5-2016

Low-Cost Inkjet Process for 3-D Printing

Christopher T. Schmitt

University of Arkansas, Fayetteville

Follow this and additional works at: http://scholarworks.uark.edu/meeguht

Part of the Electro-Mechanical Systems Commons, and the Manufacturing Commons

Recommended Citation

http://scholarworks.uark.edu/meeguht/54

This Thesis is brought to you for free and open access by the Mechanical Engineering at ScholarWorks@UARK. It has been accepted for inclusion in Mechanical Engineering Undergraduate Honors Theses by an authorized administrator of ScholarWorks@UARK. For more information, please contact scholar@uark.edu, ccmiddle@uark.edu.
Low-Cost Inkjet Process for 3-D Printing

A thesis submitted in partial fulfillment
of the honors requirements for the degree of
Bachelor of Science in Mechanical Engineering

By

Christopher Thomas Schmitt

May 2016
University of Arkansas

Wenchao Zhou, Ph.D.
Thesis Advisor

Prof. David Albers
Committee Member
Abstract

This paper presents a low-cost 3-D inkjet process design. Current commercially available 3-D inkjet printers (e.g., Objet Connex) that are capable of multi-material printing are expensive and out-of-reach of most consumers. While fused deposition modeling and other extrusion-based hybrid processes for multi-material printing are becoming available, these techniques are slow and relatively low-resolution. This research attempts to fill the gap by presenting a simple and low-cost solution to bring desktop 3-D inkjet to the community by utilizing components from an Epson inkjet printer. The mechanical system was designed with maximum utilization of the Epson carriage system with the addition of a third axis. A 3rd party ink supply system was used in replacement of the standard ink cartridges and an integrated UV LED curing system was developed. Finally, a simple software control system was implemented using Arduino. Costs were managed by exploiting the original driver electronics, power supply, and X-stage motor and feedback mechanism.
Acknowledgements

First and foremost, I would like to thank Dr. Wenchao Zhou for introducing me to this exciting field of study. His dedication as a teacher and commitment to the project has helped and inspired me tremendously. Dr. Zhou’s team of undergraduate and graduate students at the AM³ lab has been a great work environment for advice, support, and comradery. Exposure to the many diverse projects at the lab has taught me immensely, as well as given me some great friends.

I would also like to thank Danny Mora for his assistance with mechanical design, and Garrett Urban for his experience with Arduino. Without them, and their many hours of help, this project would not be where it is today. Many thanks also go to Zachary Zelenka and Joe Moquin, for their electrical and software help, especially with regards to the UV LED modules and voltage divider. Their knowledge and consultation was extremely valuable to me.

Finally, many thanks to the Honors College (including Walton Family Foundation) and Arkansas Department of Higher Education for their generous scholarships. The Fellowship and Governor’s Scholarship have made it possible for me to focus on my studies without any financial burden. It has been both an honor and a humbling experience to live and learn here at the University of Arkansas.
# Contents

Abstract............................................................................................................................................. ii
Acknowledgements.......................................................................................................................... iii
Figures ............................................................................................................................................... v
Tables............................................................................................................................................... vii

## Chapter 1. Introduction.................................................................................................................... 1
   1.1 Background of Additive Manufacturing .............................................................................. 1
   1.2 Current Capabilities .............................................................................................................. 3
   1.3 Open Source Revolution ...................................................................................................... 4
   1.4 Motivation for Study ............................................................................................................ 6

## Chapter 2. Design Overview........................................................................................................... 9
   2.1 Epson’s System ..................................................................................................................... 10
      2.1.1 WF30 Specifications ..................................................................................................... 10
      2.1.2 WF30 Mechanical System ......................................................................................... 11
      2.1.3 WF30 Electrical System & Print Head ....................................................................... 14
   2.2 Mechanical System ............................................................................................................. 18
      2.2.1 X-Y Stage .................................................................................................................... 18
      2.2.2 Z-stage ....................................................................................................................... 21
      2.2.3 Mechanical Endstops ............................................................................................... 23
   2.2.4 Ink Supply System ......................................................................................................... 24
   2.3 Electrical System ................................................................................................................ 25
      2.3.1 Arduino MEGA 2560 & RAMPS 1.4 ......................................................................... 26
      2.3.2 Voltage Divider .......................................................................................................... 26
      2.3.3 Photo-curing System ............................................................................................... 30
   2.4 Software .............................................................................................................................. 33

## Chapter 3. Results & Discussion.................................................................................................. 35
   3.1 Results .................................................................................................................................. 35
   3.2 Discussion ............................................................................................................................ 38

## Chapter 4. Conclusion & Future Work......................................................................................... 39
   4.1 Conclusion ........................................................................................................................... 39
   4.2 Future Work ......................................................................................................................... 40

## Appendix A. Software Code ......................................................................................................... 42

## Appendix B. Optocoupler Circuit Design ................................................................................... 43

## References ...................................................................................................................................... 44
Figures

Figure 1-1. CAD model of teapot, showing smooth surface features [2].........................................................2

Figure 1-2. Teapot printed using Stratasys uPrint SE Plus, showing horizontal layering.........................3

Figure 1-3. Helmets printed using Connex3 in full-color photopolymer material [6]..............................4

Figure 1-4. Tower of Pisa, printed on Ultimaker 2, surface artifacts exist on tower’s loggia.................5

Figure 1-5. Piezoelectric Inkjet, PZT represented in red [14].................................................................7

Figure 1-6. Thermal Inkjet, heater represented in red [14].................................................................7

Figure 2-1. WF30 print head nozzle layout [20]..................................................................................11

