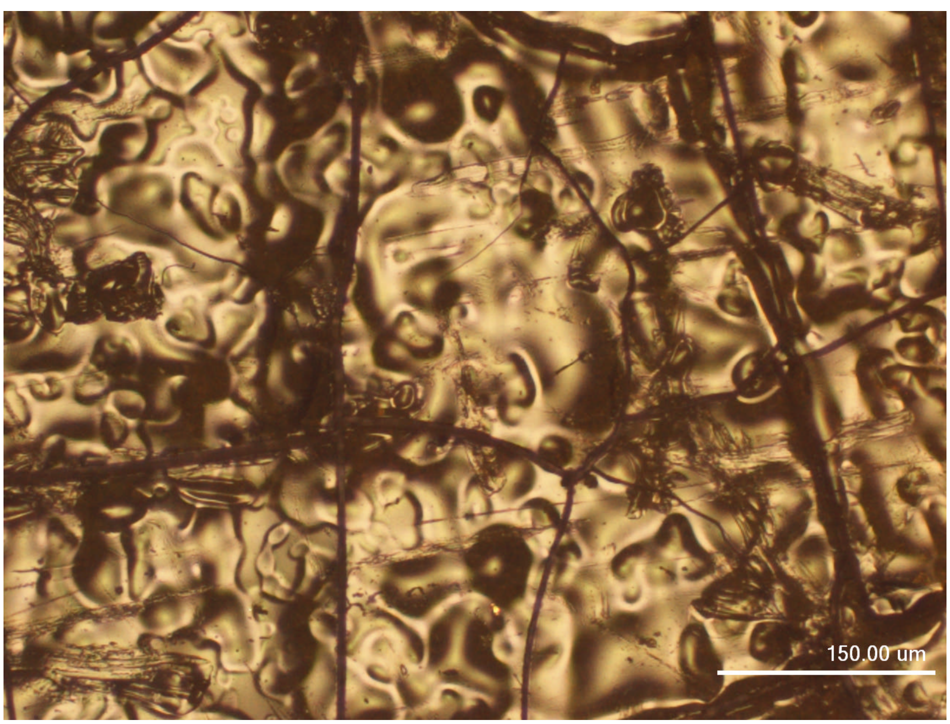

Figure 25: Magnified Image of Polymer Film

5.2 Distortion

In a typical unmodified inkjet printer, the printer arm is securely mounted on both ends. Thanks to this fixed placement of the printer arm, very little deviation in print quality occurs from one part of the print cycle to another. The design of the multilayer polymer inkjet printer, however, means the whole printer arm moves down the length of the substrate. This need for free movement leaves one end of the assembly able to swing back and forth during the print process. This additional movement leads to distortion in the printed materials, lowering the effective print quality of the modified device.

In order to measure this distortion, an ADXL276 MEMS accelerometer was attached to the base of the printer arm. Using LabVIEW, the data output from the accelerometer was recorded and plotted over 14-seconds of the printing process. During this process, the printer settings used were those that resulted in the maximum possible distortion values. The printer was set on lower quality, as well as eliminating quiet mode, causing more vibration than would be experienced under usable printing conditions. The results recorded by the LabVIEW software were only given as voltage values. By recording a 14-second calibration run with no printing, the baseline voltage reading for zero acceleration was found. From this value, the voltage deviations were determined, and from the accelerometer's sensitivity of 55mV/g, the acceleration values were calculated. Figure 26 shows the calculated acceleration values.

