Universal Circuit Fabricator

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***Abstract* — The objective of this paper is to incorporate the design, methodology and process to create a two dimensional inkjet printer that uses conductive ink to create a functional circuit without the usage of breadboards or wires. Acknowledging the rise of three dimensional printing, the Universal Circuit Fabricator uses a combination of hardware and software design derived from three-dimensional printing software in order to make the process of circuit testing more accessible to students and engineers alike.**

***Index Terms* — AC-DC power converters, conductive ink, conductivity, inkjet, microcontroller, printed circuits, printing,**

I. INTRODUCTION

When engineers need to prototype their circuits, they utilize a tool called a breadboard. Breadboards have been used for prototyping since the 1970's. It's a versatile tool that engineers use to prototype and experiment with their circuits without having to solder. Some of the biggest drawbacks of breadboards are cable organization, visual appeal, and their many troubleshooting challenges.

The Universal Circuit Fabricator (UCF) aims to alleviate these problems allowing the user to bring circuit ideas to life more efficiently than with conventional breadboards. The idea behind this project is to take a circuit diagram, made with a circuit design program, and print the circuit traces onto an insulated surface with conductive ink. With this design, the user can place the corresponding components onto the printed traces so the circuit is ready for testing.

The use of this device will not only apply to engineers in the field, but it will also help engineers who are still in college. Every engineer has to take classes that provide them with experiences to apply what they have learned. There, students build and design specific kinds of circuits, which are simulated in a circuit design program. After that is finished, the students then build the physical circuit which is done utilizing a breadboard. This is the motivation to create the Universal Circuit Fabricator. The UCF will allow the user to print their circuit schematic from serial input via USB with a computer. The Universal Circuit Fabricator is approximately the same size as conventional inkjet printers. This design makes it appropriate for prototyping purposes, as well as learning purposes.

Future applications of printing conductive materials are limitless. For example, an inkjet cartridge filled with conductive ink could be an additional tool included on a 3D printer, allowing a designer to use additive manufacturing techniques to design and build a product with electronics embedded inside the housing while being manufactured. The concept of creating built in wiring inside of a 3D printed object would allow a designer to create a smaller and cheaper product.

II. RESEARCH

The Universal Circuit Fabricator relies on the concept of depositing a liquid conductive ink onto an insulating substrate via an HP C6602 inkjet print cartridge. Conductive ink technology is a developing field that has recently gained interest in the world of electrical engineering [1]-[2].

A. Conductive Ink

While there are several commercially available conductive ink products that might meet the specifications of the UCF, they are expensive and proprietary. For the application of this project, several formulas for developing conductive ink were researched and considered for development and testing.

B. Conductive Ink Design Requirements

Conductive ink formulas were considered against the design requirements shown below in Table I to identify plausible choices. The optimal ink variety was selected by choosing the ink with the best performance to price ratio, keeping in mind the importance of low resistivity ($\Omega \cdot \mathrm{m}$). Some of the conductive ink formulas require annealing to transform the ink into a finalized state. Annealing is the process of heating a material and allowing it to cool down slowly in an effort to fuse the material into a continuous structure, thus toughening it and reducing resistivity.

TABLE I
CONDUCTIVE INK DESIGN REQUIREMENTS

The HP C6602 inkjet cartridge must be able to store the conductive ink without leaking.
The HP C6602 inkjet cartridge print cartridge must be able to print a line of conductive ink without clogging.
Electrical resistivity less than $1 \times 10^{-3}\ \Omega \cdot m$
Solid finalized state

C. Gallium-Indium Ink

The Gallium-Indium Conductive Ink is simple to produce and yields a viscous liquid metal alloy that is free of particulates. It is simple and inexpensive to produce, but is expensive in material costs when producing small amounts. The alloy is comprised of two elements: 75.5% Gallium and 24.5% Indium. Gallium, which has a melting temperature of 85.59°F (29.77°C) will melt in the palm of your hand. Indium has a slightly higher melting temperature of 313.9°F (156.6°C). When the metals are combined in a beaker of deionized water and heated to 122°F (50°C) the Gallium is melted and fuses with the indium. After stirring with a glass rod, the alloy is fully homogenized. A syringe is used to remove the ink, which is heavier than water, from the beaker [3].

