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GRADO EN INGENIERÍA EN TECNOLOGÍAS DE TELECOMUNICACIÓN

TRABAJO FIN DE GRADO

Design and Production of a Thermal Display

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Director: Casey J. Smith

Madrid

Junio del 2019

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Agradecimientos

A mi madre, mi padre y mi abuela por apoyarme a lo largo de esta larga batalla.

DISEÑO Y PRODUCCIÓN DE UNA PANTALLA TÉRMICA

Autor: Puértolas García, Santiago.

Director: Smith, Casey J.

Entidad Colaboradora: University of Illinois at Urbana-Champaign

RESUMEN DEL PROYECTO

Las innovaciones en el sector de las pantallas han sido mayoritariamente incrementales más que disruptivas desde la invención de la primera pantalla en 1927. Este proyecto tiene como objetivo principal crear una tecnología que utiliza energía térmica en vez de luz para mostrar caracteres para disrumpir este sector.

Palabras clave: Pantalla, Calor, Térmica, Termocromismo

1. Introducción

En la actualidad no existen pantallas térmicas que sean eficientes y relativamente baratas. Las que sean desarrollado han sido con fines publicitarios y con altos costes de producción debido a que se hacen a medida para cada cliente. Idealmente, para que una pantalla térmica sea comercial y pueda disrumpir el Mercado, debería de ser barata, poder mostrar imágenes y caracteres con tener suficiente resolución y claridad, y ser reconfigurable.

El objetivo de este proyecto es crear un producto Beta de una pantalla térmica compuesta por 45 píxeles, cada uno compuesto por 10 cm de alambre de nicromo que entrará en contacto con una hoja de papel termocrómico y conectados a un microcontrolador por medio de registros de desplazamiento de 8 bits. Resultando en una pantalla de 12 cm de alto por 60 cm de ancho. El alambre se activará haciendo pasar una corriente por él de tal forma que caliente el papel termocrómico y éste cambie de color para representar caracteres.

2. Definición del proyecto

La primera etapa de este proyecto conlleva una extensa investigación sobre las tecnologías a utilizar para la elaboración de los píxeles y su control, de tal forma que sea posible convertir energía en calor. Tras esta etapa, se diseñó un diagrama de bloques, mostrado en el Diagrama 1, que permite agilizar la producción de la pantalla aislando cada función en sub sistemas de tal forma que, si un proceso se ralentiza, los otros pueden seguir adelante. Por último, se procedió a la producción de la pantalla.

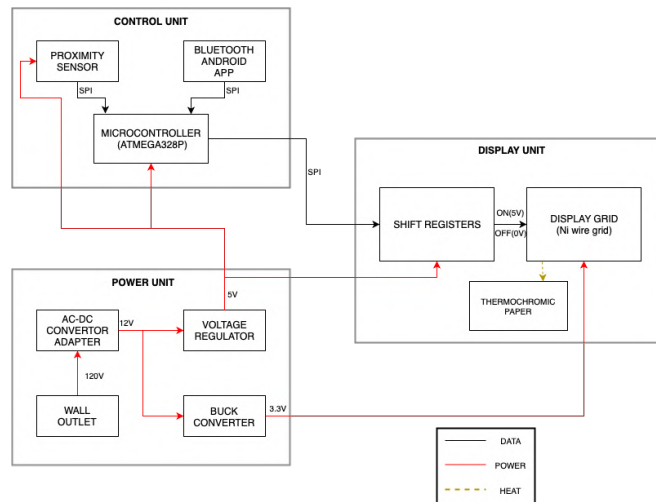


Diagrama 1. Diagrama de Bloques

El producto final será capaz de reconfigurar el texto en 10 segundos, mostrar letras de una forma clara y legible, y tendrá una retroalimentación por medio de sensores para que un usuario pueda interactuar con él. Por ultimo, como objetivo supletorio, un usuario podrá reconfigurar el texto mostrado por medio de una App de Android.