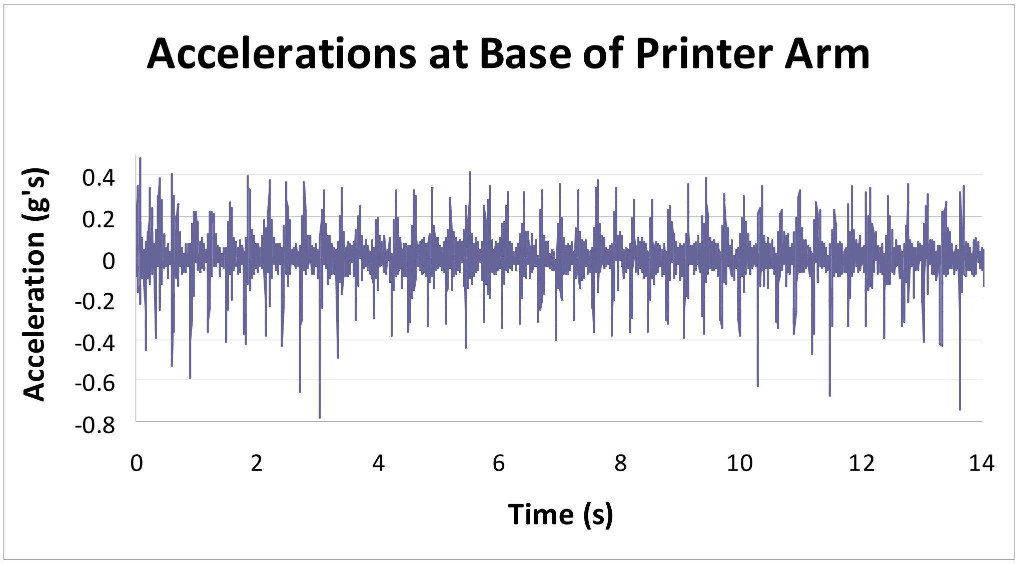

Figure 26: Acceleration Values for the Base of the Printer Arm

After recording the accelerations for the base, the previous procedure was repeated, with the same accelerometer mounted at the opposite end of the printer arm. The results are shown in Figure 27. From Figures 26 and 27 it becomes apparent that much more variance in acceleration is occurring at the free end of the printer arm than at the base.

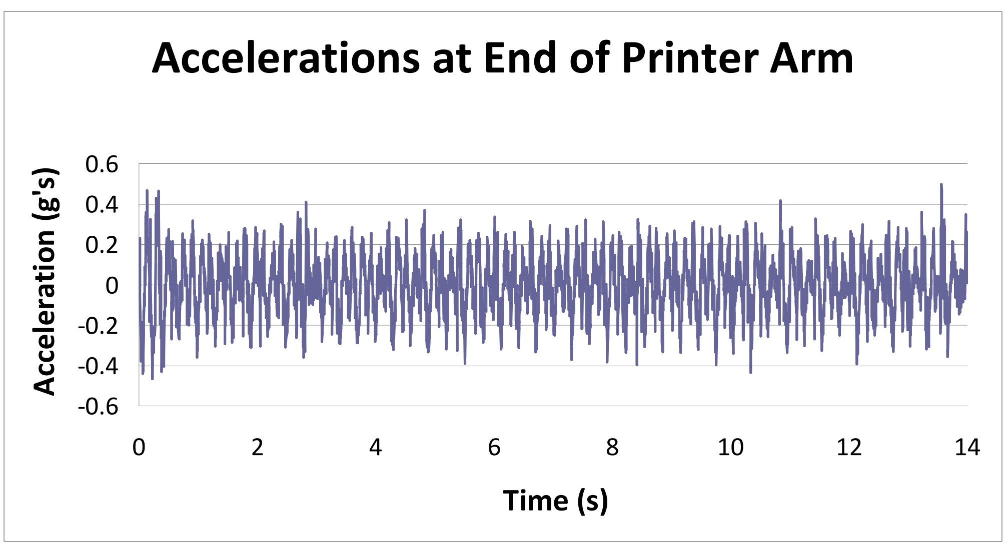

Figure 27 - Acceleration Values for the End of the Printer Arm

While the acceleration values are clearly much more erratic at the end of the printer arm, several additional steps are required to get useful distortion values. In order to convert to actual displacement values, the acceleration curve must first be integrated to find the velocity at each data point. While the curve doesn't follow a given equation, the integral can be estimated using the trapezoidal approximation method. Based on the time between readings and the velocities at the start and end of each time interval, the absolute velocity curve is again integrated, to determine the net displacement throughout the entire print cycle. The values for net displacement can be seen in Figure 28.

