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3D Polymer Printing with Desktop Inkjet Technology

A Major Qualifying Project Report

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Abstract

The purpose of this project was to modify an inkjet printer originally designed for home or office use to print three dimensional shapes composed of polymer. This concept involved the engineering of a polymer solution capable of being deposited by the printer onto a substrate, as well as modifying the mechanical components of the printer in order to produce multiple layers of that polymer. Through the development of various polymer ink solutions consisting of polyvinylpyrrolidone (PVP), isopropyl alcohol, and water, the required concentration to flow through the cartridge nozzle of a Hewlett-Packard DeskJet printer was found. With the addition of a new paper feeding system, the polymer ink was deposited on a sheet of paper becoming the first layer of a 3-dimensional object. This technology, with the addition of polymers can be applied to drug delivery systems, food packing, and other fields in which the polymer can control a release rate of an additive.

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Introduction

Today, inkjet printers are commonly referred to as an everyday computer printer. Used for transferring data such as text files or pictures, modern inkjet printers are categorized into one of three main technologies; continuous inkjets, piezoelectric inkjets and thermal inkjets. Developed by Hewlett-Packard (HP) and Cannon, thermal inkjet technology uses a heated plate to deliver ink. A vapor explosion creates an ink droplet that is ejected through a nozzle and onto a paper [1]. This same mechanism can be applied to polymer printing as well as 3 dimensional printing.

An inkjet printer has the ability to create precise patterns by controlling the delivery of volumes of liquids, in picoliters, which monitors the consumption and waste of the material used. One of the most hopeful methods used to create direct patterning techniques; inkjet printing has its advantages. Inkjet printing is simple, fast, and has a high throughput as well as providing a low cost and a non contact pattern approach [2]. Inkjet printing in conjunction with the use of polymers can be applied to a variety of fields.

The use of polymers that incorporate various additives such as anti-oxidants, sensors, drugs, enzymes and other biomolecules has increased dramatically in various applications including food packaging and biomedical devices. Polymers can be used as vehicles to protect and deliver these molecules to the targeted site. For example, a polymer could be carrying a drug, flavor inducing agent, or an antibacterial agent. These molecules can be released from degradable polymers in a controlled fashion at the targeted site. Multiple compounds can be incorporated within the polymer and be released in a controlled fashion. Food engineering and biomedical fields are not the only fields in which polymers have been used. Polymers have used to incorporate fertilizers and obtain controlled release.   Various other applications such as capacitors and resistor-capacitors circuits, hoses, pipes, gaskets and children's toys utilize polymers to incorporate a variety of molecules to control the performance of the device.

There are many processes available to include the additives in the polymer including film extrusion, injection molding and solvent casting. More recently powder processing based on 3D printing technologies have been developed to produce complex shapes with increased dimensional accuracy. In this case, the powder mixed with a binder is deposited on a sheet layer by layer and the final part is obtained after the binder is cured. The drawback of this technique is that in order for the development of the final shape, the polymer and the additives may be exposed to various chemicals and high temperatures during the curing of the binder.

The purpose of this project is to explore the use of inkjet printing technology to deposit polymers with the additives onto various substrates. Inkjet printing is a relatively simple process where the polymer can be deposited layer-by-layer at room temperature without any binders. A HP840C ink jet printer will be modified and a suitable polymer solution (with additives) will be used in a black HP No.15 ink cartridge. In addition, a new paper feeding system design will be developed to ensure the precise location of the 3D-layered polymer distribution.

1 Background

Three-dimensional polymer printing can be applied to various fields of study. The use of polymers in the medical and food industries has grown over the past years. With the ability to incorporate various additives to a polymer it is possible to control the release rate of the additive based on how the polymer degrades.

Companies have developed 3D printers dedicated toward the use of in home personal printing, two such companies are Desktop Factory and Dimension. These companies have created compact personal 3D printers shown below (Figure 1).

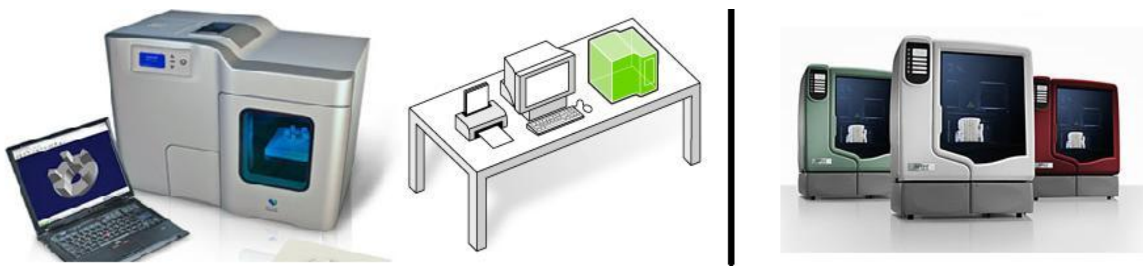

Figure 1: Desktop Factory's 125ci 3D printer 25"x 20"x 20" (left panel) costing nearly $5,000. The right panel shows Dimensions $14,900 uPrint machine with a blueprint of 25" x 60" product.

Desktop Factory's 125ci 3D Printer measures approximately 25 x 20 x 20 inches while Dimension's product uPrint has a footprint of 25 x 60 inches. The drawback of Dimensions and Desktop Factory's product however, is their cost of $14,900 and nearly $5,000, respectively [3],[4]. With an understating of previous inkjet printing technologies and 3D modeling techniques one can apply such knowledge to the modification of an everyday desktop inkjet printer at a low cost.

1.1 Inkjet Printing Technologies

Known for hundreds of years and constructed for more than a hundred, inkjet printing technology only entered the commercial world in the 1970s. Since the first commercial appearance of inkjet printers the technology has been in demand for the use of high quality text and full color printing. The main concept of inkjet printing is that the ink is sprayed onto a paper. The distinction of what type of inkjet technology, a continuous system or drop on demand, is being used is classified by the method in which the ink is sprayed onto the paper.

1.1.1 Continuous Systems

In a continuous system the ink is pushed through the nozzle creating a constant stream. Droplets are deposited on the paper while unneeded droplets are deflected. The inks used in continuous systems are water based. An advantage of continuous systems is the ability to operate at higher speeds.

1.1.2 Drop-on-Demand (DOD)

The drop-on-demand (DOD) system sends ink through the nozzle only if a drop is desired on a page. There are two types of DOD printer technologies; continuous inkjet and phase change inkjet.

In a continuous jet, the ink droplet path is controlled by its reaction to two differently charged plates. As an ink droplet is released it is charged and passes through the two differently charged plates. Due to the constant flow of ink, the ink jet is less likely to become dry or clogged [5]. DOD is capable of a smaller drop size and a greater placement precision.

DOD continuous jets use a thermal or piezoelectric method to release the ink droplet from the printer head [6]. Thermal method inkjets work in several steps. First, an electrical current is applied to a small resistor, causing it to heat. This action is dictated by signals from the computer. This resistor is submersed in a chamber full of ink. When heated, the ink that is immediately surrounding the resistor is vaporized, expands, and becomes a bubble. This bubble of vaporized ink is larger in volume than when it was in liquid form. Since the volume of the chamber is unchanged, a drop of liquid ink is ejected out of the chamber hole to make room for the bubble. The ink is deposited onto paper, and the process is complete (shown in Figure 2). Inks used in the thermal method are water-based solvents [7]. A different form of a DOD printing method is a phase change inkjet.

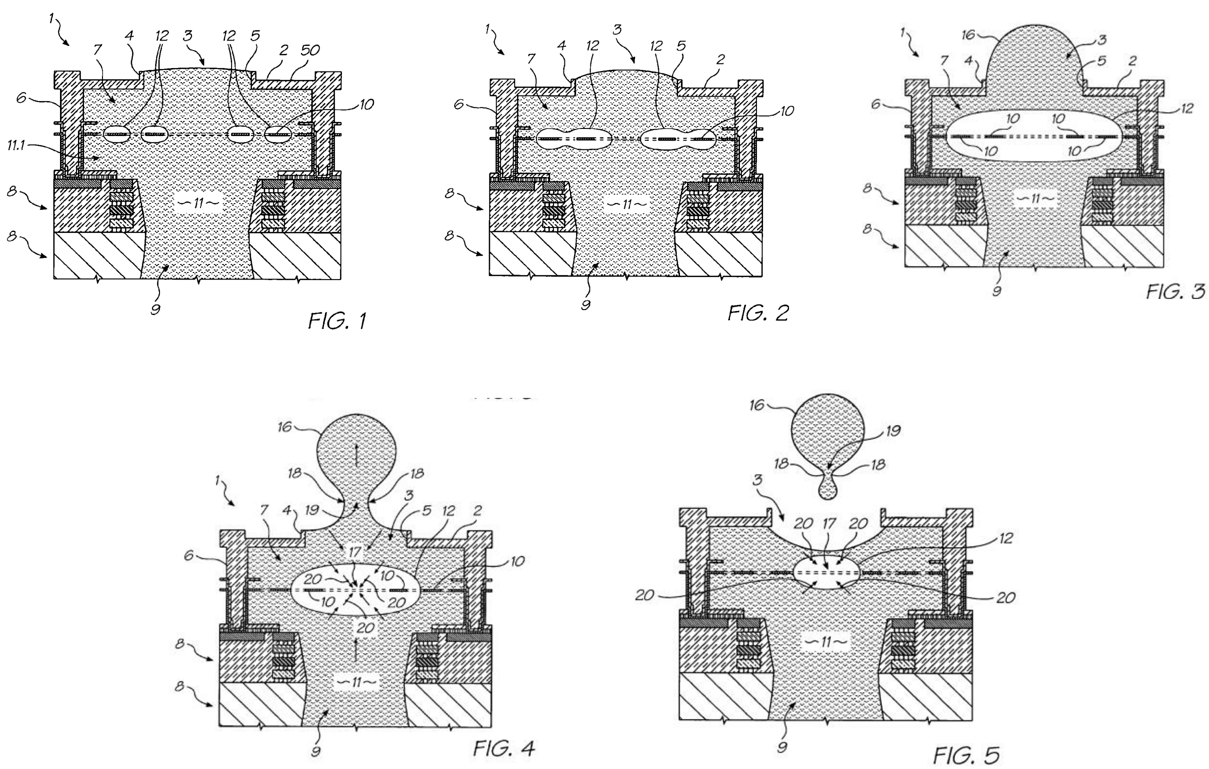

Figure 2: Steps of the thermal method of ink depositing technology is shown in the figures above.

A phase change inkjet, as the name suggests, includes a phase change of the ink. Beginning with a waxy solid the print head melts the solid. Similar to continuous jets, DOD technology is used to deposit the ink onto the paper, however, in phase change inkjets when the ink hits the paper it returns to a solid state. This specific ink property gives phase change inkjet an advantage because the ink bonds directly with the paper surface and does not depend on absorption time [5]. Figure 3 shows the difference between the depositing methods of inkjet technology. Note that in pane A, the thermal method requires an absorption time to complete. A SEM photograph of a phase change ink drop shows the bond of the droplet on a paper after it has been deposited [8]. The piezoelectric method is also a DOD printing method.

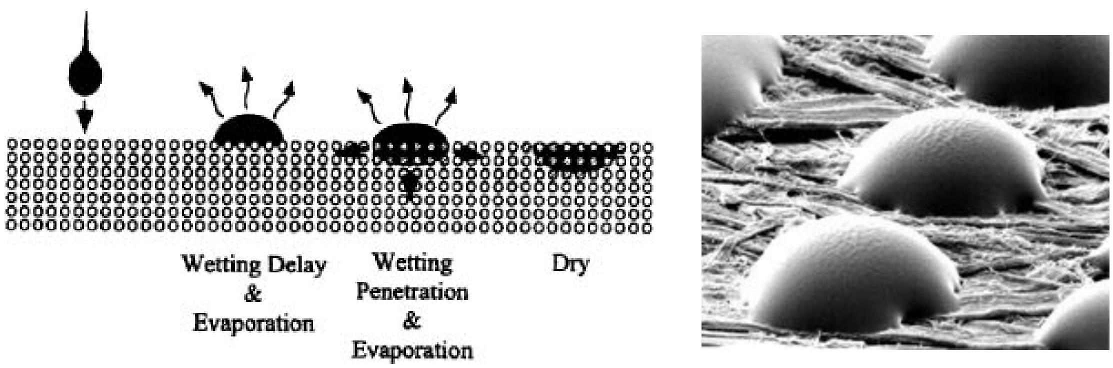

Figure 3: The difference between the depositing methods of inkjet technology. The thermal method (left) requires an absorption time to complete. A SEM photograph (right) of the phase change method shows the inks solid state after contact with a surface.

Use of piezo crystals located at the back of the ink reservoir of each nozzle identifies this technology as the piezoelectric method. The piezo crystal receives a tiny electric charge that makes it to vibrate. When the crystal vibrates inward, it forces a tiny amount of ink out of the nozzle. When it vibrates out, it pulls some more ink into the reservoir to replace the ink sprayed out [7].

Technologies used in inkjet printing can also be found in 3D modeling techniques (rapid prototyping).

1.2 3D Modeling Techniques (Rapid Prototyping)

Rapid prototyping works by using a computer drawing of a three dimensional object, such as a CAD file, that is converted by a computer into an object composed of various two dimensional cross-sectional layers. The computer sends the geometry of each layer to a device that produces these layers one at a time to form a 3D object. There are many methods for rapid prototyping, each categorized (based on the materials used) into one of three groups; Photopolymers, Thermoplastics, and Adhesives.

1.2.1 Photopolymers

A photopolymer is a substance that is kept in a liquid state and polymerizes when exposed to light. Polymerization is a chemical reaction that forms three dimensional polymer chains. The polymerization of the photopolymer simply means that when light, often ultra violet comes in contact with the photopolymer it becomes a solid. Photopolymers are used in newspapers, boxes, curved surfaces of tin cans, rubber stamps, and to make patterned impressions. Photopolymers are also being applied to the creation of 3D objects.

1.2.1.1 Stereolithography (SLA)

This process uses liquid polymer solutions that harden under ultra violet light to make 3D models. Using a highly focused, but low-power UV laser, each layer of the model is traced, while excess polymer remains in a liquid state, and eventually runs-off when cleaned. Machines the one shown in figure 2 have been produced by 3D Systems since 1988. Being one of the first machines capable of 3D model printing, stereolithography is regarded as a benchmark for other methods.