3. Resultados

El producto final es el mostrado en la Imagen 1. Como se esperaba, cumple los objetivos esenciales, pero no el objetivo supletorio debido a problemas en la comunicación entre el sensor Bluetooth y la App.

Desafortunadamente, al fabricar la pantalla, algunos píxeles fueron dañados lo cual conllevó a que éstos no se activasen plenamente o se quedasen inactivos por completo. Esto causa que las letras no sean plenamente claras, pero sí legibles.

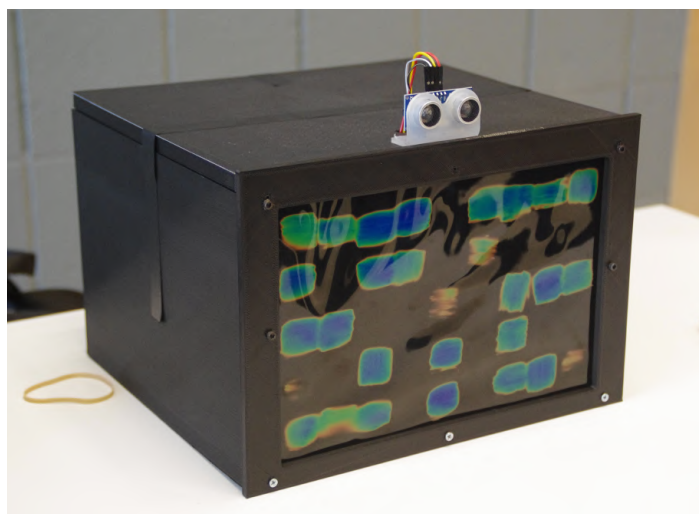


Imagen 1. Pantalla Térmica

4. Conclusiones

Las principales incertidumbres de este proyecto son relacionadas a su consumo de potencia y corriente. Esto se debe a que cada píxel necesita alrededor de 0.09 Amperios para conseguir un tiempo de activación de alrededor de 6 segundos, lo cual es esencial para el cumplimiento del primer objetivo. Sin embargo, si un píxel está activo durante demasiado tiempo, su resistencia podría cambiar debido al cambio en la temperatura, lo cual afectaría a la corriente que consume. Otras incertidumbres surgen al escalar el tamaño de la pantalla incrementando el número de píxeles. Esto causaría que el consumo de poder fuese demasiado alto, por lo que se deberían investigar formas de reducir el mismo, ya que sería difícil proporcionar tanta corriente con una diferencia de potencial de tan solo 3.3 Voltios.

5. Referencias

- [1] All about Flexible Microelectronics. [Online]. Available: <https://macroelectronics.blogspot.com/2007/10/electronic-papers-history-and-future.html>.
- [2] NanoDays. "Exploring Materials-Liquid Crystals." 2013, http://www.nisenet.org/sites/default/files/catalog/uploads/1989/materialslc_sign_15nov10.pdf.
- [3] *AmbiKraf*. [Online]. Available: <https://cargocollective.com/ambikraf>.
- [4] "Thermochromic Display," *Vimeo*, 27-May-2019. [Online]. Available: <https://vimeo.com/2616647>.
- [5] "Functional Printing," *Printed Thermochromic Display Circuits*. [Online]. Available: <http://www.hallcrest.com/our-products/special-effect-pigments/printed-thermochromic-display-circuits>.
- [6] L. L. C. H&H Graphics, "Thermochromic Printing Reveal Example," *YouTube*, 15-Feb-2017. [Online]. Available: <http://www.youtube.com/watch?v=Dt6Rb1brnZ0>.
- [7] G. Elert, "Temperature of a Healthy Human (Skin Temperature)," *Temperature of a Healthy Human (Skin Temperature) - The Physics Factbook*. [Online]. Available: <https://hypertextbook.com/facts/2001/AbantyFarzana.shtml>.
- [8] B. Hauke, "Basic Calculation of a Buck Converter's Power Stage," *Texas Instruments*, Dec-2011. [Online]. Available: <https://www.ti.com/lit/an/slva477b/slva477b.pdf>.
- [9] "Ultrasonic Ranging Module HC - SR04," *Sparkfun*. [Online]. Available: <https://cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf>.
- [10] E. Styger, "Using the HC 06 Bluetooth Module," *Instructables*, 19-Jun-2013. [Online]. Available: <https://cdn.instructables.com/ORIG/FX1/N43N/IMXQP4WO/FX1N43NIMXQP4WO.pdf>.
- [11] "IEEE Code of Ethics." IEEE - Advancing Technology for Humanity, www.ieee.org/about/corporate/governance/p7-8.html.