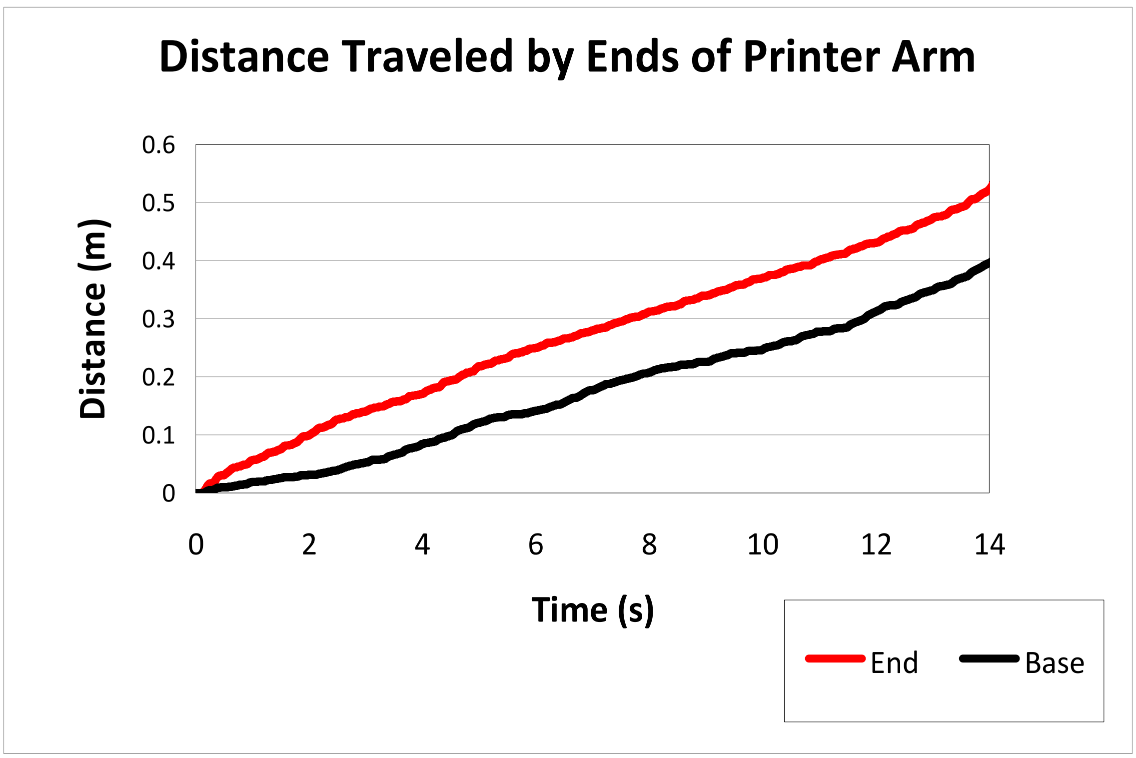

Figure 28 - Total Distance Traveled by the Two Ends of the Printer Arm

From the displacement graph, you can see that the back-and-forth vibrations at the two ends add up to a much greater displacement than the distance that was actually traveled. While the print cycle runs about 20 centimeters, the base of the printer arm moves 39.6 centimeters with all of the small oscillations taking place. Likewise, the end of the printer arm, which is only being guided by a few bearings, travels 52.3 centimeters. This difference of 12.7 centimeters is an increase of 32 percent from the base displacement to that of the end of the printer arm. While this value may be considerably higher than that actually experienced with the desired print settings, it certainly leaves room for future improvement.

6.0 Conclusion

A Canon S750 standard home and office inkjet printer was successfully modified to produce thin polymer films. This was completed by converting the printer into a dual axis design where the paper feed mechanism now feeds the printer itself over a stationary substrate. A separate motor was added to act as a return mechanism, returning the printer to starting location after each print cycle.

A polymer solution suitable for printing with the Canon S750 print head was developed. PVP polymer was used, as this polymer had desirable characteristics for this application including water solubility, ability to form films, is currently used in some inkjet printer inks, and is biocompatible. Its water solubility allows for water based solutions for printing to be made. Its ability to form films is desirable for this application, as that is the final goal. It is already used in some inkjet printing inks, ensuring that it is suitable for this application. The fact that it is biocompatible means the produced polymer film could be used for medical applications.

Initially when developing a polymer solution for printing, a small amount of PVP was added, and more was added incrementally until the most PVP was added while still being able to flow the print head. This resulted in an ink solution of 18.9 mL distilled water, 1.1 mL isopropyl alcohol, and 1.4 g PVP, resulting in a 6.61% PVP by weight solution with a dynamic viscosity of 3.71 mPa-s.

In order to develop a suitable substrate many different materials including standard paper, photo paper, card stock, various aluminum foils, wax paper were coated with various materials including starches, canola oil, PVA, and PVP and then tested. The testing resulting in card stock coated with PVP showing the best properties for printing as it wrinkled least, and did not allow significant soaking of the solution into the substrate.

A total of 250 layers were printed onto the substrate. After every 50 printed layers, the color of the ink was changed and the area printed reduced so the thickness could be measured with respect to the number of prints. The first 50 prints resulted in a thickness of 63 μm and the following layers have a polymer thickness of 114 μm, 165 μm, 216 μm, and 228 μm respectively.

The base of the printer arm slides on a track, and the end rolls on end of the frame. Ball bearings greatly reduce friction, however after each step during printing the printer arm end is free to shake, causing distortion. The accelerations of each end of the printer arm were measured using an ADXL276 accelerometer under worst case scenario high speed printing conditions. Based on the acceleration values, the total distances traveled at each end were calculated. The printer arm end traveled 32 percent more under these conditions.