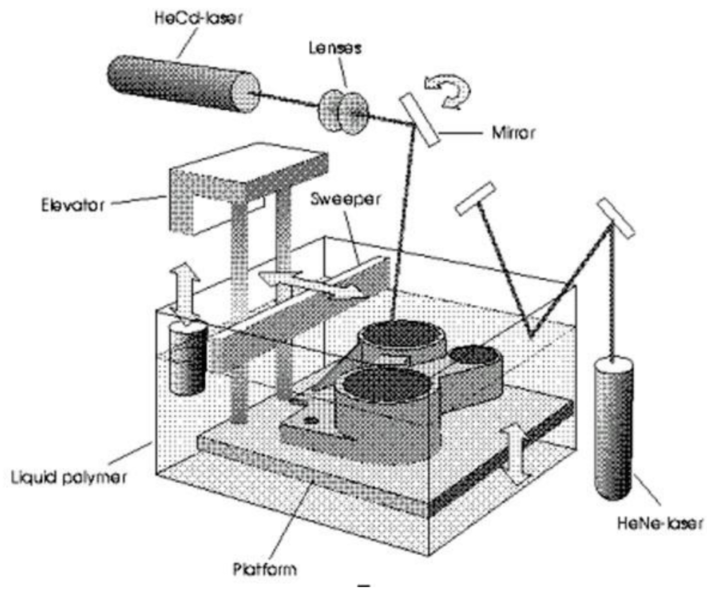

Figure 4: An SLA machine and its components. SLA machines are one of the first machines capable of 3D printing and have been produced since 1988.

1.2.1.2 Solid Ground Curing (SGC)

Solid Ground Curing (SGC), like SLA, uses an ultraviolet light to choose specific areas of photosensitive polymers that will be hardened. After a photosensitive polymer is placed in the base of the machine a trace of the desired part is created on a glass plate above the platform. This trace, called a photomask, is what monitors which sections of polymer will harden. When exposed to UV light, the light is only able to pass through the areas in which the photo mask does not exist and the polymer is hardened to create the desired model.

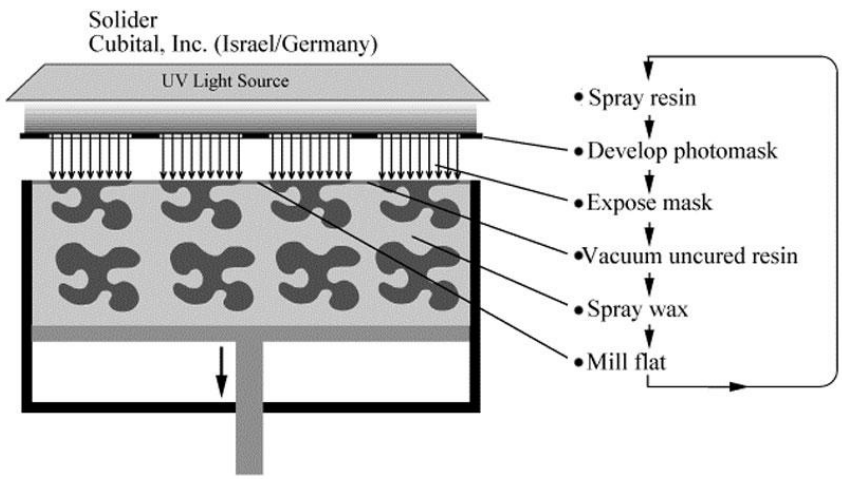

Figure 5: Solid Ground Curing uses a mask to monitor what sections of the polymer will harden to form the 3D object.

1.2.2 Thermoplastics

A thermoplastic is a type of plastic that has the ability to repeatedly soften or liquefy when heated and harden when cooled. Types of thermoplastics include acrylic, polyvinyl chloride(PVC), polypropylene, and Teflon. Used in a variety of different ways, thermoplastics range from safety shields to gaskets, battery covers, piping, counter tops, and many machine parts as well as rapid prototyping.

1.2.2.1 Fused Deposition Modeling (FDM)

Fused deposition modeling takes a heated thermoplastic filament and feeds it through a shaft the moves in the x-y plane. The filament is pulled into shaft and extruded through a tip which then deposits very thin beads of material onto a low temperature platform and hardens. The following figure depicts the direction of the shaft and the extrusion of the filament. Once the shaft reaches the end of the platform and the first layer is deposited the platform is dropped. The shaft returns to the initial position and the process is repeated. Building layer by layer the thermoplastic is extruded and deposited until the desired 3 dimensional object is complete.

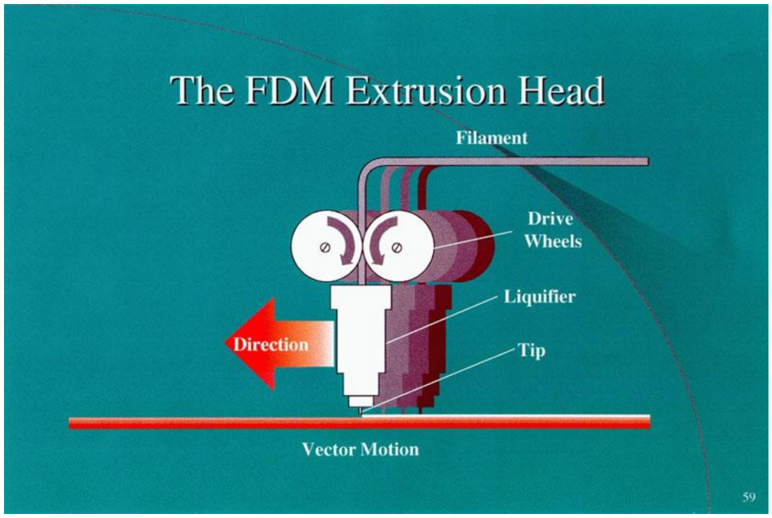

Figure 6: Fused deposition modeling feeds a filament into a shaft which is then extruded and deposited onto a platform.

1.2.3 Adhesives

Adhesives are compounds that bond items to one another. Everyday common adhesives are your simple glues, tapes, and sprays. An example of an adhesive is the sealing mechanism of a common envelope or how a stamp is held to an envelope. When applied to 3D modeling an adhesive is what binds the construction material being used together.

1.2.3.1 Selective Laser Sintering (SLS)

Selective Laser Sintering is an example of a method that works under the concept of fusing material, in the form of powder, to form successive layers of a 3D model [9]. In SLS a material is deposited whether it is a powdered metal, a polymer, or a ceramic is scanned. Next, a roller levels out the material and a powerful laser sinters the material through the use of mirrors, shown below. The cycle is then repeated [6].

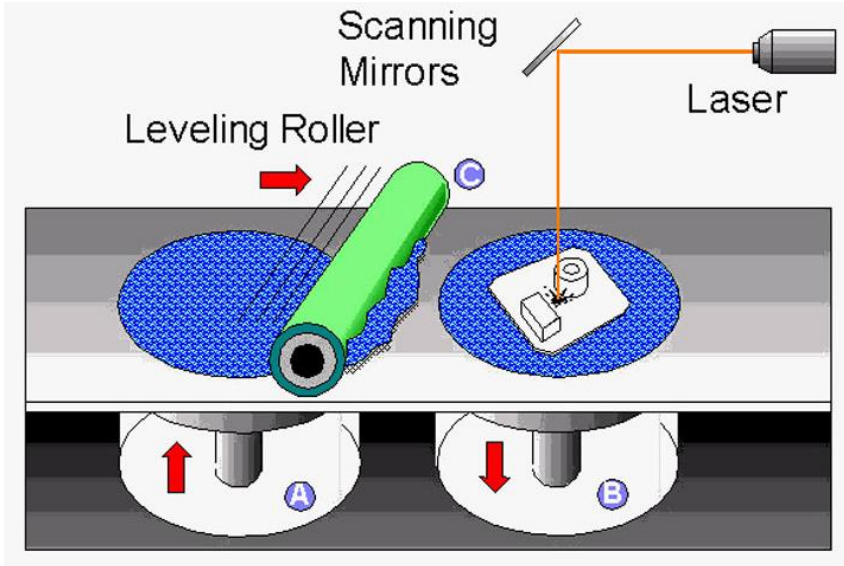

Figure 7: Selective laser sintering fuses material together through the use of a laser to generate layers of a 3D model.

1.2.3.2 3D Printing (3DP)

Developed by MIT, 3D printing uses inkjet technology to create 3D models. A binder fluid is deposited by the inkjet print head and fuses with the powered in desired areas. The powdered that is not bound to deposited binder fluid supports the part throughout its creation. Similar to SLS a platform is lowered, the powered is leveled, and the depositing method is repeated. Upon completion the part is removed and the excess powder is blown off [9].

With the knowledge and development of previously mentioned technologies, as well as others, many experiments can be preformed.

1.3 Application of Polymers

Polymers, used to transfer chemicals, have been used in conjunction with inkjet printing in various fields including ceramics, organic conductors, metals, and biopolymers. Inkjets do not consume considerable quantities of material as they are capable of controlled delivery of small volumes of liquid, which form precise patterns.

1.3.1 Biological Applications

In the biomedical field of study polymers have served as drug delivery systems. By adding a polymer to a drug it can allow for a different, more direct path to the site of delivery based on its design. The use of polymers has also been seen in tissue engineering as well as other applications.

1.3.1.1 Cell Patterning

Applied to patterning methods of cells, inkjet printing has allowed the printing of proteins to regulate cell attachment to be developed. Use in the biomaterials discipline, for biosensor development, biochips, DNA synthesis and more has already shown that ink jet printing and computer-aided design (CAD) have had an impact on the field.

For tissue engineering applications, inkjet printing techniques have been studied to aide in the development of solid free-form fabrication (SFF) process [10]. SFF is a manufacturing process for 3D solid objects, scaffolds in this case [11]. Sometimes referred to as rapid prototyping, SFF uses CAD and a layering processes to create 3D tissue scaffolds. The layer by layer technology allows for the design of biological features, like pores and channels, to be incorporated into the scaffold. SFF can be used to the construction and selective modification of biodegradable polyester scaffolds to direct 3D tissue development [10].

1.3.1.2 Chinese Hamster Ovarian Cells

Conducted by the Department of Bioengineering at Clemson University, a modified HP deskjet (HP 550C) and a modified ink cartridge (HP 51626a) were used to print specific Chinese Hamster Ovary (CHO) cell patterns. The cells were suspended in a solution which was then stored in the modified cartridge. The cells were used as the "ink" and were printed onto a "bio-paper" made of hydrogel-based substrates. Added to the cell was a chemical to allow the cells to emit a green fluorescence. This was simply done so that the cells, if living, could be visibly spotted under a fluorescent microscope. The cells were then delivered according to a specific pattern designed by a computer program.

In order to create such patterns, the cell suspension was shaken and 0.3-0.5 ml was loaded into the base of the cartridge. Designed by Microsoft Power Point, the pattern included rows of circles. The hydrogel "bio-paper" was then loaded into the tray bed of the printer and the cells were delivered based on the previously described pattern. The bio-papers containing the printed CHO cells were stored in an incubator. The cells are believed to have been living even after passing through the inkjet nozzle because they were observed to be emitting a green fluorescence. Figure 8 below shows the pattern of the printed CHO cells on the bio-paper after (A) 7days, (B) 15 days, (C) 20 days and (D) 25 days of culture[12].

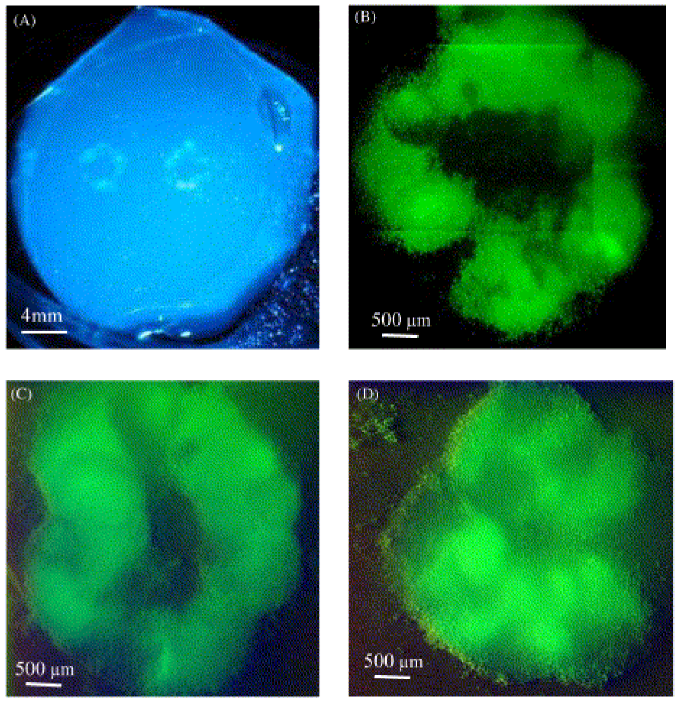

Figure 8: The pattern of the printed CHO cells on the bio-paper after (A) 7days, (B) 15 days, (C) 20 days and (D) 25 days of culture. This study provides results that viable CHO cells can be successfully deposited by the use of a modified HP thermal inkjet print

1.3.2 Microelectronic Devices

Inkjet printing has been used to develop all polymer transistors, polymer light emitted diodes, and nanoparticle microelectromechanical systems. Using a commercial Epson Stylus color 480 SXU printer one study set out to print a polymer capacitor. An insulating layer of polymimide (PI) was printed through the inkjet nozzles. Acting as the top and bottom electrodes for the all polymer capacitor was poly(3,4-ethylenedioxythiophene) (PEDOT) doped with polystyrene sulfonic acid (PSS). In its doped state PEDOT is highly conductive, making it a good candidate for applications such as transistors and capacitors.

To fabricate the capacitor, two layers of PEDOT were printed on a substrate each heated on a hot plate for 2 minutes and dried as a method of creating a more uniform layer. Three layers of the insulating polymer, PI, were then printed on the previous pattern and annealed at 50 ºC. Lastly, two layers on PEDOT were deposited onto the PI and also annealed at 50 ºC [13].