Upon testing the Gallium – Indium Conductive Ink, we found that the alloy is highly electrically conductive as seen below in Fig. 1. The Gallium – Indium Ink is liquid at room temperature due to the chemical composition and high concentration of Gallium. The viscosity of the ink and its inability to cure to a solid finalized state makes this ink formula incompatible with our design requirements.

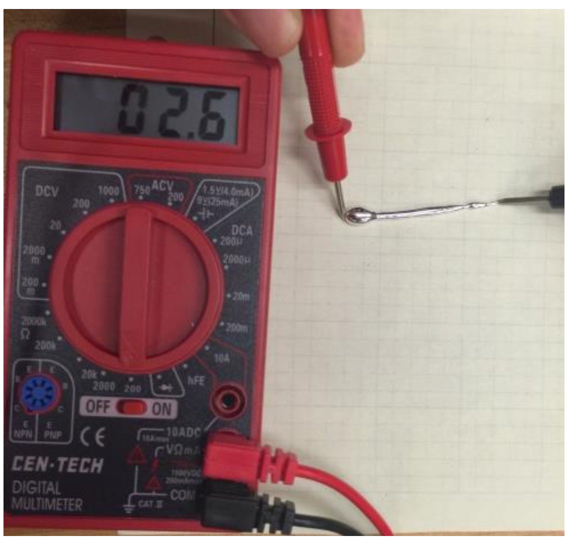

Fig. 1. Test sample of Gallium-Indium conductive ink with a multimeter measuring electrical resistance of 2.6 Ω

D. Silver Acetate Ink

Silver Acetate Ink is produced using a chemical reaction that yields elemental silver from a particulate free liquid. It must be annealed to a substrate by heating, to form a continuous trace with low resistivity that is solidified.

The Silver Acetate Ink is produced by combining 2.5mL of Ammonium Hydroxide with 1 gram of Silver Acetate in a beaker and mixed using a magnetic stir bar. Once the Ammonium Hydroxide and Silver Acetate are fully mixed, 0.2mL of Formic Acid is added to the solution one drop at a time using a needle syringe while the magnetic stir bar continues to mix the chemicals. The ink is left to settle for 12 hours in an air tight container, allowing larger silver particles settle at the bottom.

Using a 0.2µm syringe filter, the larger silver particles are filtered from the solution. Once filtered, the ink is a clear particulate free liquid. The ink is then stored in an air tight container to prevent premature reaction of the ink.

When the Silver Acetate ink is exposed to air, the Ammonium Hydroxide evaporates from the ink. The Silver Acetate and Formic Acid are left behind to react with each other. This reaction forms electrically conductive elemental silver particles.

To improve the conductivity of the Silver Acetate ink, the silver particles that have formed as a result of the chemical reaction are heated to ~200°F (93°C) in an annealing process as shown in Figure 2. The annealing process helps to evaporate away any remaining Ammonium Hydroxide and fuses the individual Silver particles into a continuous structure.

Fig. 2. Test sample of Silver Acetate conductive ink being annealed and fusing into a continuous solid

The Silver Acetate conductive ink is not electrically conductive when in its liquid form. As the Ammonium Hydroxide evaporates and the Silver particles form, the conductor fuses into a continuous trace and the electrical resistance lowers as a function of temperature. Once the ink has reached 95°C, the optimal electrical conductivity has been reached and cannot be raised further. This relationship is shown below in Fig. 3. After the ink has been heated to annealing temperature, it maintains optimal electrical conductivity after being cooled back to room temperature. Our test sample after being annealed measured the same electrical resistance at annealing temperature as well as room temperature, and even weeks after annealing.