Figure 2-2. WF30 printer mechanism diagram [20]............................................................................12

Figure 2-3. WF30 Waste Ink System [20]............................................................................................13

Figure 2-4. WF30 main board..............................................................................................................14

Figure 2-5. Print head assembly – Nozzle Plate (top), CN5 & CN7 connectors (bottom right)....15

Figure 2-6. Analog Drive Waveform of WF30 [19]..................................................15

Figure 2-7. CN5 Circuit snippet, CHA and CHB may be located [23]..............................................16

Figure 2-8. CN7 Circuit snippet, LAT, NCHG, SI1, SI2, and SI3 may be located [23]....................17

Figure 2-9. Motors and sensors in WF30 [20] ....................................................................................17

Figure 2-10. Epson “main frame assembly” (upside down), used as X-stage [20].............................18

Figure 2-11. Carriage mounts left and right, designed with the freedom of AM..............................19

Figure 2-12. X-Y stage assembled, NEMA 17 motor and drive shaft (bottom right)......................20

Figure 2-13. Carriage mount (left) connected to timing belt on its underside...............................21

Figure 2-14. Z-stage design: base mount (in red), build plate frame (in blue)...............................21

Figure 2-15. Z-stage installed into printer..........................................................................................22
Figure 2-16. X-Y-Z stages of printer with build plate.................................................................23

Figure 2-17. Mechanical Endstop................................................................................................23

Figure 2-18. Epson CISS, supply lines exit the top of the cartridge top units (left) to a major reservoir for extended printing sessions (right) .................................................................25

Figure 2-19. PF motor signal reading from oscilloscope..............................................................27

Figure 2-20. Voltage Divider Circuit Diagram...............................................................................28

Figure 2-21. Voltage divider into side of RAMPS – black (GND), yellow (A10) .........................29

Figure 2-22. Voltage divider breadboard configuration..................................................................29

Figure 2-23. Left: UV photo-curing circuit, Right: lumped element model [24] .........................30

Figure 2-24. Breadboard test of UV photo-curing circuit [24] .....................................................31

Figure 2-25. UV LED PCB design [24] .......................................................................................32

Figure 2-26. UV LED mount design..........................................................................................32

Figure 2-27. UV LED mounts installed.......................................................................................32

Figure 2-28. UV LED on print head...........................................................................................32

Figure 3-1. Nozzle check pattern printed....................................................................................36

Figure 3-2. Nozzle check pattern, according to Epson [20] ........................................................36

Figure 3-3. Rectangle printed......................................................................................................37

Figure B-1. Proposed twin optocoupler design for isolating Epson/Arduino circuits.................43
Tables

Table 2-1. Arduino Analog Signal Pins for RAMPS Endstops

24
Chapter One.

Introduction

1.1 Background of Additive Manufacturing

Commonly known as 3D printing, additive manufacturing (AM) is a process that has become increasingly popular in the recent years. Its capability to turn a computerized virtual model into existence with relative speed and ease is revolutionary. There are a wide range of AM techniques available, including stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), and inkjet (binder jetting or material jetting), to name a few. AM processes share the similarity that they are layer-based manufacturing methods, in which three-dimensional parts are built through the sequential deposition of two-dimensional layers of material. These layers are literally cross-sections of the final part – and as layers become increasingly thin, the 3-D print will appear to more closely represent the original computer aided design (CAD) model (Figure 1-1). The final physical part (Figure 1-2) can thus be considered an approximation of the initial virtual data [1].
There are numerous benefits to 3D printing that make it an attractive tool for designers. AM’s layer-based approach allows for the creation of complex geometries that would otherwise be impossible or very difficult and time-consuming using traditional subtractive manufacturing approaches. Also, AM is a digital fabrication process, meaning exceedingly customized parts could be manufactured relatively economically, in a highly automated environment. Additionally, AM has the capability for rapid prototyping – designers can prototype and redesign with enhanced speed and freedom. Finally, AM has the potential to allow anyone to design, build, and create – consolidating what used to be the need for a large workspace and a wide variety of tools into a single instrument that can become an intuitive extension of the imagination.
1.2 Current Capabilities

Since the invention of the first commercial SLA machine in 1986 by Chuck Hull (who went on to found 3DSystems) [3], current capabilities of rapid prototyping has increased tremendously. From improvements in speed, build volume, cost, materials and part strength, AM machine are starting to close the gap with traditional methods, such as injection molding, in terms of final part accuracy, quality, and end-usability. Direct Metal Printing (DMP) is a technology that allows one to create metal and ceramic parts – that has proved useful in the medical, dental, and aerospace industries [4-5].

The Objet Connex series by Stratasys are currently the only printers on the market capable of multiple material printing in high-resolution. In addition, these printers can print in multiple colors simultaneously. A sample print from a Connex3 is shown below in Figure 1-3.
Build resolution of an Objet 500 Connex3, the series flagship, for example, is 600 DPI in the X- and Y-axes and 1600 DPI in the Z-axis. Layer thickness is down to 16-micron resolution, for smooth surface features and minimal artifacts. Using *inkjet* print heads, the printer is capable of using a wide variety of materials with properties that are rigid, flexible, thermal resistant, and even translucent [7]. A preventative price tag of over a quarter-million USD, however, limits this powerful technology from many potential consumers [8].