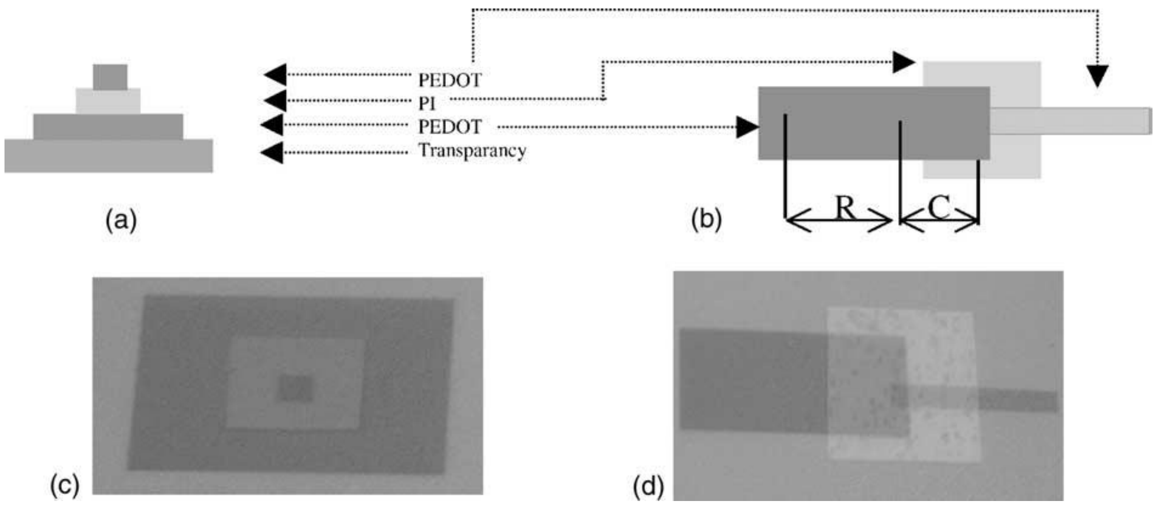

Figure 9: (a) Cross section of the all-polymer capacitor. (b) Structural design of the RC filter. (c) Picture of the printed polymer capacitor. (d) Picture of the printed polymer RC filter.

1.3.3 Fertilizers

The over consumption of fertilizers has led to the pollution of ground water by nitrates. To decrease pollution, degradable polymers have been incorporated as coatings into the development of fertilizers. By coating the fertilizer with a polymer the diffusion rate of water and the release of water-soluble active agents can be controlled. To find the correct polymer for coating the water vapor permeability is examined. Biopols and polylactic acid (PLA) showed to be the best for coating as a result of the permeability tests. However, due to its crystalline structure Biopols have a low solubility and therefore PLA is the better option. The use of two different coating methods revealed that the total release time of the fertilizer could be 46 hours or 26 days. The clear choice was to use the method which yields a 26 day total release period. In this case the use of polymers aided in the controlled release of a fertilizer as well as decreasing water pollution [14].

1.3.4 Food Packaging

Quality of food and its taste is very important to a consumer, however, it is a given that food does spoil. To help products maintain their ideal condition for as long as possible polymers have been utilized in the food world as well. One use of polymers in this field is packaging. Common polymers used for packaging include polypropylene (PP) and polyethylene (PE). A foods quality relies heavily on its packaging as it should maintain the nutritional value of the food as well as prevent physical, chemical, or biological changes that compromise quality [15].

1.3.5 Other applications

Present in a variety of fields the use of polymers is continuously growing. Polymers have proved to perform well as carriers, conductors, coatings and barriers; however, in such a growing field there is always room for research and the development of new applications.

2 Objectives

The objectives in this study were to:

- Modify an inkjet printer, originally designed for home/office use, to print three dimensionally using a synthetic ink composed of a polymer solution.
- Reengineer the printer to deposit the appropriate amounts of polymer onto various substrates.
- Determine the characteristics of polymer suited for printing.

3 Materials and Methods

The general procedure of the experiment is outlined in this section, and will provide an understanding of how tests were performed in an attempt to create a polymer solution that is compatible with an Inkjet printer.

3.1 Materials

The various materials required for this study included mechanical apparatuses, electrical components, and chemicals. These materials, their purpose, and why they were chosen are described in this section.

3.1.1 Printer

A Hewlett-Packard DeskJet 840C was chosen as the printing device. This particular device was selected based on the favorable characteristics of the ink cartridges it uses; being relatively straightforward to refill with simple means. This printer uses the printing method known as Drop-on-demand thermal Inkjet printing, with a maximum resolution of 600 x 600 dpi. This printer also accepts a maximum and minimum paper size of 8.5” x 14” and 5” x 5.83”, respectively [16]. These dimensions are important to keep in mind when determining the size of the modified paper tray. Figure 10 shows the printer in its original state, with only the left panel and top cover removed.

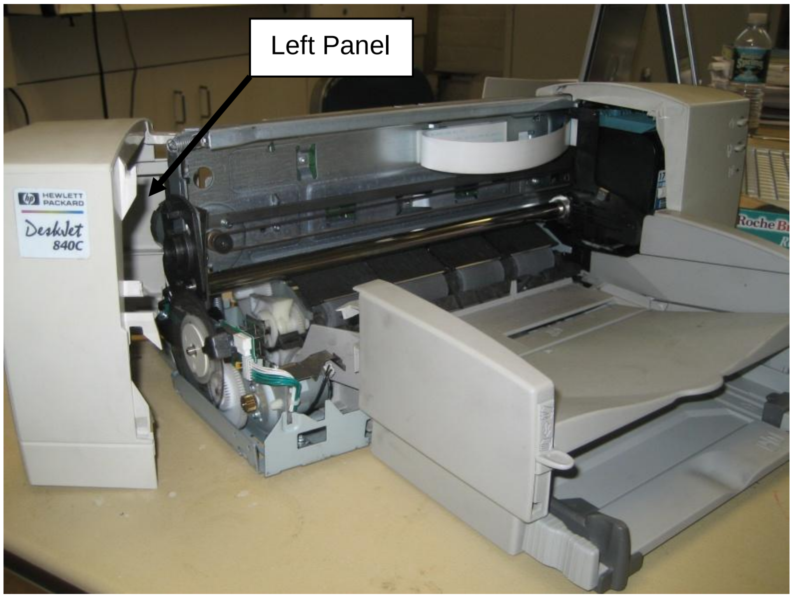

Figure 10: Start of Printer Disassembly

Looking closely at the side of the printer, shown below in Figure 11, three important components which are necessary for printing a desired image are visible.

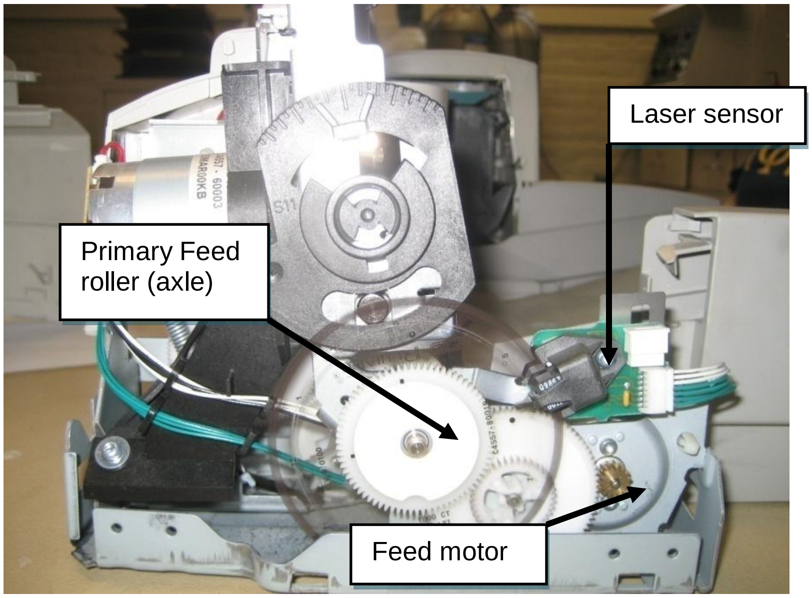

Figure 11: Paper feed mechanism (Left side of printer)

The feed motor shown in Figure 11 is advances the paper under the print head. This feed motor is controlled by a laser sensor attached to the feed roller, in order to accurately position the printing paper beneath the print head. Another function of the feed motor is to control the elevation of the storage tray below which is responsible for collecting a single new sheet of paper from the reserve stack for printing. The gears which operate this mechanism are shown from the rear of the printer in Figure 12.

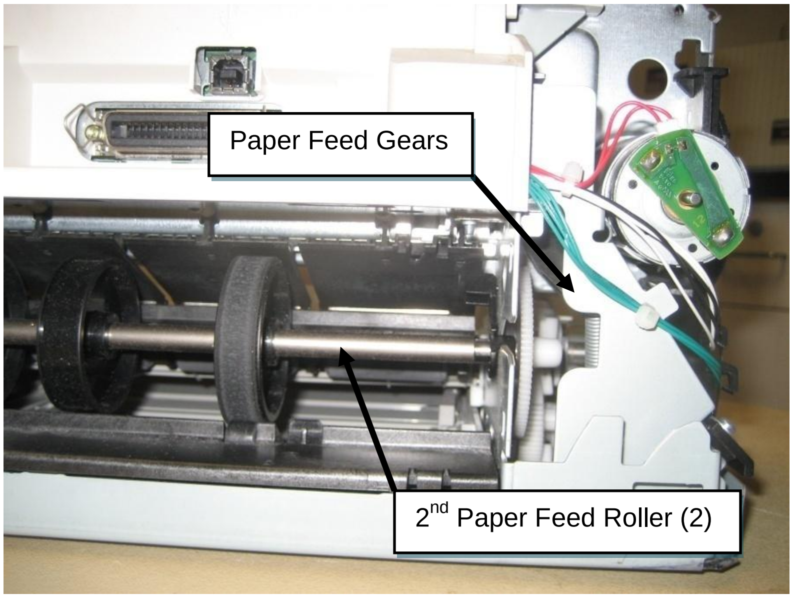

Figure 12: Printer Left side rear

However, since the objective of this study was to print an image that is layered several times onto a substrate, this mechanism was not needed and was therefore removed. Further modifications applied to the printer are outlined in the Results section of this paper.

3.1.2 Ink Cartridges

The type of cartridge used in the HP 840C printer is the C6615 Series cartridge with a 15 mL capacity [16]. These cartridges are desirable because they can be filled and sealed easily by simple means available in the laboratory. A supply of 100 used cartridges was located and purchased on two separate occasions, through eBay. Figure 13, Figure 14, Figure 15, and Figure 16 show, with detail, the insides of the ink cartridges used in a step by step dismantling.

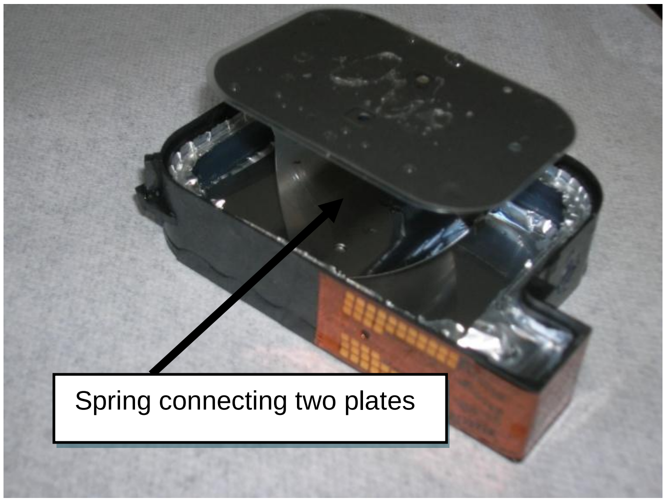

Figure 13: Photograph showing the ink cartridge. The cover has been removed to illustrate the interior of the cartridge.

Figure 14: Inside of the cartridge with metal plates and spring removed

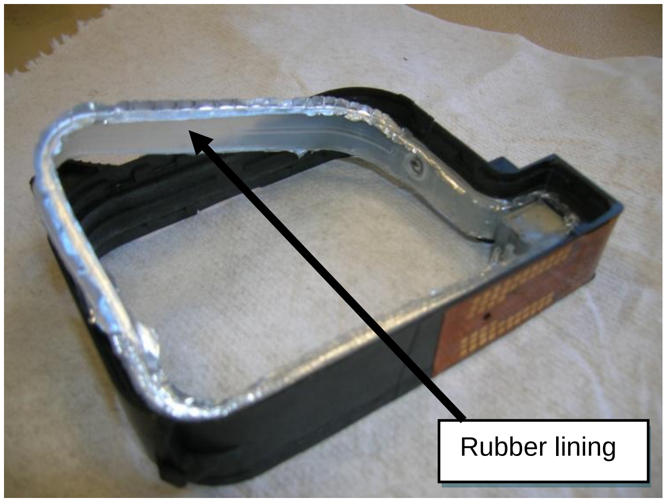

Figure 15: Inside Cartridge with Foil Removed

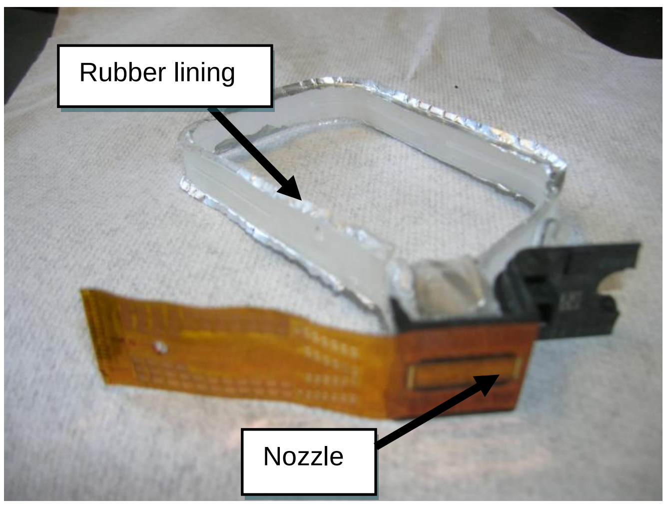

Figure 16: Cartridge Interior Lining

When the foil inside the cartridge is punctured it begins to draw in air as the chamber expands. Visible in Figure 13, a cutaway of the side of the cartridge reveals two metal plates separated by a spring. This spring, exerting a force outward from the inside of the cartridge, is causing a negative pressure in order to keep ink from dripping out of the nozzles above. Therefore, it is important to maintain an airtight seal after re-filling the cartridges.

3.1.3 Polymer Solution

Information on ink contained in the C6615 Series cartridge was readily available on the Hewlett-Packard website under the Material Safety Data Sheet (MSDS) [18]. Important information such as the composition and physical properties of the ink is revealed on the MSDS. This information is summarized in Table 1 and Table 2.

Table 1: Material Safety Data Sheet information for the original ink in the cartridge, manufactured by Hewlett-Packard [18]

Composition/Information on Ingredients		
Component/substance	**CAS number**	**% by weight**
Water	7732-18-5	>70
2-pyrrolidone	616-45-5	<15
Carbon black	1333-86-4	<5
Isopropyl Alcohol	67-63-0	<5

Table 2: Material Safety Data Sheet information for the physical and chemical properties of the original ink [18]

Physical/Chemical	
pH 7.8 - 8.4	7.8 - 8.4
Boiling point	> 200 °F (>
Solubility	Soluble in
Specific gravity	1 - 1.2 g/mL
VOC content	< 3 %
Flash point	131 - 136 °F
Viscosity	> 2 cp
Vapor density	> 1 (air = 1.0)

The most important information gathered from these tables is the composition of the C6615 Series ink, as this will form the basis of the material selection for the polymer solution to be tested.