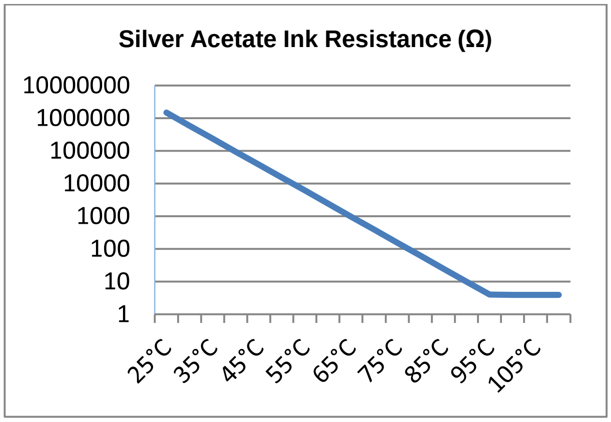

Fig. 3. Estimated relationship between the resistance of a 1cm length of Silver Acetate conductive ink and the annealing temperature in degrees Celsius

E. Conductive Ink Decision

After producing and testing both the Gallium-Indium and Silver Acetate inks, the Silver Acetate ink was selected as the conductive ink component for the Universal Circuit Fabricator. The Silver Acetate ink meets all of the design requirements as it is not too viscous and therefore does not leak out of the HP C6602 inkjet print cartridge. The Silver Acetate was also chosen because it is more cost effective than the Gallium-Indium ink, and is therefore more feasible for the constraints of our project budget. The Silver Acetate ink is filtered and particulate free, which prevents it from clogging the print cartridge. Based on the electrical resistance measurements taken from our test sample, shown in Fig. 4, the resistivity of the Silver Acetate ink was calculated after it had been annealed using (1).

$$\rho = R \cdot \frac{A}{l} \quad (1)$$

Where ρ is the resistivity of the material, R is the electrical resistance, A is the cross section area of the trace, and l is the length of the trace. The resistivity of our test sample was calculated to be approximately 3.996×10^{-4} $(\Omega \cdot \text{m})$. The low electrical resistivity achieved in conjunction with the fact that the silver acetate ink in hardened to a solid finalized state satisfies the remaining design requirements for the conductive ink used in the UCF.

Fig. 4. Test sample of Silver Acetate conductive ink with a multimeter measuring electrical resistance of 5.6 Ω

F. Printing Substrate Design Requirements

Table II below lists the design requirements for the printing substrate for a successfully functioning printed circuit.

TABLE II
PRINTING SUBSTRATE DESIGN REQUIREMENTS

Ink that has been printed from the HP C6602 inkjet print head must be able to form a continuous line on the substrate without leaching into the material and spreading out.
The substrate must be able to be heated to appropriate annealing temperatures when required by ink selection
The substrate must have a high resistivity so as to allow current to flow only through the printed ink and not through the substrate.

G. FR4 Silicon

FR-4 Silicon is a material that is constructed out of multiple plies of epoxy-resin impregnated woven glass cloth. Used mainly because it can satisfy electrical and thermal application needs, this substrate is also used in PCB construction, but it contains a copper foil. For the chosen ink, there is no need for the copper foil.

H. Glass

Glass is a material with a smooth surface that can withstand the annealing process. It provides a solid insulating surface for the conductive ink to adhere to without leakage current into the substrate.

The thermal properties of this substrate make it a great option for the silver acetate ink. The silver acetate ink will need to go through the annealing process; therefore the substrate needs to withstand at least 200 degrees F.

I. Printing Substrate Decision

Based on the research, the substrate selection chosen was glass. Glass is a good insulator that will minimize leakage current between conductive traces. It is strong and able to withstand the heating associated with the annealing process of the Silver Acetate Ink. Glass is rigid and inflexible which will reduce the risk of cracking the conductive ink traces, once printed. In addition to the electrical and material property benefits, glass is transparent, which aids in the ability to read the layout of printed circuit traces.

III. System Components

The Universal Circuit Fabricator features a steady balance of hardware and software to achieve its purpose. Each component is an integral part of the UCF design and is described in detail in the following sections.

A. InkShield

The InkShield, designed by Nicholas C. Lewis [4] allows you to connect an HP C6602 inkjet cartridge to a microcontroller. The InkShield allows the user to control all twelve nozzles within the inkjet cartridge, for better printing accuracy. It uses pulse width modulation to control the rate at which the nozzles release the ink. There is also a power booster on the InkShield that increases the 12VDC input voltage to 20VDC to power the ink cartridge.

B. Motor Control System

The Motor Control System is responsible for controlling the movement of the X and Y axis stepper motors to translate the print head across the print bed surface. It will rely on data fed from the microprocessor as an input to toggle the direction of the motor's movements and the amount of steps according to the circuit trace design. It was chosen to operate the axes independent from each other, in order to create a more accurate circuit trace.