### 1.3 Open Source Revolution

Previously, 3D printing has been largely confined to businesses, research institutions, and design professionals. Recently, however, the market for consumer-levels printers has grown considerably with the help of a strong open-source community. The RepRap printer is an open-source community project that is dedicated to the development of a low-cost self-replicating printer [9]. Here, enthusiasts can communicate, post instructions, and offer improvements on printer designs. Primarily FDM printer information is found on the RepRap site, due to the technology’s inherent simplicity and low-cost. MakerBot (now
acquired by Stratasys) spawned from the RepRap project, and is focused on producing low-cost FDM printers. The MakerBot Replicator printer uses a 0.4mm nozzle with 100-micron layer resolution at a cost of USD$2899 [10]. The MakerBot, and other similar FDM printers such as Ultimaker, are optimized for depositing polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). These thermoplastics are easy to extrude, are available in a wide variety of colors, and are relatively inexpensive. Figure 1-4 shows the capability of an Ultimaker 2 FDM printer.

![Image of Tower of Pisa printed on Ultimaker 2]

*Figure 1-4. Tower of Pisa, printed on Ultimaker 2, surface artifacts exist on tower's loggia*

However, unlike their more expensive counterparts, these printers are not capable of multi-material printing. A printer called the Fab@Home was created to address this issue. Like RepRap, Fab@Home is also entirely open-source, and was the first multi-material printer
available [11]. This project has since seemed to have fallen by the wayside, as their website is no longer in service [12].

1.4 Motivation for Study

The ultimate goal is to make the 3-D printer as simple-to-use and commonplace as an appliance. Therefore, it needs to be affordable to everyone, while still maintaining a level of performance and precision that rivals the expensive industrial printers of today. Low-cost FDM printers are widely available, however FDM performance is inherently slow because it “requires material to be plotted in a point-wise, vector fashion that involves many changes in direction” [1]. A solution, then, is to use inkjet technology, particularly drop-on-demand (DOD) inkjet technology, because it is fast, capable of multi-material, and high-resolution.

The two most common types of inkjet technology available are piezoelectric inkjet and thermal inkjet (also known as bubble jet). In a piezoelectric inkjet print head, the piezoelectric element sits atop a thin diaphragm that is positioned above the nozzle. One of the most common piezoelectric materials is lead zirconate titanate (PZT), a man-made ceramic. Its efficiency in reception and transmission makes it an ideal material for transducers, converting an electrical signal into mechanical vibrations [13]. In an inkjet print head, a voltage is applied to the PZT, causing the diaphragm to bend upwards, drawing in ink from a reservoir located above the mechanism. Subsequently, an opposite voltage is applied, causing the diaphragm to invert rapidly, expelling a single droplet of ink [14], as illustrated in Figure 1-5.
A thermal inkjet print head shares similar ink plumbing, however a small heating element sits in place of the PZT, as shown in Figure 1-6. This heater (essentially a power resistor), vaporizes the ink generating a pressure increase, thus causing a droplet to be ejected [15].

The issue with this thermal inkjet process is that the heaters have a short lifetime, due the high electrical currents necessary to run the heating elements [14, 16]. Manufacturers try to solve this issue by packaging the print head as part of the cartridge, in order to ensure that it is replaced regularly. An additional issue is that thermal inkjet can’t be used with heat-sensitive materials [14]. The thermal inkjet process can be found in nearly all consumer-
level desktop office (2-D) printers from companies like Hewlett-Packard, Lexmark, and Canon. The exception is Epson.

Epson first introduced their "Micro Piezo" technology in the early 1990s [17]. The piezoelectric inkjet process does not alter the chemical composition of the jetted material and has the ability to be finely tuned in order to produce adequate pressure for droplet generation [15]. Additionally, PZT print heads have a low operating temperature, increasing reliability and allowing for the print head to be integrated into the machine [14]. Epson has used this technology in their entire lineup of desktop office printers since 1993 with the release of the Epson Stylus 800 [17]. Utilizing the print head and components in these relatively inexpensive machines, one could build a 3-D inkjet printer at a fraction of the price of current offerings. This paper presents a low-cost inkjet process for additive manufacturing, part of a larger and ongoing effort to eventually bring the desktop 3-D printer to more homes around the world.
Chapter Two.

Design Overview

To create something that creates is an exceptional task. In order to make the 3-D printer like an appliance, it should be simple to use and unobtrusive in the user’s life – subtle and overt. Furthermore, to develop a product for the mass-market presents a significant challenge because it must be desirable and affordable. Therefore, maximum utilization of off-the-shelf components is crucial in order to manage costs. The printer was made with this design philosophy in mind. Parts such as the print head, driver electronics, power supply, and X-stage motor and feedback mechanism were all sourced from an Epson printer and are discussed in Section 2.1. Section 2.2 details the mechanical system that was built around these components, providing three axes of motion, as well as an ink supply system for the print head. Section 2.3 presents the open-source Arduino platform that was chosen for controlling the stepper motors, the voltage divider for reading Epson’s signals, and the integrated photo-curing system. Finally, Section 2.4 outlines the software ideology, as well as some basic calculations for keeping the X- and Y-stage in sync using Arduino. Arduino’s vibrant community of users, especially amongst “RepRappers”, made it an ideal platform for this
This project may very well be the first inkjet RepRap incorporating a Micro Piezo print head [18].

2.1 Epson’s System

The desktop inkjet printer chosen for this project was the Epson WorkForce 30 (WF30). The relatively large amount of information available on this printer was the main reason for choosing this model at the time. A similar project, the MultiFab, conducted at the Massachusetts Institute of Technology, used the WF30 print head because of its high performance and low cost [19]. In addition, a service manual was obtained for the WF30, aiding substantially in the understanding of the printer’s mechanical and electrical systems.