Inkjet printing can be applied as a manufacturing process to produce functional materials including medical patches, organic LEP screens, solar cells, and even thin-film transistor circuits. Further testing needs to be completed to improve printing characteristics, but a dual axis multilayer polymer inkjet printer has been constructed capable of reliably printing thin polymer films of significant thickness for a variety of applications.

7.0 Future Recommendations

7.1 Substrate Development

The most important aspect of the project that needs to be improved is developing a new substrate. Even with the PVP immersed card stock, some polymer solution still partially soaked into the substrate. This means that it takes more layers to build up thickness of the polymer film. It also caused some, although minor, wrinkling of the substrate during printing which is not desirable.

The ideal substrate would be a non porous one that does not allow the ink to form beads on the surface. A good place to start would be forming a thin sheet of PVP itself. Some testing was done to create a substrate like this, but it was found that without a specifically controlled drying rate, the sheet would crack significantly during the drying process, resulting in a completely useless substrate. Future research could look into methods to produce a PVP or other polymer sheet that could allow for the PVP solution to adhere to it without beading on the surface.

7.2 Speeding the Printing Process

Currently, the process to print a polymer film takes a lot of time. It can take hours to create a relatively thin polymer film. This is primarily due to slow drying time of the solution. A drying fan has been added to the printer, but it is not enough. Other methods of drying the polymer solution could be looked into. These could include a more powerful fan, or possibly using radiated heat to dry the solution.

Another approach to solving this problem would be altering the polymer solution itself to give it quicker drying properties. This could possibly be done by adding more isopropyl alcohol, or other quickly evaporating agents. This would probably take significantly more development time, as even small changes to the polymer solution cause large differences in the way the solution prints.

7.3 Using Multiple Polymers

At this point, only PVP has been printed with this printer. If the printer were able to print multiple polymers, its potential applications would be much greater. The printer has four ink cartridges, and a different polymer solution could be deposited into each cartridge. This would allow for the printer to produce polymer films with up to four different polymers. Much more complex films would be able to be produced, making the printer even more useful.

7.4 Reduce Distortion

As was discussed earlier, there is significant distortion during printing, reducing the quality of the printed polymer film. Reducing these distortions could improve print quality. The problem comes from the fact that the end of the printer simply rolls on the frame during printing, rather than sliding in a track like the base of the printer arm. A track system could be developed for the end of the printer arm to slide in, which would reduce distortion to a very minimal amount. Currently print speed is reduced in order to avoid large amounts of the distortion, but if a track system were developed, it would allow increased print speeds reducing the overall time required to produce a polymer film.

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Appendix A: Printing Instructions

1. The desired printing substrate should be mounted onto the print table first. After the substrate is attached to the table, ensure that the print head will not come into contact with the print head by manually moving the printer over the substrate and checking clearance. The print head should be close to, but not touching the substrate.

2. Ensure that the control switch for the return motor is in the off position. Also ensure that the printer is in the correct starting position, which is all the way against the end of the track at the end the return motor is located. The print head should be removed from the printer. Finally ensure that there is a sponge located under the purge system, so excess ink will not be spilled.

3. Before turning on the printer, the tension on the drive belt must be released. This is because the printer automatically sends power to the drive motor when powering up to ensure that there are no errors during start up. In order to do this, press in the spring loaded release mechanism located at the opposite end of the belt from the drive motor. Now turn on the printer while holding in the release mechanism, the motor will spin freely for a short amount of time during start up, when it stops, let the release mechanism back to its original location, putting tension back onto the belt. When the light stops blinking and remains solid green, it is ready for printing.

4. Press the open button before loading the ink head, this ensures the printer operates as it normally would in original form and will ensure that the purge system with prepare the printer for printing. When the print carriage stops in the center, it is ready for the ink head to be loaded.

5. Load the print head into the printer. Before pressing the open button again to return the print head to starting position, deposit the ink into the ink cartridge. This should be done with the ink cartridge already loaded into the printer to ensure no ink leaks.

6. Press the open button again to return the print head to beginning location. Now the printer is ready for printing.

7. Plug a USB cable into the printer and a computer, and the driver should automatically be installed onto the computer. Using your desired program, design the required shape to be printed. When printing, the printer will show up as Canon S750 on your list of available printers. Use the number of copies option to select how many layers to be printed

8. During printing ensure that the USB Cable does not cause a jam. The printer will continue to print until the selected amount of layers is completed.

9. When done printing, power down the printer. Then remove the print head and thoroughly clean out the print head with isopropyl alcohol. Wash out the ink cartridge with warm water. This will ensure no polymer dries and clogs the print head or causes ink flow problems for the cartridge. Ensure that everything is completely dry before printing again.