C. Microcontroller

The microcontroller is a combination of the microprocessor and the motor control system, featuring the ATmega328P. The specifications are listed below on Table III. The microcontroller features a USB connector, in order to connect to a computer through an RS232 serial connection. The microcontroller also uses headers that allow it to interface directly with the InkShield. Also, the microcontroller has additional headers in place, in case additional features are added. The microcontroller can be powered by two options, either the USB connection with the computer that supplies 5VDC, or a barrel jack connection that supplies 12VDC.

TABLE III
ATMEGA328P SPECIFICATIONS

Clock Speed	16 MHz
Voltage	7-12 V
EEPROM	1 KB
SRAM	2 KB

D. Power Supply

The power supply features a 120VAC/15VAC transformer, an AC/DC full wave bridge rectifier, a large capacitor to smooth ripple voltage, and two linear voltage regulators. The first linear voltage regulator is the LM7805 which reduces the input voltage to 5VDC to power the motors and hardware switches. The second linear voltage regulator is the LM7812 which reduces the input voltage to 12VDC to power the InkShield subsystem. Both linear voltage regulators are limited to 2.5A each. Fig. 5 below displays a schematic of the power supply that was generated using the Multisim 12.0 circuit simulation suite.

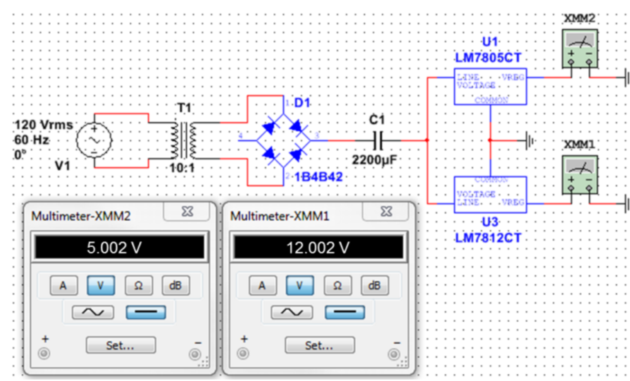

Fig. 5. Multisim schematic simulation of the Universal Circuit Fabricator power supply

IV. System Overview

To represent a general overview of the Universal Circuit Fabricator, software and hardware system representations in the form of block diagrams were created. The block diagrams serve to provide a top level view on how each part of the system interacts. The following sections cover both the hardware and software system overviews.

A. Hardware

Each block in the hardware block diagram on Fig. 6 below represents an important system component. The figure also visualizes what systems are implemented in the PCB and how it will integrate with external hardware.

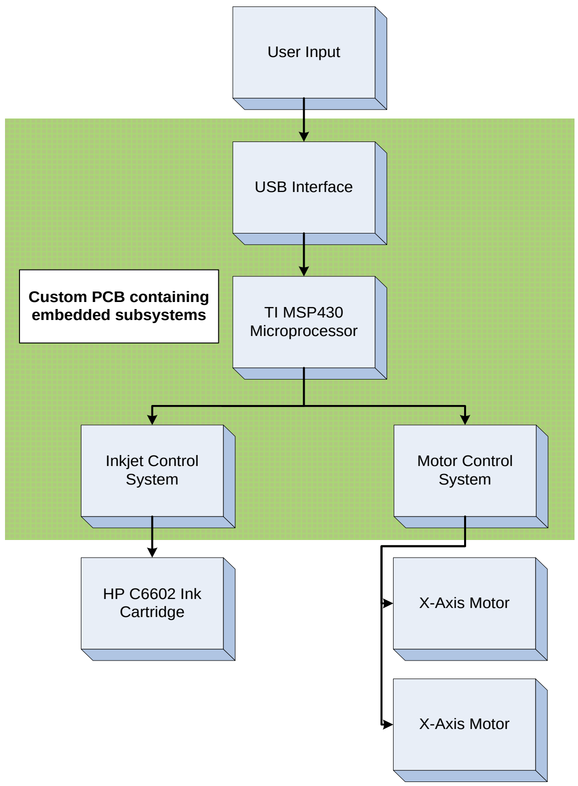

Fig. 6. Universal Circuit Fabricator Hardware Block Diagram

B. Software

The software block diagram gives the complete overview for all the software interactions in regards to the Universal Circuit Fabricator. As seen in Fig. 7 below, the microcontroller code is the main software system, which receives user input data from the external PC, then goes through a data conversion and processing system, then into control software for each individual subsystem.