2.1.1 WF30 Specifications

The WF30 uses drop-on-demand piezoelectric ink jet technology developed by Epson. The print head is Epson’s F3-3 Mach Turbo II, containing 540 nozzles, divided into 3 rows of 180 nozzles each. The print head accepts 5 ink cartridges: cyan, magenta, yellow, and two cartridges of black (CMYK). The first and second row are both devoted to black, while the third row is subdivided equally into 3 nozzle banks for cyan, magenta, and yellow (60 nozzles each), shown in Figure 2-1 [20]. The print head can eject droplets of 6 pl, 13 pl, or 26 pl of color ink and 13 pl or 26 pl droplets of black ink [21].
2.1.2 WF30 Mechanical System

The WF30 shares the same printer mechanism with the Epson Stylus C110, C120, D120, Office B30, T30, T33, and ME Office 70 [20]. The printer may be divided up into the print head, carriage mechanism, paper loading mechanism, paper feed mechanism, and ink system, as shown in Figure 2-2.

Figure 2-1. WF30 print head nozzle layout [20]
Similar to most 2-D printers, the carriage unit with print head traverses along a metal main frame assembly, driven by a timing belt and DC motor (CR motor). In the transverse direction, paper feeds in through a series of rollers, driven by another DC motor (PF motor). During the printer initialization sequence, nozzle priming, and after printing completes, the carriage unit travels back to its “home position” above the waste ink system. This is where it is stored when the printer is off. The waste ink system (Figure 2-3) contains a deployable wiper, rubber cap, pump, and waste ink chamber.
This system is surprisingly intricate. As the carriage unit travels back to the waste ink system, the PF motor reverses direction, causing the wiper to raise by a cam. This rubber wiper, essentially a squeegee, cleans the nozzle plate of residual ink. When the carriage reaches the end of its travel, it bumps the cap slider, thus pulling the rubber cap up into the nozzle plate, forming a seal. The PF motor then spins in a rapid state, driving the pump unit, which removes any waste ink through a mesh screen in the cap and into a reservoir underneath. This act of drawing ink from the channels and applying suction to the nozzle plate helps to mitigate the PZT print head susceptibility to entrapped air [22]. Finally, the carriage lock lever raises, securing the carriage in its home position. This means that the PF motor serves two functions – to feed paper past the print head and to drive the waste ink system via a clever clutch mechanism.
2.1.3 WF30 Electrical System & Print Head

The main circuit board of the WF30 (Figure 2-4) is where the analog drive waveform for the PZTs is created, printer interfaces with the PC, and is the central hub for all of the printer's electrical components.

![WF30 main board](image)

Figure 2-4. WF30 main board

The main ribbon cables CN6, CN7, and CN5 (each with 17, 17, and 18 leads, respectively) connect the main board to the carriage unit, with CN5 and CN7 connecting directly to the print head (Figure 2-5). CN6 splits at the carriage unit and goes to the CR Scale (optical sensor for X-stage feedback) and the Head FFC Connector for reading the ink cartridges. Other important nomenclature on the main board: CN8 connects to CR motor, CN9 to PF motor, CN10 to PF encoder sensor, and CN3 to paper empty (PE) sensor.
The print head utilizes a trapezoidal analog waveform for driving the PZTs and a series of digital signals for nozzle selection and droplet size. One period of the analog waveform (Figure 2-6) contains four sub-waveforms. Combinations of these sub-waveforms results in the three droplet sizes possible: 6, 13, and 26 pl [19].

Figure 2-6. Analog Drive Waveform of WF30 [19]
In order to control printing, there are eight digital signals: NCHG, LAT, CHA, CHB, SI1, SI2, SI3, and CK. Their corresponding pins on CN5 and CN7 may be seen in Figures 2-7 and 2-8, respectively. NCHG determines whether the analog waveform activated the ink chambers. CHA, CHB, and LAT show the start of a sub-waveform. SI1, SI2, and SI3 are responsible for specifying drop size. Finally, CK is the signal of the clock [19]. This information about Epson’s electrical signals was sourced from Joyce G. Kwan.

Figure 2-7. CN5 Circuit snippet, CHA and CHB may be located [23]
The WF30 is powered by a 42VDC power supply. The high voltage is necessary for driving the PZTs. As mentioned briefly in section 2.1.2, there are two 42V DC motors: the CR and PF motor. The CR motor has a photo interrupter sensor with a resolution of 180 pulse/inch [20] for use as a feedback mechanism on the carriage unit’s whereabouts. Similarly, the PF motor has a rotary photo interrupter sensor for tracking motor movement. The paper empty (PE) sensor is another photo interrupter for detecting the top and bottom edge of sheets of paper. These components are pointed out in Figure 2-9.
2.2 Mechanical System

The idea was for maximum utilization of the Epson components in order to minimize costs. The entire “main frame assembly”, containing the carriage unit with print head, CR motor, and CR Encoder Sensor was taken from the Epson printer. In addition, the power supply and main board unit were utilized. The 3-D printer was designed according to a Cartesian coordinate system, with the three axes situated perpendicular to one another.

2.2.1 X-Y Stage

In Epson’s system, the printing surface is fed under the fixed print carriage. Conversely, for this 3-D printer, the print carriage should instead be moved over the fixed printing surface (build plate). With this idea of relative motion in mind, the entire main frame assembly was lifted from the Epson printer. It was unmodified with the intention that it would be the ideal X-stage, since motor and feedback mechanism were already integrated (CR motor and CR Scale, respectively). The main frame may be seen in the Figure 2-10 (CR motor and CR Scale removed).