DESIGN AND PRODUCTION OF A THERMAL DISPLAY

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Collaborating Entity: University of Illinois at Urbana-Champaign

ABSTRACT

Display technologies have been stagnant during the last decade. Ever since the invention of the first display in 1927 there have barely been any disruptive innovations in the way displays work. This project aims to change that by exploring how not only light, but also heat can be used as energy sources for a display.

Keywords: Display, Heat, Thermal, Thermochromism

6. Introduction

Thermally activated display technologies do not exist in a feasible form yet. The ones that do exist, are expensive, fixed and mainly used for advertising. Ideally, for a thermal display to be marketable and truly disrupt the display technologies market, it should be cheap to make, able to display images and text with reasonable resolution and reconfigurable.

The objective of this project is to make a proof of concept that will allow to open the door to future research with thermally activated displays. The proof-of-concept will be a thermochromic display composed of a grid of 45 'pixels', each of which is a tightly wound Nichrome wire, pressed against the thermochromic paper and connected to a microcontroller via 8-bit shift registers. This would be a 12 cm x 60 cm reconfigurable display monitor to display texts with high quality. The Nichrome wires for the different pixels will be heated individually, which would change the color on the thermochromic paper with rising temperature, based on the text set to be displayed on the screen.

7. Definition of the Project

To approach this project, first and foremost, a broad research will be done into the different materials used to convert electricity into heat. Then, once a material has been chosen, a block diagram shown in Diagram 2, will be designed. This block diagram will allow the project to be broken into small subsystems so that it can be pipelined and a problem in one subsystem won't affect directly another subsystem. Lastly, once every subsystem has been designed, production will start.