Therefore, with the help of the information provided by the MSDS, the materials needed are determined.

3.1.3.1 Water

In

Table 1 it is shown that the ink is made primarily of water. Therefore, we must assume the use of water to some extent in our solution.

3.1.3.2 Polyvinylpyrrolidone

Table 1 also shows that the next largest substance present in the ink solution is Polyvinylpyrrolidone (PVP), with a molecular weight of 85.1 g/mol. In this experiment, PVP of two different molecular weights were used (58,000 g/mol and 1,300,000 g/mol), though the two were never mixed in a single "batch". Both polymers were purchased from Acros, a division of Fisher Scientific.

3.1.3.3 Isopropyl alcohol

Isopropyl alcohol helps to dissolve the polymer into the solution. For this reason, it is a necessary chemical to include in the solution. Varying the amount of alcohol in the solution will also allow a greater amount of polymer to be dissolved if necessary.

The solution used in this experiment, as opposed to the C6615 Series ink, is absent of any carbon black, since we are not trying to reproduce printer ink, but rather a solution of dissolved polymer suited for 3D printing. Furthermore, by demonstrating that it is not necessary for the printer to function, this would also open the possibilities for adding alternative substances, en lieu of carbon black, in the hopes of seeking a variety of printable functions.

3.2 Methods

The following section provides a detailed description of the methods used throughout this experiment.

3.2.1.1 Preparation of Ink Cartridges

Second hand ink cartridges are used in this experiment, so it is important to consider possible errors that could occur as a result of faulty units. In order to reduce error, the first step in preparing the ink cartridges is to test each cartridge, without any modification, to determine which ones are positively in working order. First, the cartridge being tested was cleaned; specifically on the nozzles using Kimwipes and a solvent (ethanol). This was to remove any dried ink that would clog the nozzles. Next, the cartridge was placed in the printer and several test pages were printed. The cartridge was then marked with either the word, “Works”, “Semi-Works”, or a question mark, “?,” based on whether or not the cartridge fully worked, partially worked (only certain nozzles worked), or if nothing was printed. Although most of the cartridges did not work this time, they were not discarded because they could simply be out of ink. The purpose of this test was to identify cartridges that we know for certain are working, so that we may include at least one of these working cartridges in each test batch of polymer solution, in order to reduce error.

Next, it is necessary to make a hole in the cartridge so that leftover ink may drain out, and the cartridge may be cleaned. It was determined that the best place to make a hole would be on a corner, so that the air inside the cartridge could be channeled to that corner, in a bubble, and forced out the hole. From this, the hole was placed on the top corner of the cartridge, by puncturing the foil with a syringe. The location/technique for this approach is illustrated in Figure 10.

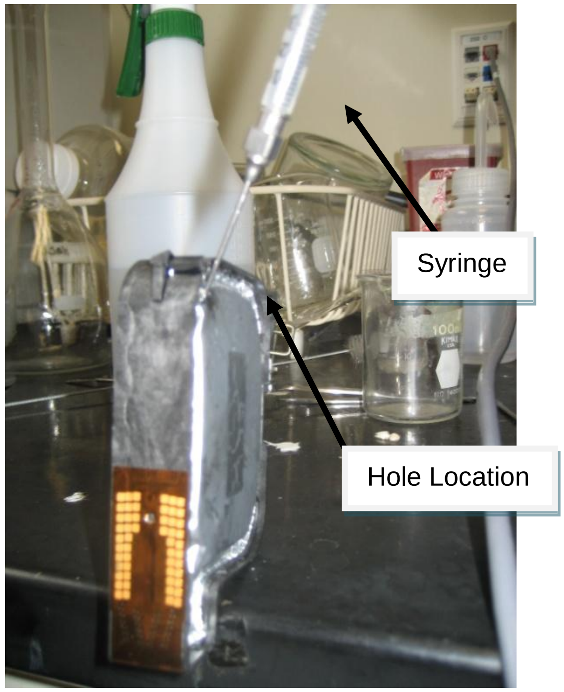

Figure 17: Initial hole design

This location was sufficient for draining and cleaning purposes, however it was found to be nearly impossible to form an airtight seal over the hole after filling the cartridge with test solution.

It was then decided to drill a hole in the same corner, but in the middle of the plastic boarder, and subsequently, thru the rubber lining beneath (*see* Figure 15 and Figure 16). The logic behind this was that it would be easier to form a seal over the hard surface of a hole in a plastic rather than the soft surface of a foil.

Thus, a hole was drilled using an electric hand drill and a 1/16th inch steel bit, on the corner opposite of the nozzles, to drain the ink from the cartridge. The location of our hole is shown in Figure 18 and Figure 19 [19].

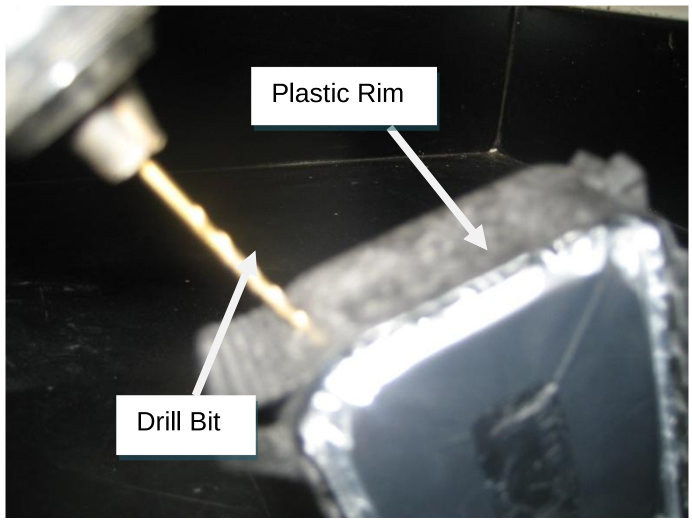

Figure 18: Location of Drilled Hole

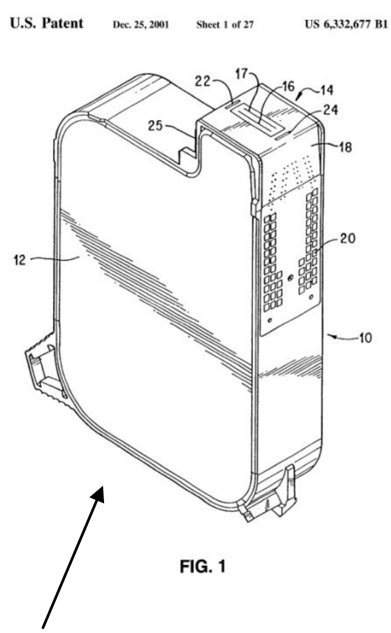

Figure 19: Location of Drilled Hole [19]

Next, the ink was squeezed from the hole until no more ink would emerge. Then, using a syringe, a solution of water (95%) and isopropyl alcohol (5%) was injected into the cartridge, shaken, and drained. This step was repeated until the runoff from inside the cartridge was a completely clear solution with no tint from remaining ink. At this point the cartridge was considered to be clean and ready to accept an experimental polymer solution.

3.2.1.2 Preparation of Polymer Solution

The composition and information on ingredients outlined by the Material Safety Data Sheet for Hewlett-Packard's C6615 Series ink is given according to percents by weight, rather than by volume. Thus, in order to make our own solution, an electronic scale was used to measure the amounts of each ingredient used.

To do this, a test beaker was first placed, with magnetic stirrer inside, on the scale and the reading was zeroed. Once the total amount (in grams) of solution to be produced is determined (arbitrarily), the amount of ingredient needed can be calculated (based on desired weight percentages). To insure the correct amount of a certain ingredient was used, simply calculate the total mass value for the mass of the ingredient plus the initial mass reading on the scale, and then check the reading after adding the ingredient to make sure this was indeed the correct amount.

It was found that it was best to start by adding water first and PVP second. This was so because if PVP was added first, it tended to stick to the magnetic stirrer when the liquids were added, and interfered with the rotation of the stirrer once mixing was to occur. Alcohol was added last in order to minimize its exposure time to air, and minimize the amount of evaporation that would occur.

Finally, each batch of solution was placed on the stirring machine, without heat applied, until all PVP was dissolved. This final step is shown in Figure 20 and Figure 21.

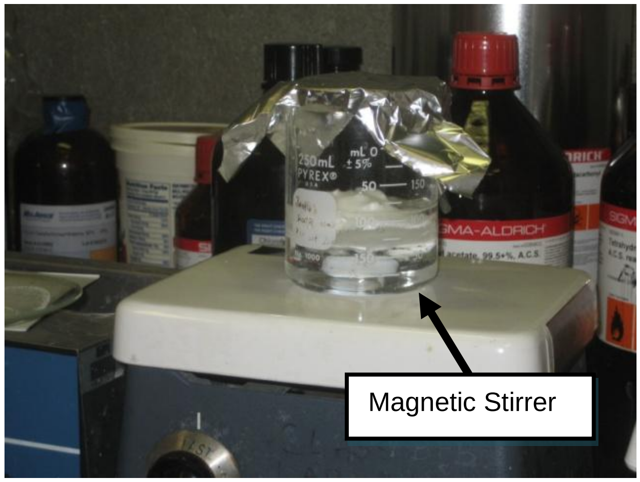

Figure 20: Mixing of Polymer and Solvents

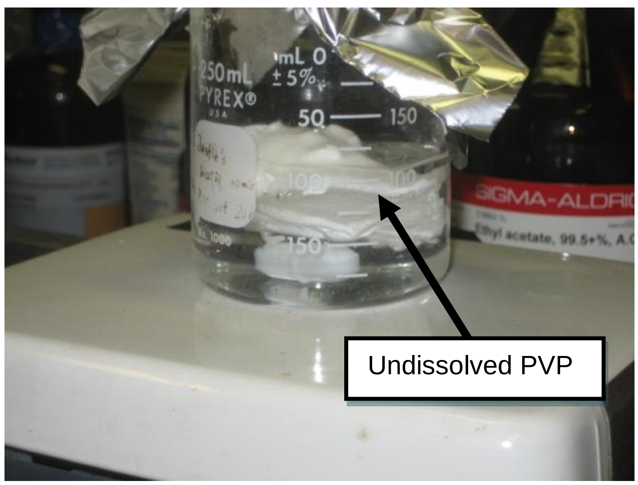

Figure 21: Mixing of Polymer and Solvents (close)

3.2.1.3 Replacing Ink with Polymer Solution

The polymer solution was injected into each cartridge thru the drilled hole using a syringe; a quite trivial process. Next, the hole was sealed by heating a flat-tipped metal rod under a flame and then carefully applying the heated end across the cartridge hole to melt the plastic and form an airtight seal. During this process, the middle of the cartridge must be squeezed on both sides until the polymer solution becomes visible at the entrance hole (If the cartridge is held upright, with the hole at the highest point, squeezing will ensure that all of the air inside the cartridge is ejected out before it is sealed). This step is very important, because the cartridge is designed to have a negative pressure inside in order to work properly.

3.2.1.4 Printing Test Pages

After the cartridge has been sealed and labeled with the solution batch number it contains, testing of that cartridge may begin. This consists simply of replacing the standard ink cartridge with our modified unit, then sending a print job from the computer to the printer. We chose Microsoft Word as the printing program, using various characters and shapes.

Multiple cartridges (at least 3) were used for testing each batch. This is because the most apparent issue with our experiment is that since we found it impossible to locate empty, and virgin, ink cartridges, we have no way of being absolutely sure that a cartridge is working properly or not. Using multiple cartridges per batch does not eliminate this error, but it certainly reduces it.

4 Results and Discussion

The results in this study were produced in two general areas: (1) The successful modification of the printing apparatus, and (2) the successful manufacture of a polymer solution compatible with the C6615 Series ink cartridge. These areas, and their results, are illustrated and discussed in this section.

4.1 Printer Modifications

In order to produce a three dimensional object it is necessary to print layer upon layer with each layer generating a certain thickness of the desired shape. Specifically, this requires several steps in the printing process.

First, a sheet of paper is fed through the printer in one direction as the print head appropriately deposits one layer of ink (or solution). Considering that the paper is being fed in only one direction there must be a mechanism to retract the paper (printing substrate) back to starting position of the initial layer. It is necessary to position the substrate accurately so that another layer may be deposited directly in line with the previous

Then, depending on the desired thickness of the final printed object a mechanism to lower the substrate may have to be added. This is the case when there is not sufficient clearance between the cartridge nozzles and the printed object. In this situation a lowering mechanism must be designed to prevent the cartridge from colliding with the layered object, potentially causing damage, as well as providing ample space for following layers. A lowering mechanism was not needed in this project. Thicknesses of printed objects were small with ample clearance between the two points in question.

For these reasons, unnecessary components must be removed so that a substrate tray may be added.

4.1.1 Unnecessary Components

The HP DeskJet printer in this project, like most other desktop printers, contains a mechanism (spring loaded arms) to force each sheet of paper downward, holding it in place between the feed rollers and the mechanism arms. This mechanism is shown in Figure 22.

This current design would not serve the purpose of this project, as the structure of a three dimensional object would be disturbed by these arms. For the same reason, the mechanisms that feed the paper from the tray, would destroy a three dimensional model as the substrate bends. Therefore, all but the primary feed roller (and the gears that operated it) was removed.

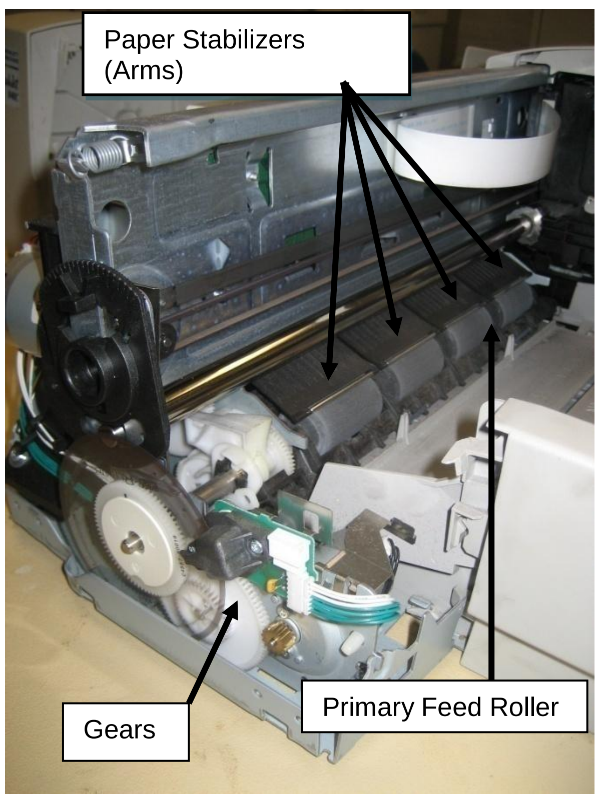

Figure 22: Spring loaded arms; originally designed to hold paper in place during printing

This modification is shown in “before and after” photographs of the front of the printer in Figure 23 and Figure 24; and of the rear in Figure 25 and Figure 26. After “gutting” the printer, the tray system could be added. This was done by screwing the four support wheels to the printer’s base, and resting the tray on top. The printer was now ready to test polymer solutions.