Figure 2-10. Epson “main frame assembly” (upside down), used as X-stage [20]
The main frame (hereinafter referred to as the carriage) assembly is made out of sheet-metal, thus subject to flex, as it was clearly not intended by Epson to be moved about. Several iterations of 3-D printed carriage mounts (Figure 2-11) were created so that the carriage assembly could slide transversely along some smooth rod in the Y-direction using press-fit bearings. These brackets take on somewhat odd shapes in order to integrate with the carriage assembly and as well as reduce flex and distribute load via four linear bearings (two per mount).

![Carriage mounts left and right](image)

*Figure 2-11. Carriage mounts left and right, designed with the freedom of AM*

Belt connection points were positioned on the bottom side of both of the carriage mounts. Since the carriage assembly is relatively heavy, driving it from both sides was
necessary. Commonly found in RepRap printers, GT2 pulleys and timing belts were used to create the Y-stage, driven by a NEMA 17 stepper motor. Figure 2-12 shows the fully assembled X-Y stage.

![Figure 2-12. X-Y stage assembled, NEMA 17 motor and drive shaft (bottom right)](image)

The NEMA 17 stepper motor connects to a drive shaft via a short closed-loop timing belt. The drive shaft then connects to the underside of both carriage mounts (Figure 2-13) via timing belt, thus powering the carriage from both ends. This design results in smooth Y-stage travel.
2.2.2 Z-stage

The Z-stage was inspired by the cantilevered Ultimaker 2 design. It is completely decoupled from the X-Y stage (Figure 2-14). This allows for some freedom in its placement underneath the X-Y stage, as well as an ability to be utilized in future 3-D printer designs.

A base mount for the Z stepper motor was 3-D printed that supports two smooth rods. The base mount attaches to a base plate of medium-density fiberboard (MDF) by 4 screws, one
at each corner. The motor was directly connected to a lead screw via a segment of vinyl tubing. In order to keep costs down, the X-Y stage was mounted above the Z-stage using 2 in. x 4 in. lumber. The entire assembly was then mounted to a MDF base plate. The printer assembly can be seen below in Figure 2-15. An 8 in. x 8 in. MDF build plate (Figure 2-16) sits atop the build plate frame (in blue). As the X-Y stage travels over the build plate, the Z-stage drops down layer-by-layer.

Figure 2-15. Z-stage installed into printer
2.2.3 Mechanical Endstops

Basic mechanical switches were fitted at each end of the Y-stage motion, as a preventative safety stop mechanism to prevent the motor from burning out in the event the carriage assembly over-travels (Figure 2-17).
These mechanical endstops were packaged with the RAMPS 1.4 and are commonly found on most RepRap printers. The endstops have three pins: S (signal), + (positive), and – (ground). The + pin accepts 5V from the Arduino. The S pin outputs 0V (low) or 5V (high) if triggered. RAMPS 1.4 makes connecting endstops easy by providing S, +, and – male connector pins on the board. For reference, Table 2-1 lists the analog pins on Arduino that RAMPS uses. For purposes of this project, only two endstops for \( Y_{\text{min}} \) and \( Y_{\text{max}} \) were utilized.

<table>
<thead>
<tr>
<th>Arduino Pin</th>
<th>( X_{\text{min}} )</th>
<th>( X_{\text{max}} )</th>
<th>( Y_{\text{min}} )</th>
<th>( Y_{\text{max}} )</th>
<th>( Z_{\text{min}} )</th>
<th>( Z_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Pin</td>
<td>3</td>
<td>2</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>19</td>
</tr>
</tbody>
</table>

### 2.2.4 Ink Supply System

A 3\textsuperscript{rd} party Continuous Ink Supply System (CISS) was obtained. The CISS effectively tricks the Epson into thinking it is a genuine cartridge by using the same cartridge contact modules of a genuine cartridge. It replaces the individual cyan, magenta, yellow, and two black cartridges with an entire packaged unit. The CISS has a much larger ink reservoir than a standard cartridge – supply lines extend from the tops of the cartridge sub-units to a major reservoir. The major reservoir is easy to fill with different inks/materials (Figure 2-18). In addition, the CISS has a reset button that tells the printer that it is refilled, whether or not there is actually ink present. This is useful for testing printer operations without actually jetting material. After loading ink into the CISS, air in the supply lines must be drawn out.
using a syringe, simultaneously filling the cartridge sub-units with ink. The major reservoir must be positioned approximately the same elevation as the cartridges print head. If the major reservoir is positioned too high, unwanted ink may drip from the print head when not in operation. If it is too low, the PZTs may have trouble drawing in ink. The CISS may be seen installed into the printer in Figure 2-16.

![Image](image.png)

*Figure 2-18. Epson CISS, supply lines exit the top of the cartridge top units (left) to a major reservoir for extended printing sessions (right)*

### 2.3 Electrical System

In order to manage costs, the main board unit from the WF30 was used because it already contains the driver electronics to activate the print head. This eliminates the need to design a custom board that is capable of producing the trapezoidal analog waveform and digital signals that control printing. In addition, the main board integrates with a PC via USB, allowing one to easily send image slices from computer to printer (further explained in Section 2.4).
2.3.1 Arduino MEGA 2560 & RAMPS 1.4

The Arduino MEGA 2560 microcontroller and RAMPS 1.4 (RepRap Arduino Mega Pololu Shield) combination was chosen based on its open-source and popularity among the RepRap community. An inexpensive 400W, 12V standard PC power supply was sourced for powering the RAMPS. The RAMPS provides an interface between the microcontroller and stepper motors. NEMA 17 stepper motors were used for the Y- and Z-stages.