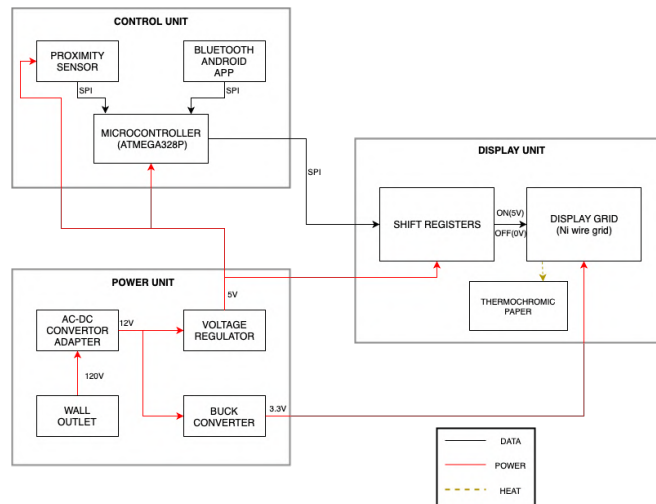


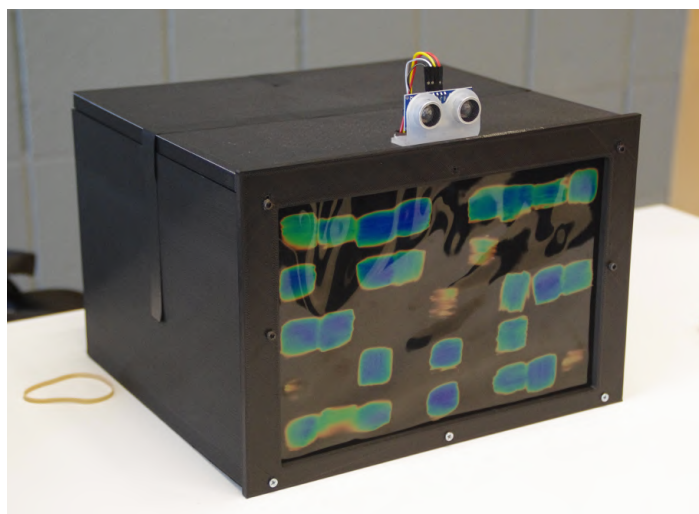
Diagram 2. Block Diagram

The final product will be able to reconfigure the text displayed within 10 seconds, show clear and legible letters and have a feedback mechanism so that a user can interact with it. Furthermore, ideally, the user will be able to decide what text is displayed through the use of an Android app.

8. Results

The final product is shown in Picture 2. As expected, it fulfills successfully all of the essential objectives, but not the reach goal of allowing the user to reconfigure the text displayed by using an Android app.

Unfortunately, in the making of the display, some pixels were damaged and which lead to them either not activating fully or remaining completely inactive. Which affects the first objective, but the letters are still legible, yet not clear.



Picture 2. Thermal Display

9. Conclusions

The project mainly deals with uncertainties in power and current draw. Currently, each Nichrome wire draws about 0.09A of current to generate an average ramp-up rate of 6 seconds to blue. However, if a pixel is left turned on for too long, the resistance of the wire could change and this would change the current draw accordingly. Other uncertainties arise for future work on the project, such as, if the display were to be scaled from the current 45 pixels to a larger number of pixels, the current draw would be very high depending on the number of pixels used. Thus, it may become difficult to provide such a high amount of current at a low potential difference of 3.3V as electrical components rated for such high current are difficult to come by.

10. References

- [1] All about Flexible Macroelectronics. [Online]. Available: <https://macroelectronics.blogspot.com/2007/10/electronic-papers-history-and-future.html>.
- [2] NanoDays. "Exploring Materials-Liquid Crystals." 2013, http://www.nisenet.org/sites/default/files/catalog/uploads/1989/materialslc_sign_15nov10.pdf.
- [3] *AmbiKraf*. [Online]. Available: <https://cargocollective.com/ambikraf>.
- [4] "Thermochromic Display," *Vimeo*, 27-May-2019. [Online]. Available: <https://vimeo.com/2616647>.
- [5] "Functional Printing," *Printed Thermochromic Display Circuits*. [Online]. Available: <http://www.hallcrest.com/our-products/special-effect-pigments/printed-thermochromic-display-circuits>.
- [6] L. L. C. H&H Graphics, "Thermochromic Printing Reveal Example," *YouTube*, 15-Feb-2017. [Online]. Available: <http://www.youtube.com/watch?v=Dt6Rb1brnZ0>.
- [7] G. Elert, "Temperature of a Healthy Human (Skin Temperature)," *Temperature of a Healthy Human (Skin Temperature) - The Physics Factbook*. [Online]. Available: <https://hypertextbook.com/facts/2001/AbantyFarzana.shtml>.
- [8] B. Hauke, "Basic Calculation of a Buck Converter's Power Stage," *Texas Instruments*, Dec-2011. [Online]. Available: <https://www.ti.com/lit/an/slva477b/slva477b.pdf>.
- [9] "Ultrasonic Ranging Module HC - SR04," *Sparkfun*. [Online]. Available: <https://cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf>.
- [10] E. Styger, "Using the HC 06 Bluetooth Module," *Instructables*, 19-Jun-2013. [Online]. Available: <https://cdn.instructables.com/ORIG/FX1/N43N/IMXQP4WO/FX1N43NIMXQP4WO.pdf>.
- [11] "IEEE Code of Ethics." IEEE - Advancing Technology for Humanity, www.ieee.org/about/corporate/governance/p7-8.html.