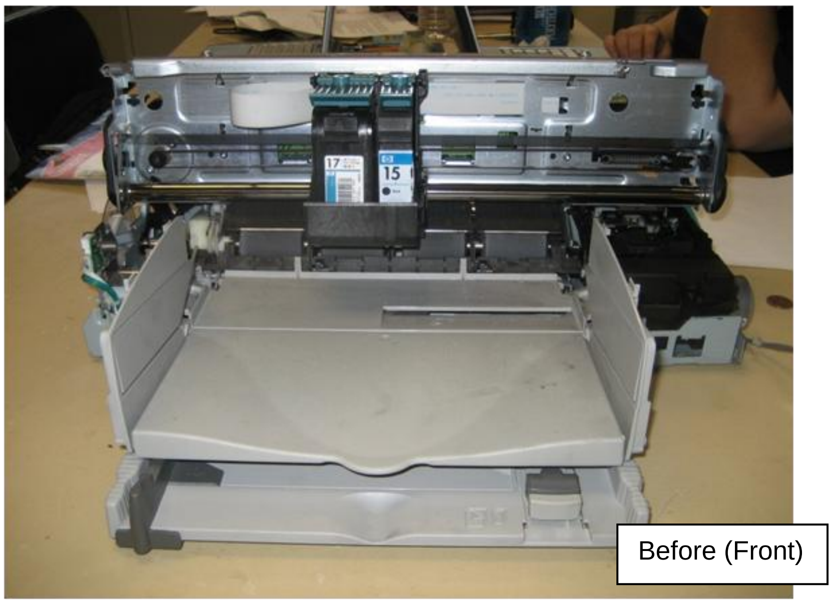

Figure 23: Front of printer (Before modification)

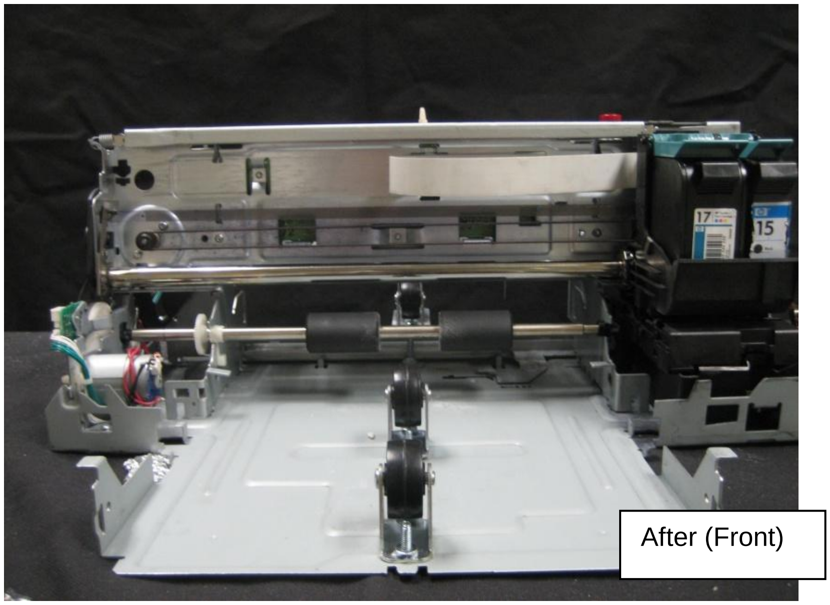

Figure 24: Front of printer (After modification)

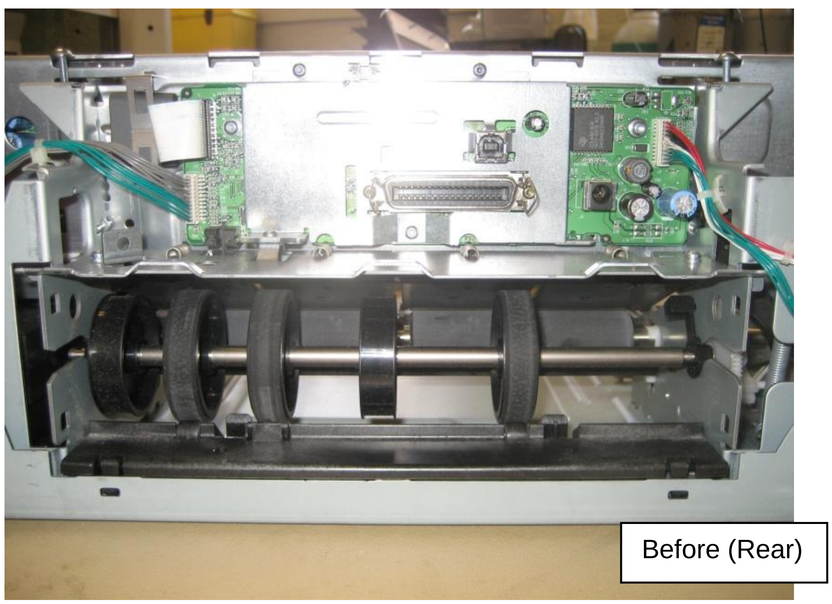

Figure 25: Rear of printer (Before modification)

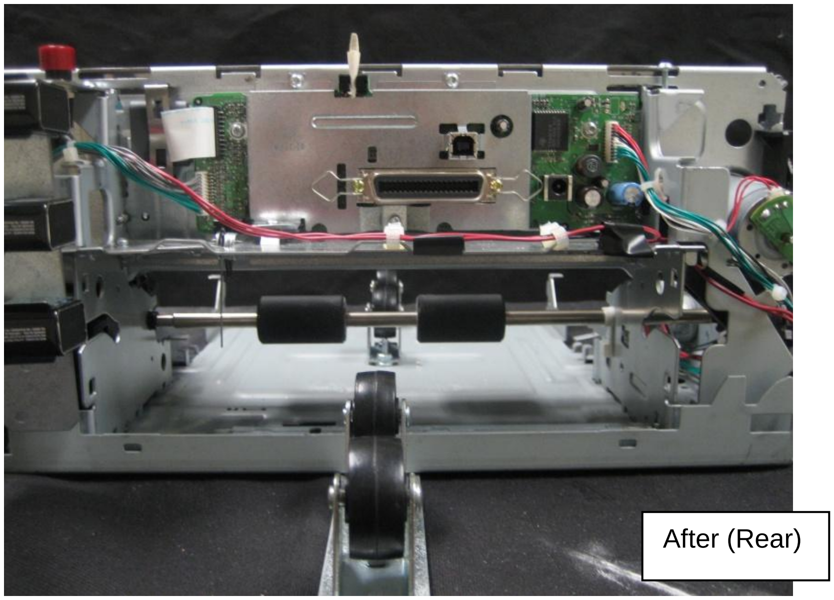

Figure 26: Rear of printer (After modification)

4.1.2 Substrate Tray

It is important to consider that a traditional printer such as the Hewlett-Packard DeskJet 840C prints an individual layer of ink on paper. For this reason, the design of the printer allows the paper to bend considerably while being fed by the motor. However, for a three dimensional object to be printed without disturbing the structure of the object the substrate cannot bend. Therefore, a rigid tray is needed to hold the substrates in place during printing. For this purpose, several tray designs were considered.

4.1.2.1 Alternate Designs

The first design, shown in Figure 27 and Figure 28, involved two plates which rested on top of each other. The idea was that the top plate would be the surface to hold the substrate sliding forwards and backwards (horizontally) as the solution was deposited by the print head above.

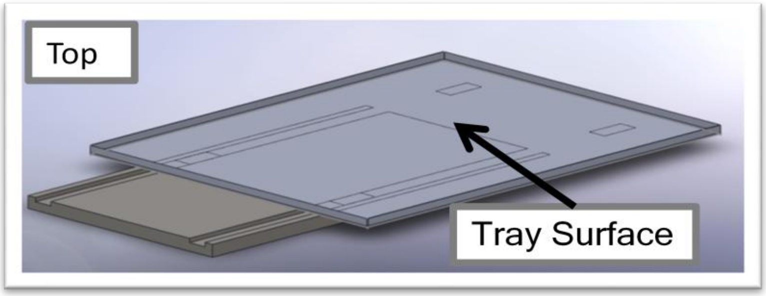

Figure 27: First tray design; Tray surface glides over a bottom plate, guided by tracks in the plates

As the top portion moved back and forth in a horizontal motion, the bottom plate would move downward (vertically), so that each printed layer could be stacked without interfering with the print head. This design was not used, however, because it was decided that a lowering mechanism was not needed for this particular project.

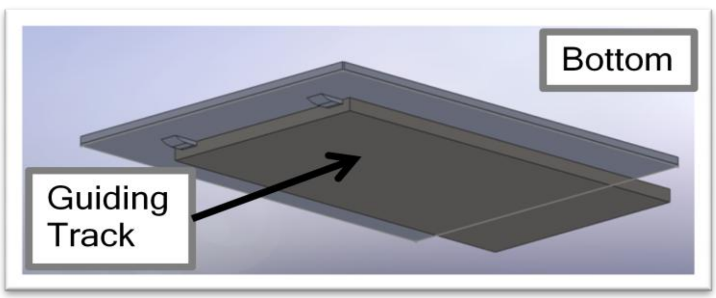

Figure 28: First tray design; bottom view

The second design was to use a thin piece of sheet metal (26 gauge steel) and bend it on opposite sides at 90 degrees. Then two slits would be cut on the bent sides and the existing feed roller in the printer would be placed through those slits. With the feed roller in place the tray could be guided as it o that the tray could be guided as it slid back and forth. This design is shown in Figure 29 and Figure 30.

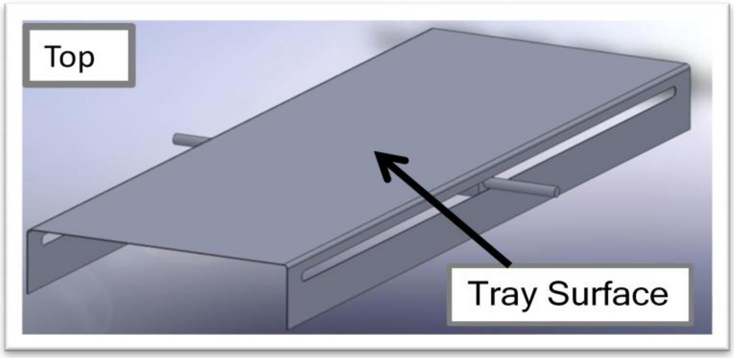

Figure 29: Second Tray design; 26 Gauge sheet metal glides over existing feed roller. Slots cut in each side for guidance.

This design was eventually replaced with the final design, because it was overlooked that there would not be enough clearance between the print head and the tray for it to be functional.

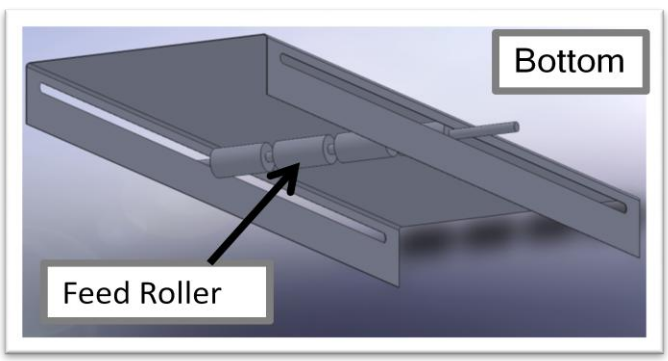

Figure 30: Second tray design; bottom view

4.1.2.2 Final Design

The final design was composed of a small (1.5” x 9”, 3 Gauge) metal plate, originally designed as a strap for support in wooden structures, as the surface of the tray. Thin strips were then cut from rubber door molding, and glued to the bottom of the tray surface. This was to increase friction between the printers feed roller and the tray, reducing slip. A quantity of four 1” cart wheels were used to hold the tray upright as it passed over the feed roller. All of these items were purchased from the Home Depot. This design is shown in Figure 31 and Figure 32.