Finally, as the code moves out of the microcontroller, it is converted into basic firmware code for each subsystem in order to either move the motors or spray from the ink nozzles.

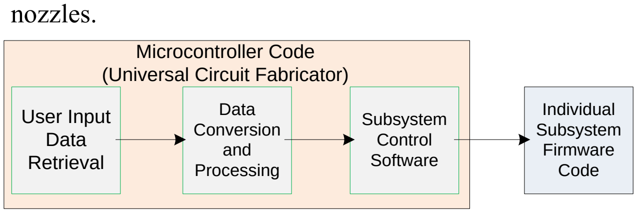

Fig. 7. Universal Circuit Fabricator Software Block Diagram

V. Hardware Detail

The following section focuses on the primary hardware systems both purchased and designed for the Universal Circuit Fabricator. These components represent components like the InkShield, the motor control drivers, and finally, the ATMega328P microcontroller integrated circuit within its own custom designed printed circuit board (PCB).

A. InkShield

The InkShield is responsible for controlling the flow of conductive ink from the HP C6602 inkjet cartridge. The HP C6602 has a 96dpi resolution with 12 inkjet nozzles. The InkShield drives the inkjet cartridge by supplying 20V to the HP C6602 via boost converter. The InkShield also has a 4 to 16 multiplexer that allows the microprocessor to only utilize four analog pins to control the 12 nozzles on the inkjet. This gives the user the possibility to trigger the nozzles in any possible configuration. The InkShield utilizes pulse width modulation to control the trigger mechanism of the inkjet cartridge. The HP C6602 works by utilizing a PWM with the following iterations: 5µs ON and 800µs OFF. This is used because if there is no delay in between pulses, the InkShield will overheat the nozzles, therefore making them nonfunctional. In order to use this feature, the InkShield uses one digital pin from the microprocessor, which translates to using a total of five pins. Fig. 8 below is a picture of the assembled InkShield inkjet control system.

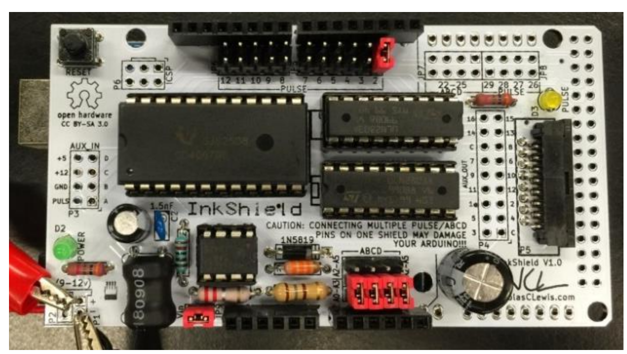

Fig. 8. Assembled InkShield circuit board

B. Motor Control System

The Motor Control system features a PWM Driver, and two TB6612FNG DC motor drivers. The PWM Driver allows us to only utilize two analog pins from the microprocessor. The advantage of utilizing the TB6612FNG motor driver is that it creates lower voltage drops across the motors to increase torque and accuracy.

The motor driver chip contains 2 H-Bridges, which allows the UCF to utilize bidirectional motors. The H-Bridge motor drivers will control two NEMA 17 stepper motors for the X and Y axes. The use of only two analog pins makes the use of this PWM driver essential in the design of the Universal Circuit Fabricator.

C. Microcontroller

Discussed earlier, the Universal Circuit Fabricator uses a customized version of an Arduino UNO development board with an ATMega328P 8-bit AVR RISC-based microcontroller. Within the design, only the components that were necessary for the design functionality of the UCF were used in the final PCB. The main use of the ATMega328P was to interface the input circuit design from the external PC with the primary components of the UCF, such as the InkShield and the motor control system. Other functions needed were the USB and UART communications to communicate with the external PC, as well as the digital I/O pins in order to interface the ATMega328P with the motor control driver chips used to move the stepper motors.