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Part 1. INTRODUCTION

1.1 MOTIVATION

Display technologies have come to a point where innovation has somewhat been stunted. Since the first LCD displays came out, most displays after that (LED, OLED, etc.) looked essentially the same, but with improvements towards making images more realistic. With one exception being the creation of electronic paper displays that were invented in 2008, following 35 years of research [1]. Leaving us with over ten years where there haven't been any disruptive innovations in the field of display technologies.

Thermally activated display technologies do not exist in a feasible form yet. The ones that do exist, which we will look into more deeply in Chapter 2, focus on building thermochromic paper with printed designs or text underneath them. They have been marketing their product for advertising. On touching the paper long enough, the body heat increases the temperature of the surface of the paper. This causes the thermochromic paper to become transparent and the text underneath is then revealed. Ideally, for a thermal display to be marketable and truly disrupt the display technologies market, it should be cheap to make, able to display images and text with reasonable resolution and reconfigurable.

The objective of this project is to make a proof of concept that will allow to open the door to future research with thermally activated displays. The proof-of-concept will be a thermochromic display composed of a grid of 45 'pixels', each of which is a tightly wound Nichrome wire, pressed against the thermochromic paper and connected to a microcontroller via 8-bit shift registers. This would be a 12 cm x 60 cm reconfigurable display monitor to display texts with high quality. The Nichrome wires for the different pixels will be heated individually, which would change the color on the thermochromic paper with rising temperature, based on the text set to be displayed on the screen.

1.2 OBJECTIVES

‘Thermal Display’ is a thermally activated display that uses Thermochromic paper, otherwise known as ‘Liquid Crystal Sheets’, as its viewing screen. The liquid crystals respond to changes in temperature by changing color [2]. With an increase in temperature, their color changes to red, orange, green, and then to blue. There is a heating grid composed of tightly wound Nichrome wires, pressed against the thermochromic paper, that allow heating up specific areas of the display. These Nichrome wires are connected to a microcontroller via 8-bit shift registers that allow them to be controlled individually.

The main objective for the project is for it to set grounds for future work in the field of thermal displays. In order for that to happen, the display will have to cover some key goals that will be broken down and explained in section 4.2.

Part 2. DESCRIPTION OF THE TECHNOLOGIES

2.1 THERMOCHROMIC PAPER

The most important component of the project is the Thermochromic paper as it is going to be what really transforms heat into a visible display.

Thermochromic paper was first invented in the 1990s and it is a thin paper that by the use of encapsulation techniques holds together thermochromatic liquid crystals. These TLCs are the agents that allow for the paper to show different colors with different temperatures, as TLCs are liquid crystals that change color with different temperatures.

For the project, the paper used is able to go from dark brown to blue between the temperatures of 30°C and 35°C, staying inactive below 30°C and deep blue above 35°C.

2.2 NICHROME WIRE

Nichrome wire is a type of wire made out of an alloy of Nickel, Chromium and Iron in different measures. It is used as a resistance wire, as it has a larger resistance than regular wire, depending on its gauge. Another property of Nichrome is that it can hold really high temperatures, reaching them with very little current.

For the project, both properties will be used to heat up the thermochromic paper that will display characters. In order to do this, current will be applied to the wire which will heat up to a specific temperature depending on the current applied and the wire's gauge, which sets the wire's resistance.

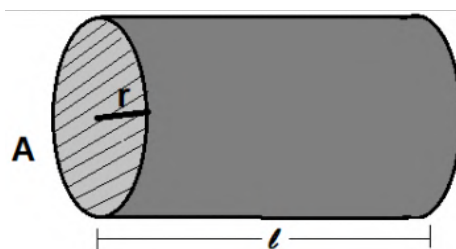


Figure 1. Cross-sectional area of Nichrome wire

In order to understand how temperature varies with current applied to the Nichrome wire, it is necessary to look at the formula for electrical resistance of any material:

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

$$\rho = 1.3 \times 10^{-6}$$

Further on, using the formula for electrical Power, it is possible to calculate the charge, Q .

$$\text{Power} = i^2 \times R = \frac{Q}{t}$$

$$Q = t \times i^2 R$$

Where t is the amount of time during which current will be applied to the wire. In this period of time the pixel should be able to become fully activated, meaning that the Thermochromic paper will reach a temperature of 35°C, this will be referred to as the ramp-up rate. Lastly, the charge can also be obtained through the following formula:

$$Q = mC(T_f - T_i)$$

Knowing that the initial temperature, T_i , would be 21°C (room temperature) and that the final one, T_f , is 35°C, it is possible to calculate the current needed to activate a pixel in a given time t .