2.3.2 Voltage Divider

One design challenge was getting the X- and Y-stages to move in sync. Since the X-stage is operated by the Epson main board and the Y-stage by the Arduino, the Arduino had to somehow be able to read and interpret the signals of the Epson. Therefore, the objective was to figure out how to be able to read the signals of the PF motor. This is because, in Epson’s system, the PF motor can be thought of as their Y-stage motor (the carriage holds the print head as it travels along the X-direction, as paper feeds transversely in the Y-direction). If the PF motor’s signals could be read, the Arduino could interpret that information, and then, in turn, drive the Y-stage stepper motor. The reasoning behind not using the PF motor as the Y-stage motor is because returning the carriage assembly to its starting position between “pages” is necessary for layered printing.

An issue, however, is the large voltage differential that exists between the Epson and Arduino. Since the PF motor operates at a voltage of 42V and the Arduino MEGA 2560’s analog pin can only accept 5V maximum, a solution had to be developed to either (1) electrically isolate the two systems or (2) reduce this voltage differential without affecting
either system. Either way, it had to do so at a frequency that could keep pace with Epson’s X-stage movement.

One of the proposed solutions was to use an optocoupler to electrically isolate Epson’s circuit from the Arduino. A twin 4N35 optocoupler circuit was designed that would allow the Arduino to read the PF motor’s movement and direction (Appendix B). However, testing revealed the optocoupler to be unreliable, possibly due to its reliance on an LED and phototransistor, and thus this solution was abandoned.

Another solution was a voltage divider. A capture of the signal sent to the PF motor may be seen in Figure 2-19, where $V_{in,max} = 45\text{V}$ and $V_{in,min} = 17\text{V}$, approximately.

![Figure 2-19. PF motor signal reading from oscilloscope](image)
To keep maximum output voltage of the voltage divider under 5V and avoid high current flow into the Arduino, resistance values $R_1=220\,\text{k}\Omega$ and $R_2=10\,\text{k}\Omega$ were used, based off the voltage divider equation below.

$$V_{out,max} = V_{in,max} \frac{R_2}{R_1+R_2}$$  \hspace{1cm} (1)

Following Equation 1, $V_{out,max} = 1.96\,\text{V}$ and similarly, $V_{out,min} = 0.74\,\text{V}$, both sufficiently less than 5V, yet separated enough to be distinguishable using Arduino’s analogRead() command. A circuit diagram of the voltage divider may be seen in Figure 2-20.

![Voltage Divider Circuit Diagram](image)

*Figure 2-20. Voltage Divider Circuit Diagram*

When connected, RAMPS commands nearly all of the Arduino’s analog pins. Fortunately, it does not use pin A9, A10, A11, and A12. This voltage divider design used A10 as the analog input from the Epson. Since the RAMPS does not have pass-through connections for these
pins, the wire has to be wrapped around the RAMP’s support pin and smashed between the
RAMPS and Arduino for a secure connection, as shown more clearly in Figure 2-21 and 2-22.

![Image of RAMPS and Arduino setup](image)

*Figure 2-21. Voltage divider into side of RAMPS – black (GND), yellow (A10)*

![Image of breadboard setup](image)

*Figure 2-22. Voltage divider breadboard configuration*

This configuration produced excellent results, with Arduino’s Serial Monitor outputting a
clean “0” (when PF motor is feeding paper) and “361” when it is in idle (on a scale of 0 to
This large difference in the “analogRead()” inputs allowed for code that was relatively tolerant. This means that if there were ever any analog signal less than “200”, for example, the Y-stepper was instructed to move (because 0 is less than 200). If the signal was over “200” (since 361 is greater than 200) then the Y-stepper was told to hold position. The code for the voltage reading may be found in Appendix A.

2.3.3 Photo-curing System

Similar to the large-scale industrial 3-D inkjet printers, photo-curable polymer was the logical material to use in this setup. Therefore, a photo-curing system had to be developed. UV LEDs seemed to be the most reliable and economical choice for this project. Two banks of 6 LEDs at 390 nm wavelength, connected in parallel with a bipolar junction transistor (BC547) and 67 Ω resistor, were designed. The circuit of the photo-curing system may be seen in Figure 2-23, designed for 12V DC input from the PC power supply.

![Photo-curing circuit diagram](image)

*Figure 2-23. Left: UV photo-curing circuit, Right: lumped element model [24]*
The 390 nm wavelength UV LEDs were selected based on their similarity with the 405 nm violet laser found in the FormLabs 1+ printer [25]. Using OrCAD PSpice Designer voltage simulation and sweeping the resistance (R7) required in Figure 2-23, the 67 Ω value for the resistor was calculated. Sweeping the resistance allowed for the optimal resistor to be selected for the circuit. After successfully testing the circuit on a breadboard and finding acceptable penetration and curing of FormLabs’ methacrylate photopolymer resin (viscosity 850-900 cP, Figure 2-24 [25]), the circuit was created on an Accurate A427 CNC PCB router, located in John A. White, Jr. Engineering Hall, University of Arkansas. This allowed for a robust and compact design that could easily be mounted on the underside of the print head.

![Breadboard test of UV photo-curing circuit](image)

*Figure 2-24. Breadboard test of UV photo-curing circuit [24]*

The PCB have power, ground, and signal pins on both sides for a design that integrates willingly with many future 3-D printer designs (Figure 2-25). A simple mount was created
(Figure 2-26) that gives the modules the proper angle towards the print area when glued to the print head (Figure 2-27 and 2-28).