D. Printed Circuit Board Design

CADSOFT Eagle was utilized in order to create the custom printed circuit board (PCB) design for the Universal Circuit Fabricator. The PCB houses all the subsystems of the UCF, as well as the ATMega328P microcontroller. The PCB design contains a USB input for both power and communication between the external PC and the UCF, powered by the ATMEGA16U2 chip which acts as a serial to USB converter. It also contains two TB6612FNG motor control drivers which power the two stepper motors. Finally, it includes a series of headers from the I/O pins of the ATMega328P that interfaces directly with the InkShield in order to provide seamless integration.

The primary design considerations were simplicity to control costs, as well as functionality within the original design. For those reasons, it was decided that the primary power supply of the system would remain off the board in order to reduce troubleshooting. The PCB manufacturer chosen for the UCF was OshPark as it provided great service for a reasonable price, as well as providing three copies of the printed circuit board in case an error in assembly occurred. The PCB board layout is presented below in Fig. 9 and the printed physical PCB in Fig. 10

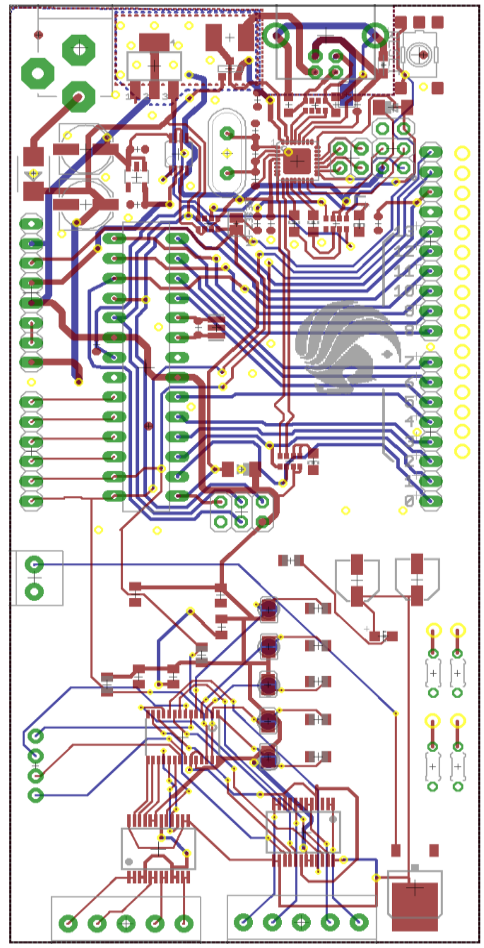

Fig. 9. Universal Circuit Fabricator Custom Printed Circuit Board layout

Fig. 10. Universal Circuit Fabricator Custom Printed Circuit Board

VI. SOFTWARE DETAIL

The software of the Universal Circuit Fabricator interacts with the user via serial communication over USB with an external computer. The software is designed to allow the user to create, on an external computer, a text file (.txt) that contains G-Code commands which describe the design to be printed. The user then opens GcodeSender, a java based serial communication graphical user interface, on an external computer to connect to the USB COM port that the Universal Circuit Fabricator is interfaced with. Once the UCF has been successfully connected, the main menu is displayed in the graphical user interface of GCodeSender. This allows the user to type and send individual lines of GCode at a time. GCodeSender also allows the user to select a .txt file from the hard drive of the computer. Once selected, the text file is sent to the UCF one line at a time until every command has been performed.

A. Subsystem Software

The InkShield code utilizes a set of libraries that are compatible with the ATMega328P. These libraries are small in size which allows the user to use the memory within the microprocessor with more flexibility. There are a few commands incorporated in the libraries that allow the user to set the configuration of the nozzles that will be used during the printing process. Those commands were made into functions that can be called within the overall code for the UCF. The functions give us the flexibility to create a more elaborate code.

The Motor Control System code utilizes four possible ways to drive the motors: single steps, double steps, micro steps, and interleave. The UCF uses the interleave setting for all of the motor commands. The motor code takes the commands from the G-Code text file and depending on the type of command, will operate the respective stepper motor. There are several motor command functions that make the InkShield Code and motor commands run simultaneously.