Part 3. STATE OF THE ART

3.1 SIMILAR PROJECTS AND STUDIES

Since the invention of TLCs there have been some attempts by researchers to use them to create displays for different reasons, but they all seem to be very focused and inflexible, as well as not modular.

First of all, AmbiKraf [3] is a thermal display created by Roshan Lalintha Peiris and her team that uses Peltier elements to heat a piece of thermochromic ink fabric to display characters. This project worked great to heat up the fabric, but it had very long ramp-up rates of the pixels as fabric needs more energy to be heated as it is a relatively bad thermal conductor.

Next, the Thermochromic Display by ‘Che-wei Wang’ [4] consists of standard light bulbs arranged in a grid, with a layer of thermochromic paint on them. When each light bulb is turned on, it heats up and the increase in temperature causes the Thermochromic paint to change color. This display can only produce linear patterns and its size is limited to the size of a lightbulb, making it very large.

Large companies such as LCR Hallcrest [5] and H&H Graphics [6] have developed thermal printing technologies that allow for a specific image to show when heat is applied. These techniques take virtually no space as they are made of two layers of paper, but they are also very inflexible, allowing to only show one word, image or character.

Part 4. PROJECT OVERVIEW

4.1 JUSTIFICATION

Innovation in the display technology sector has been stagnant since almost 15 years ago. Marketers have found a technology that is scalable, marketable and already adopted by the public and have found ways to make users buy new incremental inventions that don't really have an impact on the user's life other than slightly improving their experience. Further on, the advances in technology over the past few years are allowing to explore and discover new technologies but the companies were too focused on investing in what's safe and marketable, so these new possibilities have not been explored yet.

The objective of this project is to prove that thermal displays are a viable alternative to regular displays with the added pro that they don't harm your eyes when using them and also, can display characters in a more artistic way.

4.2 OBJECTIVES

In order to make sure that the project can set grounds for future work it is essential that the display made has the following characteristics:

- The display must be able to reconfigure text within 10 seconds.
- The display must show legible letters using the "Seven-segment" font character representations.
- The display must have a feedback mechanism such that when a user places their hand in front of it, the text would change.

Then, some objectives that would add utility to the display but are not essential for it to accomplish the main objective are:

- It must be possible to reconfigure the characters displayed easily by the user through an Android app.

4.3 METHODOLOGY

In order to make sure that the project is successful, it is important to make sure that the right materials were chosen, the technology works, and that a final product is made on time. In order to achieve this, a three phase process will be put in place as follows:

Phase 1 will be dedicated solely to testing different materials that will be used in the making of the display. This is important as based on these materials chosen, and more importantly on the materials chosen for the pixels, the display's total current draw, its aesthetics and its ramp up rate will be determined. The objective of phase 1 is to find the combination of thermochromic paper, nichrome wire gauge and possibly, insulating material that allow for the best pattern to show on the pixels and the least amount of power consumption. To do this, first a temperature range for the thermochromic paper will be chosen. Next, different nichrome wire gauges will be tested with the chosen thermochromic paper. Lastly, the need for an conductor to be placed in between the paper and the wire will be assessed.

Phase 2 will involve the making of the first prototype. This prototype will be one character with 15 pixels plugged directly to a voltage source with a set current and voltage that will be controlled through a microcontroller to display a letter. This is essential as it will allow to prove that the technology works correctly, as expected. Given the case that the prototype doesn't work as desired, phase 1 will have to be reassessed until a new combination of nichrome wire and thermochromic paper is found that allows for the technology to work.