**Figure 2-25. UV LED PCB design [24]**

**Figure 2-26. UV LED mount design**

**Figure 2-27. UV LED mounts installed**

**Figure 2-28. UV LED on print head**
2.4 Software

In order to simplify the systems necessary to develop this 3-D printer, the idea was to “trick” the printer into thinking it was doing nothing different from its original intention. In addition, the main goal was to develop a machine that can print 2-D layers of JPEG images over-and-over again to develop a 3-D object. The process for taking a 3-D model and converting it into slices and then into JPEG images that could be sent to the printer was of less-importance to the author. As a proof of concept, the author’s intentions were to load JPEGs of various geometries into Microsoft Word and feed those images directly to the Epson main board. Each JPEG “slice” would be on its own page in Word, with multiple pages (a.k.a. a “ream”) stacking to form the 3-D object. This creates a straightforward procedure for the user: \textit{Open \rightarrow File \rightarrow Print}.

The Epson PF motor moves approximately 1mm for each “step” during a high quality printing sequence. This was determined from some basic experiments in which a ballpoint pen was held lightly above some paper the PF motor was feeding during a 2-D test print. The markings measured consistently to be 1mm in length. The NEMA 17 motor used for the Y-stage completes a full-rotation from 12,800 steps in Arduino IDE, equating to 35.55 steps/degree or 0.0281 degrees/step, as shown below in the following calculation.

\[
\frac{12800 \text{ steps}}{\text{rotation}} \times \frac{1 \text{ rotation}}{360 \text{ deg.}} = 35.55 \frac{\text{steps}}{\text{deg.}} \text{ or } 0.0281 \frac{\text{deg.}}{\text{step}}
\]

In order to move the Y-stage 1mm as well, the 22.4mm diameter pulley needs to rotate 2.5578 degrees, as calculated by the following.
1mm of travel = \(2\pi \cdot 22.4mm \cdot \frac{x}{360}\)

\[ \therefore x = 2.5578 \text{ deg}. \]

Multiplying this number by steps/degree of the NEMA 17, this equates to approximately 91 steps in Arduino code, as shown by the following.

\[ 35.55 \frac{\text{steps}}{\text{deg.}} \times 2.5578 \text{ deg.} = 90.93 \text{ steps} \]

In other words, 91 steps on the stepper motor equates to 1mm of travel on the Y-stage. A way to think of how this works is: (1) the Epson main board sends a signal to the CR motor telling the X-stage to make a pass, during which the PF motor remains idle; (2) at the end of the pass, the PF motor is instructed to move 1mm; (3) simultaneously with Step 2, the Arduino reads and interprets the PF motor’s signal, thus driving the Y-stage. An important note is that the print head can print in both directions, thus the PF motor will move once for each pass of the X-stage (meaning, once for a pass and once again for a return pass). This process repeats until the carriage reaches the end of the Y-stage, which is approximately 2 full rotations of the pulley (which is 25,600 steps on the motor or approximately 281mm of travel). The software was coded in Arduino IDE and may be found in Appendix A.
Chapter Three.

Results & Discussion

3.1 Results

Shortly after the printer had been fully designed and built, and before significant testing was conducted, an unfortunate issue with cartridge recognition arose. The printer suddenly refused to communicate with the CISS as well as genuine Epson cartridges, halting any ability to print. A second WF30 had also been purchased for spare parts in case an event such as this occurred. However, within just a week of using the spare parts from the backup printer, the same issue occurred, despite careful disassembly and procedures to eliminate electrostatic discharge. After discovering of similar issues with other users of the WF30, the author has hypothesized that this issue may be due to planned obsolescence by Epson. The author has proposed some solutions in Section 4.2 for future work.

Despite this ill-fated circumstance, several photographs were obtained before the cartridge failure, indicating some positive results. Figure 3-1 shows a photo of a nozzle check pattern conducted. The gaps in the lines suggest many of the nozzle were still clogged after an attempt at using Objet Cleaning Fluid to test jetting higher-viscosity material. The nozzles and ink reservoirs were in the process of being cleaned with
isopropyl alcohol (IPA), which is the reason for the faded prints. Figure 3-1 is the result of IPA mixed with Objet Cleaning Fluid and some residual black ink.

![Figure 3-1. Nozzle check pattern printed](image)

Note: The numbers shown in the figure are nozzle numbers. They are not printed on an actual nozzle check pattern.

![Figure 3-2. Nozzle check pattern, according to Epson [20]](image)
Shortly after, in order to continue purging the nozzles, a rectangle was printed (Figure 3-3). The result appears to be a gradient; however this is due to the IPA diluting the residual inks.

![Rectangle printed](image)

*Figure 3-3. Rectangle printed*

These results suggest that the Arduino is interpreting Epson’s signals correctly from the PF motor. The X-stage and Y-stage are in sync. A video captured by the author shows the printer reaching the end of the Y-stage, returning back to its initial position at the completion of a “page”, dropping the Z-stage, and continuing on the next page.
3.2 Discussion

Due to the cartridge malfunction, testing of the printer ceased until the issue could be resolved. The plan was to test the printer using Stratasys materials: VeroWhitePlus RGD835 (Part No. OBJ-04054) photopolymer resin, since it is used in the Objet30 3-D inkjet printer, available in the University of Arkansas, Dept. of Biomedical Engineering. Therefore, the purchasing and testing of this material was not followed-through with as it costs USD$300 for two 1kg cartridges, with no guarantee of compatibility. The author agrees that this high material price seemingly defeats the purpose of a low-cost printer.

Ideally, a custom in-house photopolymer material would be created for this printer, taking into account jettability and curability with the UV LED system. A dimensionless number called the Ohnesorge number (Oh) is one way, to some extent, determine if a material is jettable. The Ohnesorge is related to the Reynolds and Weber numbers [15], denoted by

\[ Oh = \frac{\sqrt{We}}{Re} = \frac{\mu}{\sqrt{\rho \sigma L_c}} \]  

where \( \mu \) is the dynamic viscosity, \( \rho \) is the density, \( \sigma \) is the surface tension, and \( L_c \) is the characteristic length. If a liquid’s Oh is between 0.1 and 1, it is potentially jettable [26].