B. G-Code

G-Code is a common programming language used in the CNC and 3D printing industries. It is a vector based motor control algorithm that uses a Cartesian coordinate system to define present location of the tool in use and standard increments to precisely control movement in the X, Y, and Z directions. In the software configuration of the UCF, only a select number of G-code commands are necessary. For example, Z axis control, alternate tool selection, and circular movement are not required for printing two dimensional lines for circuit traces.

Prior to a design being printed, the UCF requires that a homing sequence be completed so that the print nozzle is moved into the origin of the coordinate axis. The homing sequence is initiated by sending "G28;" through the COM port. The UCF then moves the X motor in the reverse direction until a hardware switch mounted on the frame is pressed, signaling that the carriage has been moved to the origin of the X axis. Similarly, the Y axis origin is found using a hardware switch mounted on the frame. Once the homing sequence is completed the UCF is ready to print a design.

Table IV lists all commands that the UCF has been programmed to execute. These commands are sent to the GcodeSender graphical user interface upon startup of the UCF to tell the user what commands it is able to complete.

TABLE IV
UCF G-CODE COMMANDS

G00	[X(steps)] [Y(steps)] [F(feedrate)] linear move – no ink
G01	[X(steps)] [Y(steps)] [F(feedrate)] linear move – spray ink
G04	P[seconds] - delay
G28	move to Home-Position/Origin
G90	absolute mode
G91	relative mode
G92	[X(steps)] [Y(steps)] - change logical position
M18	release motors
M100	this help message
M114	report position and feedrate

Multiple lines of G-Code commands can be completed sequentially when saved in a .txt file and sent using the GCodeSender graphical user interface. For example the commands listed below in Fig. 11 result in the printing of a star in Fig. 12.

```
G28;
G00 X7.523 Y6.275 F130;
G01 X4.865 Y4.451 F130;
G01 X5.776 Y7.544 F130;
G01 X3.221 Y9.509 F130;
G01 X6.444 Y9.598 F130;
G01 X7.523 Y12.635 F130;
G01 X8.603 Y9.596 F130;
G01 X11.825 Y9.509 F130;
G01 X9.270 Y7.544 F130;
G01 X10.183 Y4.452 F130;
G01 X10.182 Y4.451 F130;
G01 X10.181 Y4.451 F130;
G01 X7.523 Y6.275 F130;
```

Fig. 11. G-Code commands for printing a star

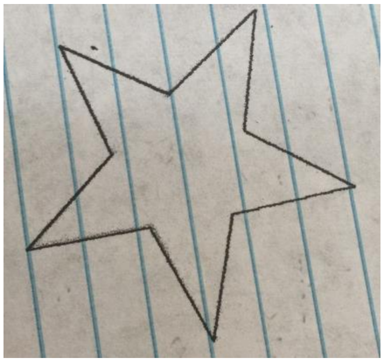

Fig. 12. Star printed using G-Code commands saved in star.txt

VII. Conclusion

The Universal Circuit Fabricator was created in order to remove the challenge and hassle of the prototyping breadboard, as well as to challenge ourselves by using our knowledge in electrical engineering within our senior design project. Along with the difficulty of the initial design, there was a large amount of obstacles that we had to overcome in order to have our final design completed. Mainly, our design completely changed when our microprocessor changed from the MSP430 microprocessor to the Arduino platform.

However, we found the process was greatly rewarding, as we learned how to combine and use the knowledge we received over our many semesters at school to create something that we are proud to share with our class as well as the engineering department. Our experience in senior design also prepared us for careers within the engineering field. Specifically, we have learned how to work in a group and function within a deadline oriented environment. Additionally, we have gained experience working on a long-term, complex project that had multiple unforeseen variables. However, ultimately, we are proud of our work with the Universal Circuit Fabricator, and are satisfied with our accomplishment within Senior Design.

Acknowledgement

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Engineers

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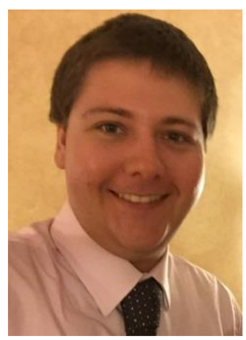

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