Phase 3 will be the making of the final product, a three-character display with 45 pixels in total. In this phase, the 3D printed case will be designed, as well as the code for the microcontroller will be written, all the pixels will be made and the PCB will be designed and produced. Finally, everything will be put together and tested to make sure that the final product is works.

4.4 *TIMELINE AND ECONOMIC FORECAST*

For any project, it is essential to set from the beginning an expected economic forecast so that enough funds can be allocated and the project is not underfunded, which could lead to its failure, and an expected timeline with set objectives to rest assured that the project is going in the right direction.

4.4.1 **TIMELINE**

Having a timeline for the project will make it possible to detect malfunctioning parts of the project and delayed processes so that it is possible to pivot the project before it is too late.

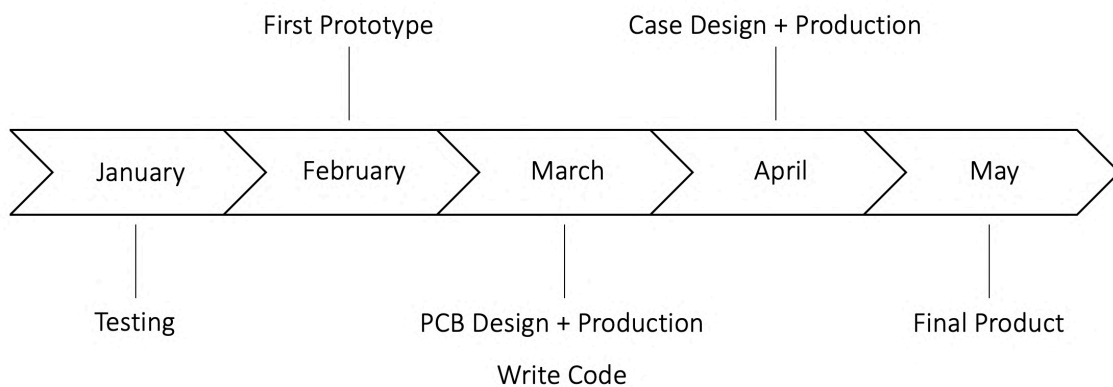


Figure 2. Project's Timeline

As shown in Figure 2, first, some testing will be carried out to find what materials are most suitable for the project as there are different gauges of Nichrome wire as well as different activation ranges for the thermochromic paper. Next, a prototype will be made to prove that the technology works. Lastly, the final product will be made with the microprocessor programmed and the case designed.

4.4.2 **ECONOMIC FORECAST**

This project's economic forecast is shown Table 1. It is important to keep in mind that the forecast takes into account all materials that will be used in the project, both for the final version and for the prototyping, thus, inflating the project's total cost.

<i>Part</i>	<i>Description</i>	<i>Manufacturer</i>	<i>Q</i>	<i>Cost</i>
25-30°C Thermochromic Paper	4"X4" Used for Research/Prototyping 1 pixel	Education Innovations Inc.	1	\$7,95
30-35°C Thermochromic Paper	4"X4" Used for Research/Prototyping 1 pixel	Education Innovations Inc.	1	\$7,95
35-40°C Thermochromic Paper	12"X12" Used for Research/Prototyping 1 pixel	Edmund Optics.	1	\$25,00
30-35°C Thermochromic Paper	4"X4" Used for main display pixels	Education Innovations Inc.	27	\$7,95
Nichrome Wire	Resistive wire	Master Wire Supply	1	\$17,99
AC-DC Converter	In: 100-240V AC Out: 12V 2A	eBoot	1	\$6,99
Voltage Regulator	TPS76333DBVRG4	Texas Instruments	2	\$1,10
Microcontroller Chip	A TMEGA328P-PU	Microchip Technology	1	\$2,50
Temperature Sensor	RTD Probe	Walfront	4	\$6,00
Aluminum Plate	0.25" ALUMINUM PLATE 6061-T651 12"x36"	OnlineMetals	1	\$60,00
Step Down Converters	Mini MP1584EN DC-DC Buck Converter Adjustable Power Step-Down Module pack	eBoot	2	\$7,85
PCB	Printed Circuit Board to hold all electrical components	PCBway	1	\$75,00
IRF510x45	Transistors	Vishay Siliconix	45	\$43,80