The author recognizes that simply sourcing a material that works with the printer is a very important aspect, whether or not it follows the low-cost philosophy. This matter will have to be left as future work.
4.1 Conclusion

First and foremost, this project attempted to design and build something that doesn't exist, with minimal experience and a low-budget. While the project hit an unfortunate wall just as the printer was nearing completion, there are several contributions that were made. This paper has presented a genuinely low-cost method for inkjet 3-D printing that has promise and potential. The author believes the hardware in desktop inkjet printers is entirely capable of becoming multi-material manufacturing devices, and that the prices of printers like the Stratasys Object Connex series could be significantly reduced with the introduction of a low-cost competitor.

This project also leaves behind hardware that can be utilized in future printer designs. The Y- and Z-stages were designed with the ability to be easily modified or taken from the printer for use on new iterations. The simple, modular design also allows for significant adjustment to be made, especially with regards to build volume.

From a learning perspective, this project has provided the author with a rather extensive knowledge of the operations and mechanisms of the WF30 that are not readily
available on the Internet. The idiosyncrasies of the printer were discovered through many hours of dissection and tinkering. Additionally, the knowledge acquired about Arduino and RAMPS has inspired the author to use these devices in future projects. Although there is still much work to be done and much that could be improved, this paper has laid the foundation for future development. It is meant to be a comprehensive documentation of this project’s history and current status for use as a reference for the next student willing to take on the challenge.

4.2 Future Work

As with any research, there is always more to be done. Firstly, the author suggests abandoning the WF30 printer, as the hardware is nearly 8 years old and parts are becoming increasingly difficult and expensive to acquire. For reasons unknown, a used WF30 on the Internet can be double or more of its original MSRP. In addition, if the hypothesis that planned obsolescence killed the WF30 is true, then it should most definitely be avoided. A much newer, inexpensive Epson printer model would be the best choice for hardware moving forward, as print head technology has presumably changed very little. Something like the Expression Home XP-420, one of Epson’s budget printers (approximately USD$50 currently) would be a viable option. The main downside might be the many features that even low-cost printers of today have – such as touchscreens and Wi-Fi. The WF30 benefits by not having these distractions from its focused intent. They simply add complexity to the circuitry that will have to be dissected and understood. Nevertheless, printer functions are likely quite similar, allowing the carriage from the new printer to be mounted on this frame and similar code to be used to read its signals. The author admits that this project relied
heavily on Epson’s functions for driving the print head, X-stage, and software from PC to printer. If reliance on the Epson main board was eliminated, then theoretically the WF30 hardware should still be adequate. This brings up the second suggestion – taking over the print head entirely via Arduino. This process is already underway, with Garrett Urban spearheading this operation. A more complete understanding of the printer electronics and circuitry is necessary for this. The high voltage driving waveform that the WF30 main board creates would have to be simulated with Arduino. The ability to alter the waveform, though, would allow for precise tuning of the PZTs to the jetted material in question. This flexibility would allow for multi-material printing. As mentioned in Section 3.2, a custom photopolymer formulated for the print head could help optimize the printing process. Multiple print heads could even be added to the carriage for increased build speed and coverage. Complete control of the print head would provide the ultimate freedom and truly is the future of this project.
Appendix A

Software Code

The main code used for printer operation, provided below:

```c
#include <Stepper.h>
#define Y_ENABLE_PIN 56
#define Y_MIN_PIN 14
#define Y_MAX_PIN 15

Stepper X_STEPPER(12800, 54, 55); //Z-stepper motor, using X pins for convenience
Stepper Y_STEPPER(12800, 60, 61); //Y-stepper motor

const int Y_Trigger_Input = 10; //analog input from Epson for Y-stage movement
int stepCount = 0;       //initial=0, number of steps the motor has taken
int pageCount = 0;       //initial=0, number of pages the printer has completed
const int maxStep = 120;  //printer defined, number of steps Y-stage can fit
                         //absolute max is ~280
const int layers = 50;   //user defined, layers (in z-direction)

void setup() {
  Serial.begin(9600); // initialize the serial port:
  pinMode(Y_ENABLE_PIN, OUTPUT);

  Y_STEPPER.setSpeed(150); //Speed (rpm)

  while (pageCount < layers){
    Serial.println(analogRead(Y_Trigger_Input)); //prints the voltage read to the
    delay(10);

    int VoltageRead = analogRead(Y_Trigger_Input);
    if (VoltageRead < 200){       //this is on a 0 to 1023 scale, voltage @ Epson idle
      Y_STEPPER.step(91);        //should be 91 for regular printing
      Serial.print("steps:");
      Serial.println(stepCount);
      stepCount++;
      delay(100);
    }
    pageCount++;               //resets stepCount
    X_STEPPER.step(12800);
    Serial.print("Completed Page: ");
    Serial.println(pageCount);
    delay(100);
  }
}
```

42
Appendix B

Optocoupler Circuit Design

Figure B-1. Proposed twin optocoupler design for isolating Epson/Arduino circuits
References


   Diss. 2014. Web.


17. "Epson Stylus 800 - The First Inkjet Printer Equipped with Micro Piezo Technology." 


20. Service Manual - EPSON Sylus C110/C120/D120/WorkForce 30/Stylus OFFICE B30/T30/T33/ME OFFICE 70, Rev. C. Seiko Epson Corp. PDF.