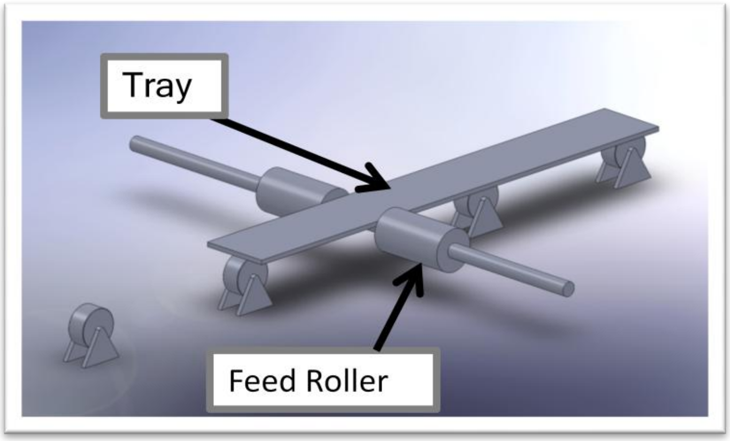

Figure 31: Final tray Design; CAD drawing

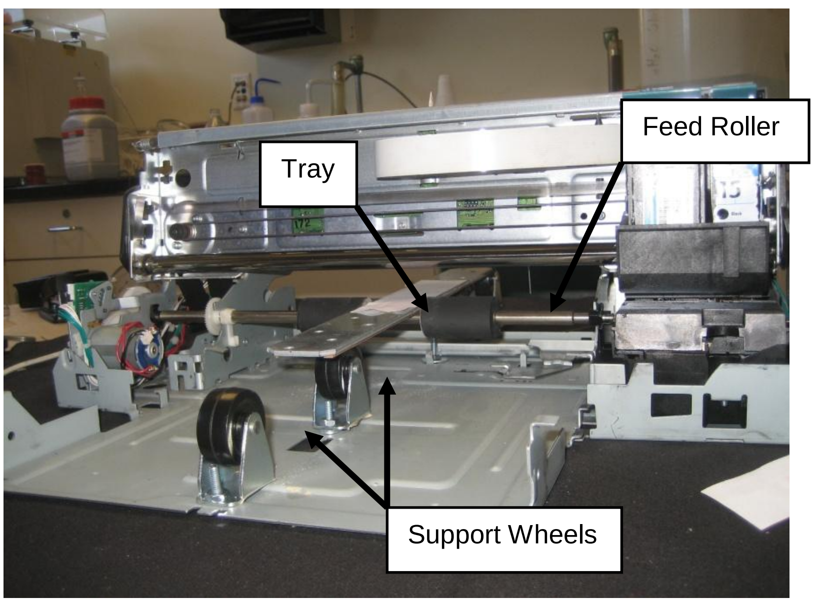

Figure 32: Final tray design; front of printer

4.1.2.2.1 Computer Output Modification

The final design that was chosen needs the tray to rest on the feed roller axle (between the rubber rollers), rather than on the rubber roller themselves. This will create a problem when printing a desired image, because the roller axel is much smaller in diameter than the rubber rollers. In other words, when the printer receives a command from a program, such as Microsoft

Word, to print a single page, the printer will feed what it believes to be 11” of paper, based on the diameter of the rubber roller. Since we are decreasing that diameter, the image will become “squished”, as the paper moves less distance beneath the print head. Therefore, it is necessary to change the output from the computer, so that the final image is normalized. To do this, the original diameter of the rollers was measured and compared to the new diameter. The ratio of the two diameters then determined the percentage that the image would need to be “stretched” in the printing program, to compensate for the “squeezing” that occurs. The calculations for this modification are shown below:

$$D = Rubber\ roller\ diameter = 0.953\ in$$

$$d = Roller\ axle\ diameter = 0.317\ in$$

$$r = \frac{D}{d} = 3.01$$

$$r * 100 \sim 300\%$$

Therefore, and image in the printing program (Microsoft Word) must be stretched 300% to be printed normally.

4.1.3 Feed Motor Modifications

For printing of multiple layers the tray must be fed back through the printer to its original starting position. To accomplish this it is necessary for the feed motor to reverse direction. The motor that this particular printer uses is a 24 Volt electric motor, Model HC385MG-001 manufactured by Johnson Electric [17]. To reverse the motor three 9 volt batteries were wired in series and connected directly to the poles of the motor. Also added was a push-button switch to manually control the timing of the motors reversal. This set-up is shown in Figure 33 and Figure 34. Figure 35 shows the circuit diagram detailing the motor assembly.

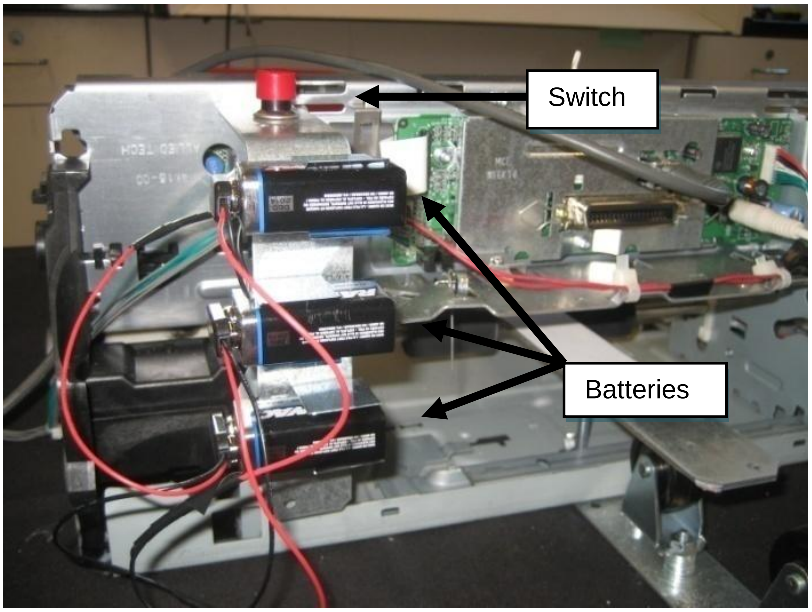

Figure 33: Rear of printer showing battery and switch assembly

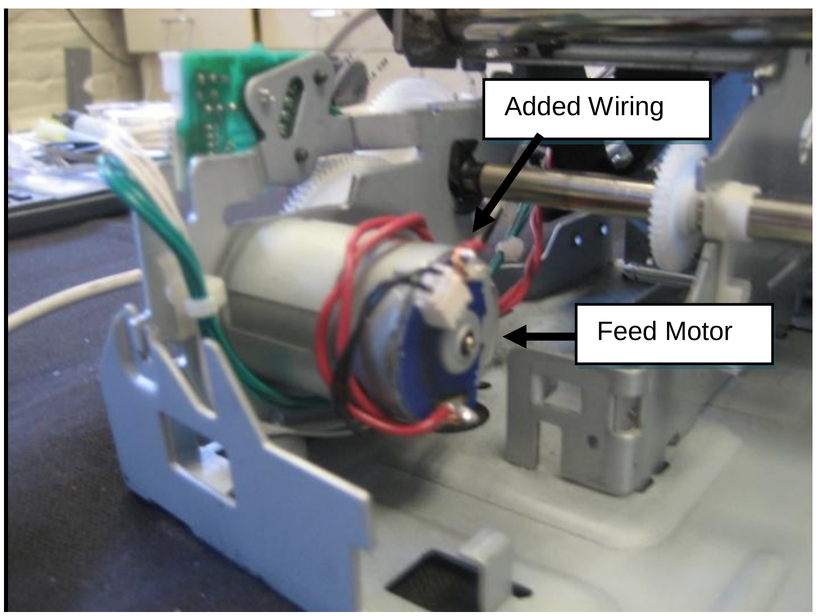

Figure 34: Front of printer showing feed motor and added wiring

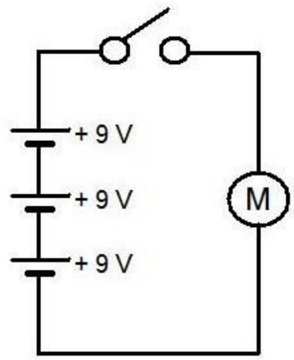

Figure 35: Circuit diagram for reversal of feed motor by overriding the printer commands

4.2 Polymer Solution

Based on the process described in the Methods section, a polymer solution composed of water, isopropyl alcohol, and PVP (M.W. 58,000 g/mol) was found with the appropriate concentrations of each ingredient that would work properly with the C6615 Series ink cartridge. A summary of the components and their concentrations in this polymer solution is shown in Table 3.

Table 3: Concentrations for specific ingredients for polymer solution; found experimentally

Experimental Polymer Solution		
Component/ substance	CAS number	% by weight
Water	7732-18-5	83
2-pyrrolidone (58,000 g/mol)	9003-39-8	13
Isopropyl alcohol	67-63-0	4

In addition to the components listed in Table 3, a small amount of red food dye and florescent ink were added to different batches of polymer solution, in an amount less than 0.01% by weight. This was done in order to get better visual results from the prints, as well as to demonstrate the ability of the polymer solution to accept additives. Two samples of polymer solutions (one with florescent ink and one with red food dye) and one sample of the original manufacturer's ink (extracted from the cartridge) were tested in a rheometer to compare their viscosities. The results, shown in Figure 36, revealed that each solution had very similar viscosity characteristics. The manufacturer's ink had the highest viscosity, at 236.49 cP. The viscosity of the florescent ink was 227.9 cP, and the red food dye ink had a viscosity of 223.37 cP. The data is shown in Table 4.

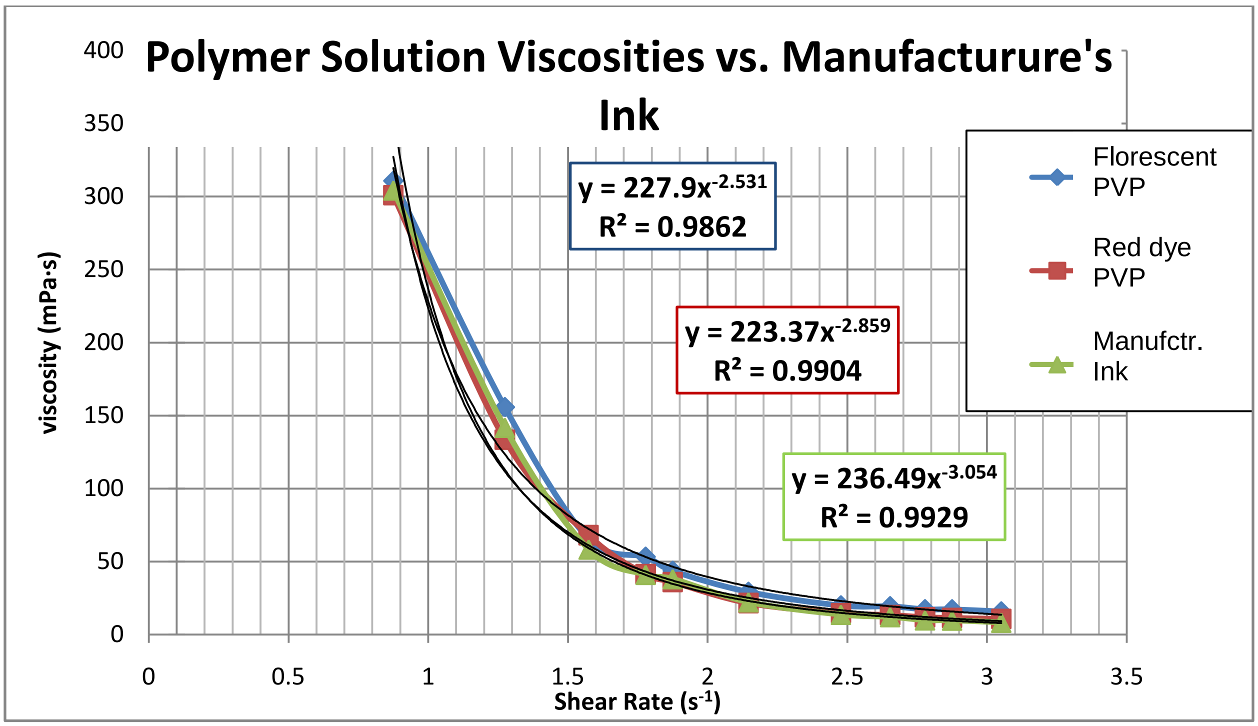

Figure 36: Viscosity measurements graph for polymer solutions versus manufacturer's ink

Table 4: Sample solution viscosity measurements

Solution	Viscosity (cp)
Polymer Solution with red food dye	223.37
Polymer Solution with florescent ink	227.9
Manufacturer's Ink	236.49

These polymer solutions were injected into multiple ink cartridges, and printed onto various substrates for testing. A summary of the results for the solutions when printed onto non-porous, semi-porous, and highly-porous substrates is illustrated in the following sections.

4.2.1 Non-porous Substrate

The first substrate that was tested was a transparency, and was considered to be non-porous. When printing on this type of substrate, the polymer tended to condense into small beads. Using Microsoft Word, multiple layers of a black rectangle (1” x 3”) were printed. An example of this rectangle used is shown in figure 37.

As the number of layers increased (from 1, 5, 10, and 15 layers), so did the size of the beads; each bead taking on a different shape as well. This phenomenon is shown in figure 38, figure 39, figure 40, and figure 41, at one (left) and (five) times magnification.

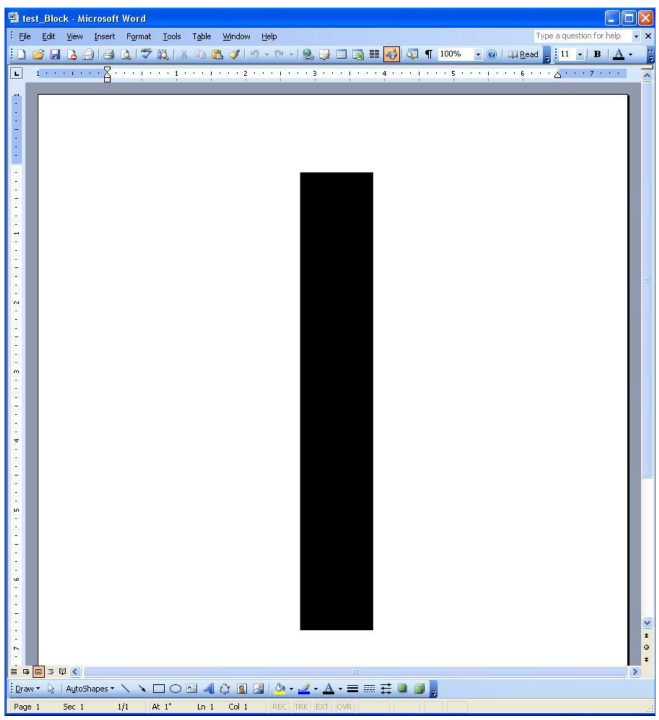

Figure 37: Rectangle made in Microsoft Word used for printing

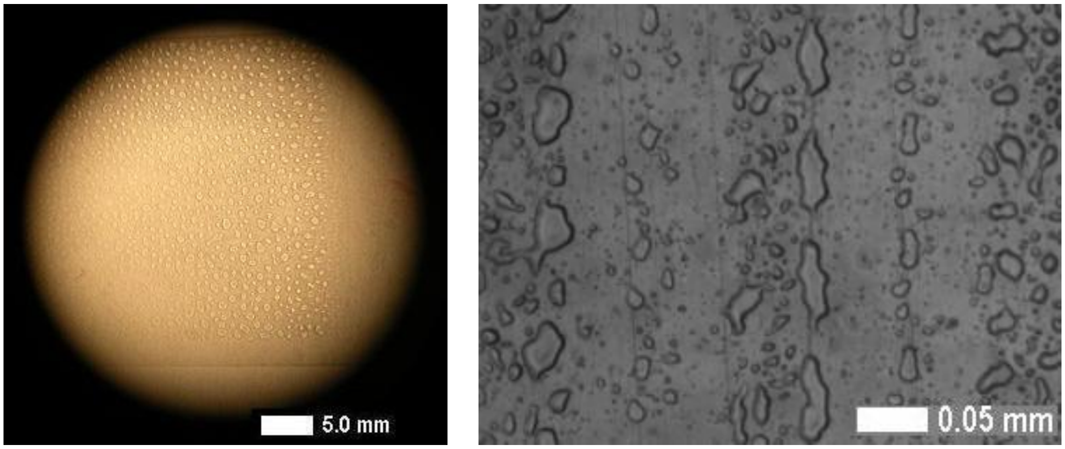

Figure 38: One layer of polymer solution printed onto a non-porous substrate

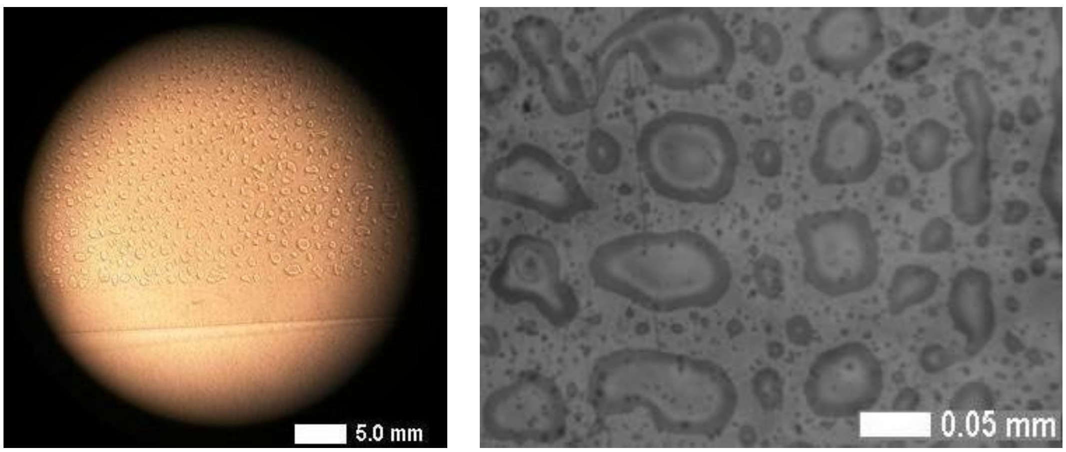

Figure 39: Five layers of polymer solution printed onto a non-porous substrate

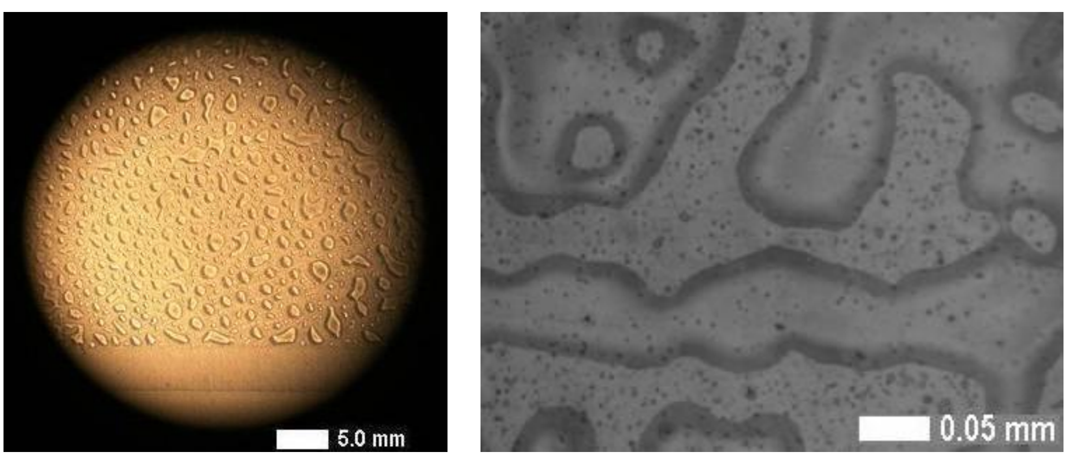

Figure 40: Ten layers of polymer solution printed onto a non-porous substrate

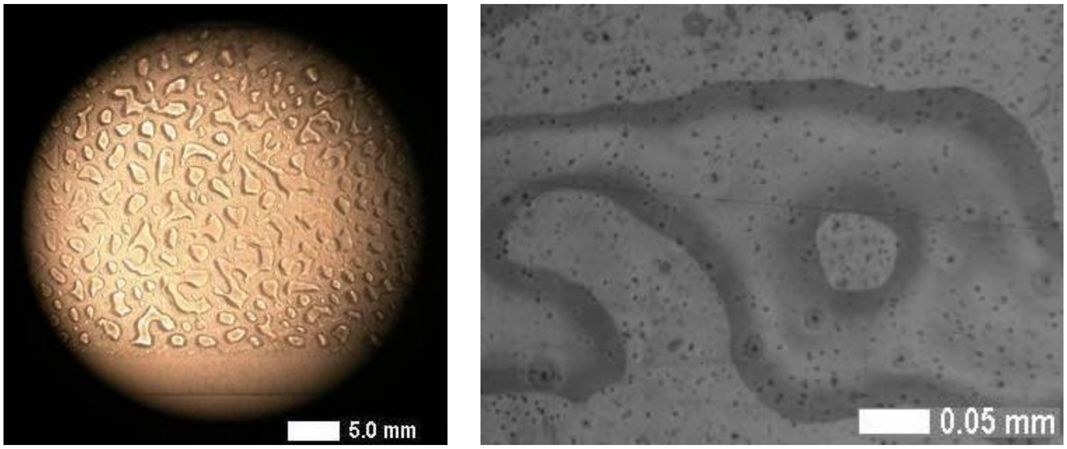

Figure 41: Fifteen layers of polymer solution printed onto a non-porous substrate

Although the polymer beads did not have a uniform shape, the placement of the beads was very accurate. Figure 37 shows the letter “P” printed onto the non-porous substrate. A small amount of red food dye (<0.01% by mass) was added to the solution to give the print color, and make it more visible to the naked eye.

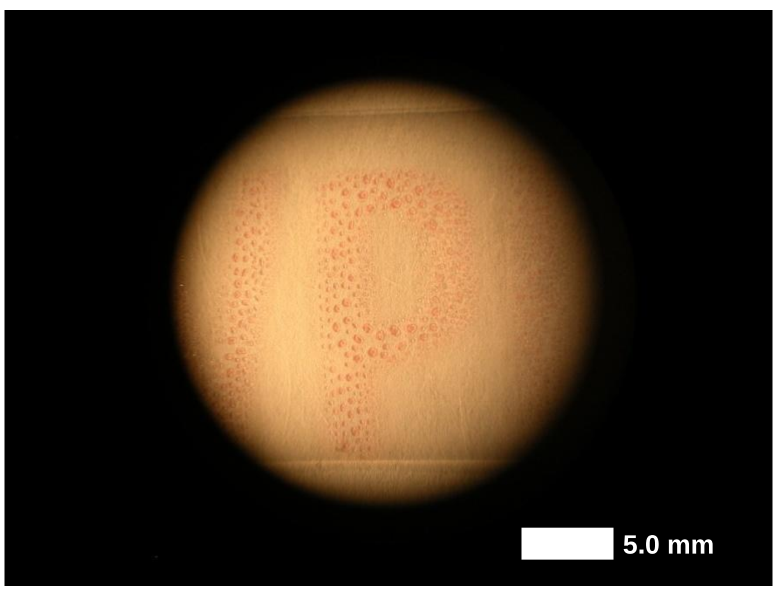

Figure 37: The letter "P" printed onto a non-porous substrate with a polymer solution containing red food dye

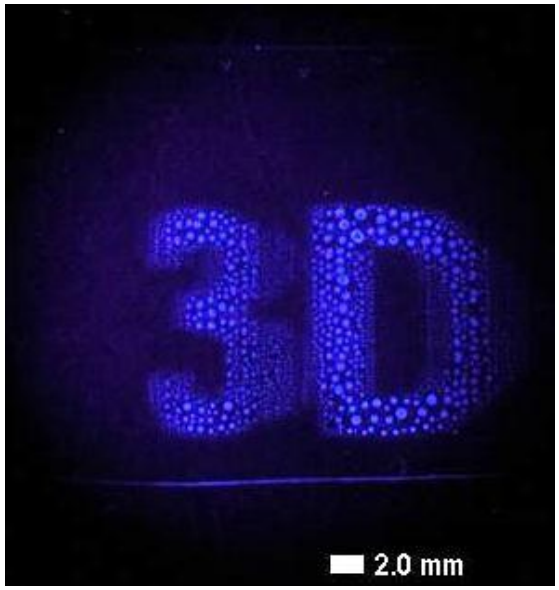

Figure 38: "3D" printed with polymer solution containing florescent ink

In Figure 38, the characters “3D” can be read as the solution reacts to an ultraviolet light source. This was done by adding a small amount (<0.01% by mass) of florescent ink to the polymer solution. Figure 39 is a magnified view of the “3”, first shown in Figure 38, in order to show the detail of the print.

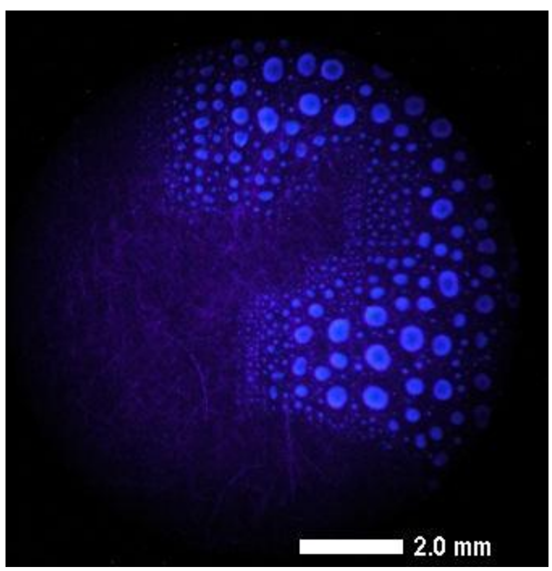

Figure 39: Close-up of the upper-left portion of the "3", printed with polymer solution containing florescent ink.

The Microsoft Word document to print the characters “3D” is shown in Figure 40, which was stretched 300% to adjust for the change in gear ratios resulting from the printer modifications.

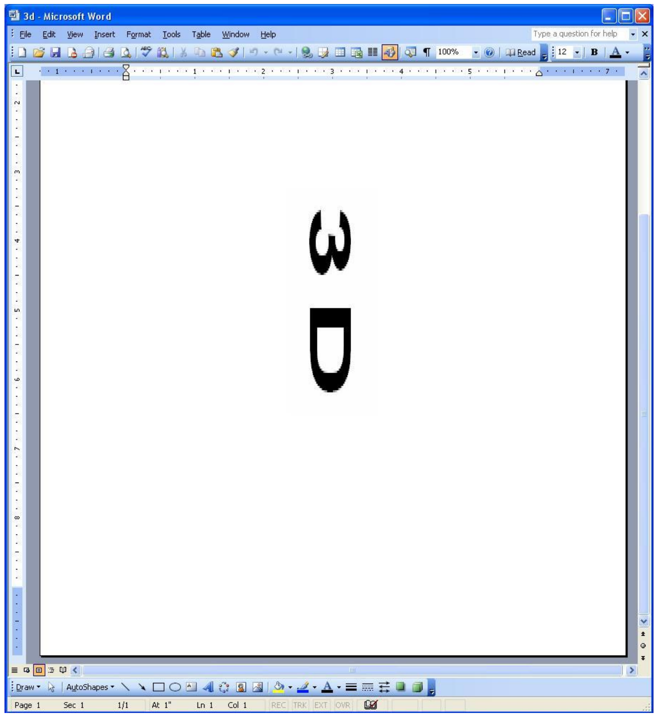

Figure 40: Word document used for printing "3D" (stretched 300%)

Another non-porous substrate that was tested was made from a polystyrene sheet, as seen in appendix A.

4.2.2 Semi-porous Substrate

The next substrate that was printed on was paper. This kind of substrate was considered to be semi-porous. To examine this substrate, and the polymer printed, the same methods as used on the non-porous substrate were used. However, as expected, the polymer did not form beads on the substrate; not even on the first layer. Red food dye was added to the solution (<0.01% by mass), in order to visually gauge a change otherwise unnoticeable by eye.

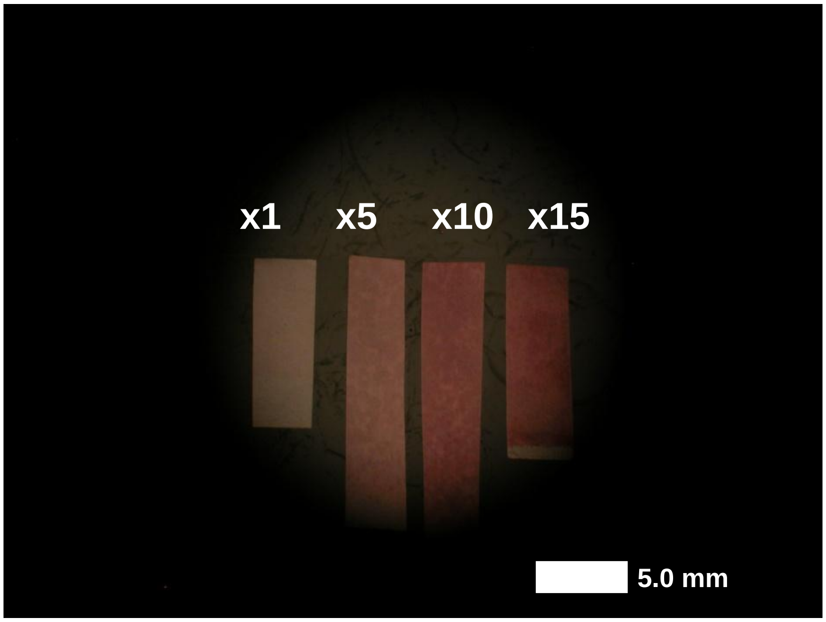

Figure 41: Successive layers of polymer solution with red food dye printed onto a semi-porous substrate (From left: 1, 5, 10, and 15 layer(s))

The effect of multiple layers did not produce a thicker object, but rather stiffened the paper as the solution soaked in (as well as produced a darker image). Also, each sample was weighed using an electronic scale. The mass results for each sample are shown in Figure 42.

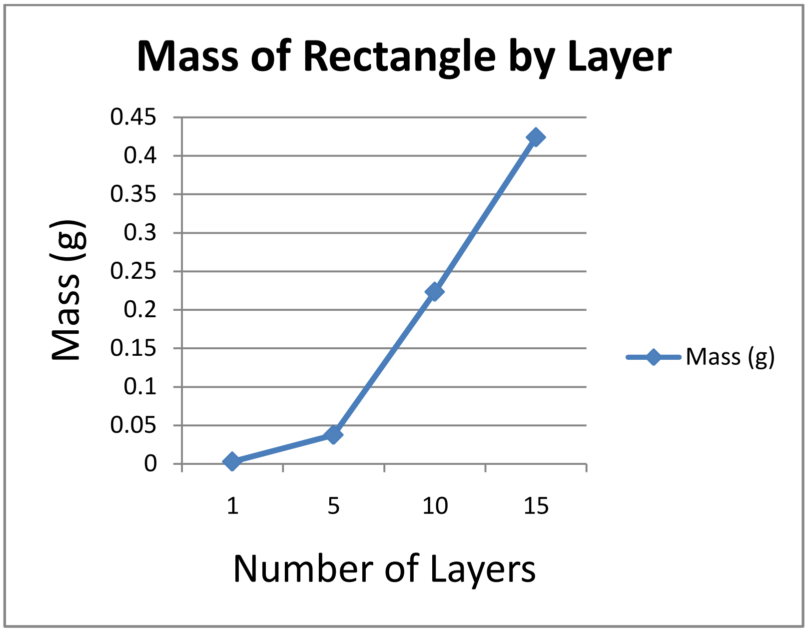

Figure 42: Graph of masses (g) for polymer layering of 1"x 3" rectangle

4.2.3 Highly-porous Substrate

A highly-porous substrate was created by laying out a smooth bed of PVP powder (58,000 g/mol) to create a surface. Then, that bed was transferred onto the substrate tray and the letters “WPI” were printed, using the polymer solution containing red food dye. The results were images of the three letters that could actually be taken off the substrate. It was determined that this occurred because the polymer solution being printed was acting as an adhesive, rather than a solvent, causing the powder that was directly printed on to stick together. An Image of this product is shown in Figure 43 and Figure 44.

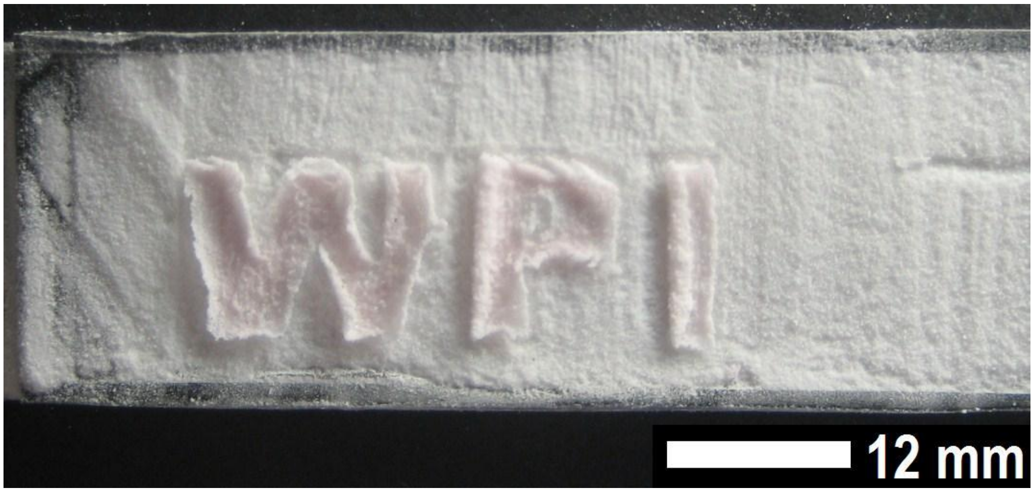

Figure 43: The letters "WPI" printed solution containing red food dye, onto a highly-porous substrate

Figure 44: The letters "WPI" individually taken from the substrate and placed on the laboratory table

These letters had a thickness of about 0.5 mm. After drying (all water and isopropyl alcohol evaporated), the letters were composed of 100% polymer, making them very brittle, and would crumble when touched.

5 Conclusions and Future Work

An HP-840C DeskJet was modified through a new feeding system which included a tray design. A simple circuit consisting of three 9V batteries and push switch button was wired to the existing motor to reverse the motor's direction manually on command. This modification allowed for the printing of multiple layers on the same substrate.

A polymer ink solution composed of PVP, isopropyl alcohol, and water was developed through various trials. The concentration of the final solution was selected based on its ability to flow through the ink cartridge nozzles. Through the design of a new paper feeding system combined with a simple circuit to manually reverse the tray, the polymer solution was deposited onto various substrates.

Non-porous substrates showed the uniform pattern of the droplets at 1 and 5 layers while surface tension joined multiple small droplets to form larger droplets at the 10 and 15 layers taking away from its uniformity. With the addition of red food coloring to the selected solution, layers on a semi-porous substrate were examined. As the number of layers increased the substrate became a darker shade of red showing the substrate was absorbing more polymer. On a highly porous substrate the polymer solution served as an adhesive to the PVP powder bed to create a tangible 3D object.

The ability to print multiple layers using this approach can be applied to various fields. In the area of drug delivery methods or food packing, additives can be combined with a polymer solution to print three dimensionally. These polymers can then control the release rate of the incorporated additive.

Future research for this project should focus on a lowering mechanism for the tray as well as a software approach of overriding the printer motor. A new polymer ink solution should be developed to reduce clogging of the nozzles. Clogging may also be prevented with the addition of a cleaning apparatus while the cartridge head is in the rest position. Experiments using different polymers as well as substrates should also be examined.

6 References

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7 Appendix A

To examine the mechanical properties of the polystyrene sheet developed a simple stress-strain analysis experiment was carried out. The polystyrene sheets were compared to plain printing paper sheets. Samples of both materials were cut to size according to the standard set out in the Handbook of Polymer Testing.

Once the samples were ready, a strain gage was adhered. Connections were then soldered to the strain gage and wired to a data acquisition (DAQ) board, Figure 45, and then to a DAQ system box to record the measurements in LabView.

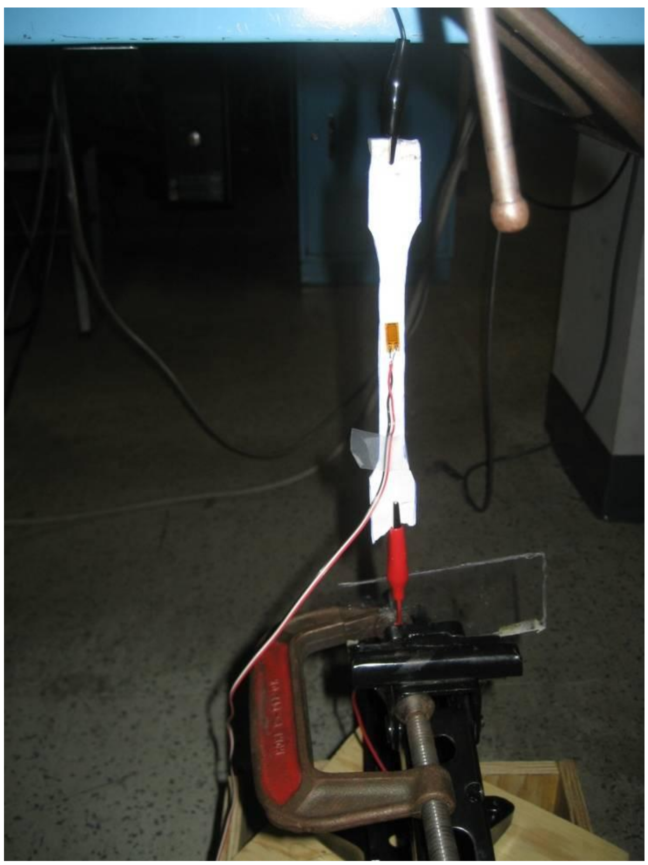
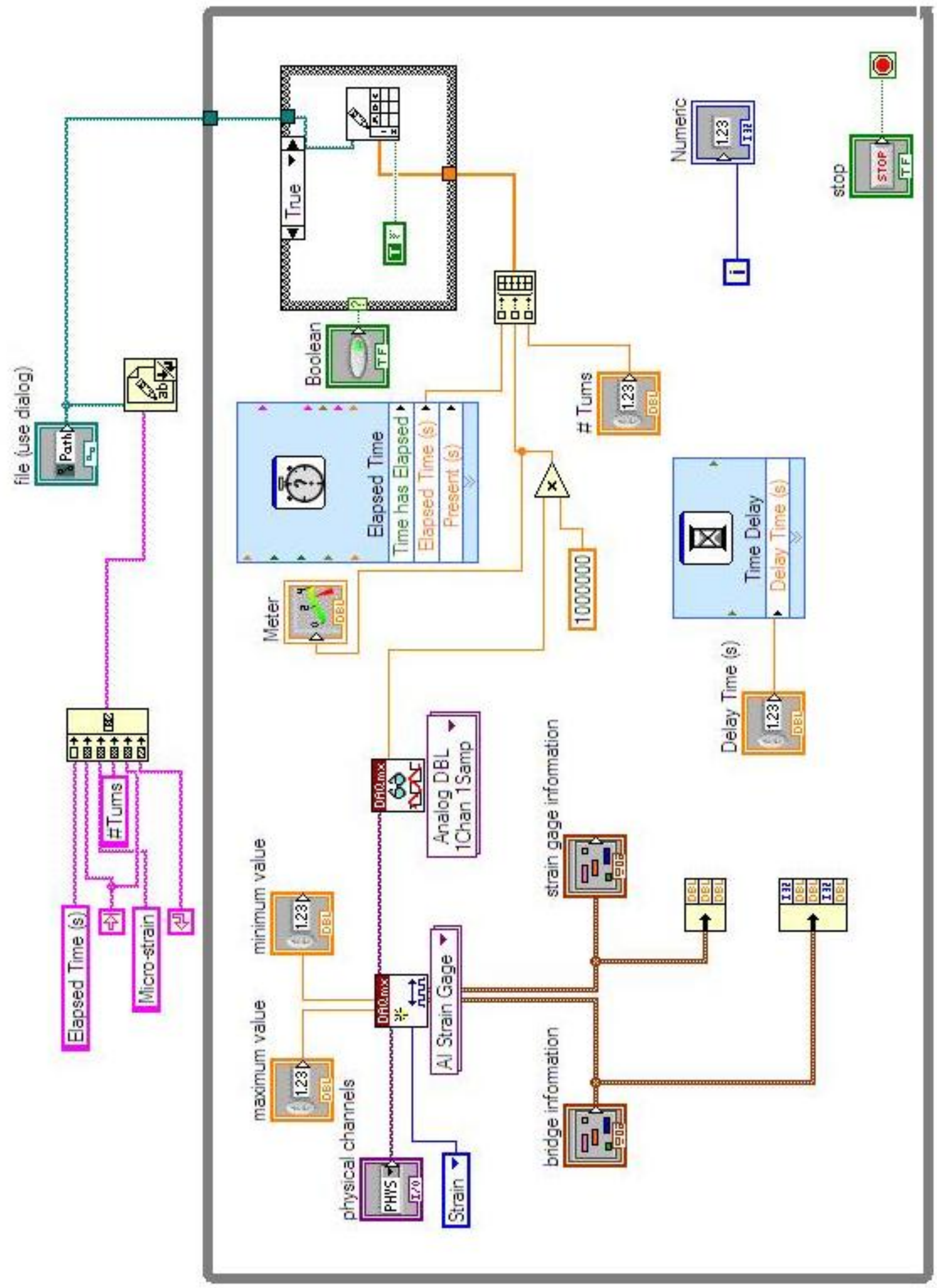


Figure 45: Setup of Micro-strain Experiment

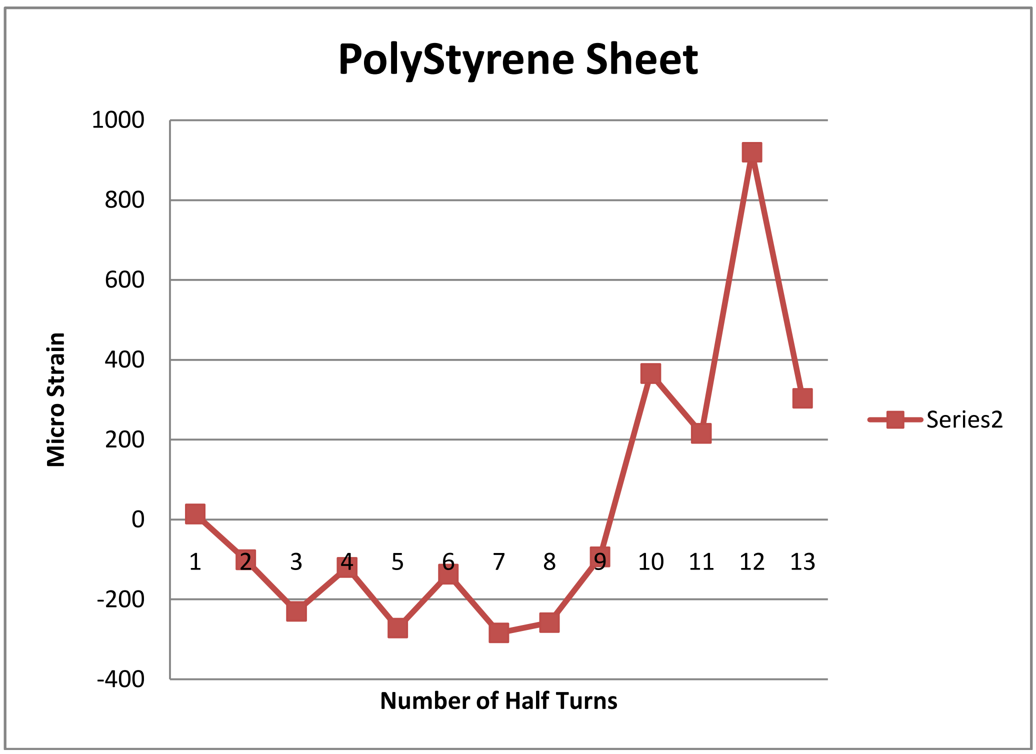
Data from testing the micro strain of paper and polystyrene sheets. The results show that the mechanical characteristics of the polymer sheet that was produced by solvent casting was similar to the polystyrene sheets tested.

Use of Lab View 8.5



Condensed Numerical data

Polystyrene	
Micro-strain	# of Turns
14.22745	0
-100.487	0.5
-229.51	1
-119.477	1.5
-271.471	2
-136.269	2.5
-283.189	3
-257.738	3.5
-93.2696	4
365.6202	4.5
215.822	5
919.113	5.5
303.7963	6



Paper	
Microstrain	# Turns
-51.4067778	0
194.9391698	0.5
545.8778182	1
191.2542718	1.5
240.3586108	2
674.0606667	2.5
298.4814388	3
227.3796482	3.5
303.3245397	4
836.1731467	4.5
915.3172128	5
93.50719782	5.5
-28	6
83.15227509	6.5
-34.33696	7