12V 5A 60W AC DC Power Supply Adapter	Voltage Supply	CHANZON	1	\$15,84
MAX7219CNG	LED Driver	Maxim	18	\$9,98
8-bit Shift Register SN74HC595N	SR for pixel control	Texas Instruments	6	\$4,54
Ultrasonic Sensor	U500.DA0.2-IAMJ.72F 1000mm	Baumer	5	\$4,00
			Total	\$304,44

Table 1. Economic Forecast

Part 5. DESIGN OF THE PROJECT

Without a good design the project would be unfeasible, which is why, in this chapter it will be explained how this project was designed, from both a physical and systems point of view.

5.1 *PHYSICAL DESIGN*

The physical design of the project is broken into two parts. First, the pixel size is determined. Second, the general dimensions and specifications of the project are determined based on the pixel size and number of pixels desired.

5.1.1 PIXEL DESIGN

The final product will be able to display three letters at a time, each letter having 15 pixels of 2.54 cm in height by 2.54 cm in width, as can be seen in Figure 3, and will be controlled by a microprocessor and other peripherals.

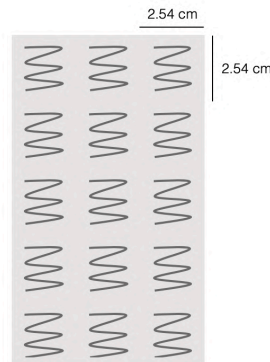


Figure 3. Schematic View of a Letter

Each individual pixel is made up of three layers, as can be seen in Figure 4. The top layer being a sheet of 30°-35°C thermochromic paper, the second, 10 cm of nichrome wire and, the third, a piece of adhesive foam of 0.5 cm thickness, 2.54cm in thickness.

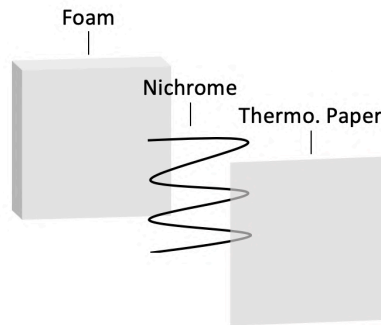


Figure 4. Exploded View of a Pixel

5.1.1.1 Thermochromic Paper

The only decision that had to be made regarding this layer was the temperature range of the paper from the four available options: 20° – 25°C, 25° – 30°C, 30° – 35°C and 35° – 40°C.

The first option with activation ranges between 20° and 25°C would not be suitable for the project as when exposed to room temperature, which is around 21°C, the paper would be active, making it impossible to read the characters displayed. Unless fans were used to cool down the pixels constantly, which would add an unnecessary complexity and more power consumption.

The second option with activation ranges between 25° and 30°C would work for the project, but there is a small inconvenience, if a hand were to touch the paper, it would quickly become active as a human's internal body temperature tends to be around 37°C and that of its skin around 34°C [7].

Between the two remaining options, the smarter choice would be to choose the one that would require the least power consumption, thus, the one that would need less heat for the project to work. Thus, the most suitable temperature range for the thermochromic paper is the one between 30° and 35°C as each pixel's temperature would only need to be raised around 10° to 15°C for it to be active, as opposed to 15° to 20°C if the paper with temperature range between 35° and 40°C were to be chosen.

5.1.1.2 Nichrome Wire

Nichrome wire can be found in a range of gauges (g) which is the standard measure for the wire's thickness being a small gauge a large thickness and a large gauge, a small thickness. Eight different gauges were offered, from 22g to 36g in intervals of two.

As the formula for resistance (1) shows, an object's resistance is inversely proportional to its cross-sectional area, which is in accordance to the measurements made for the nichrome wire shown in Figure 5.

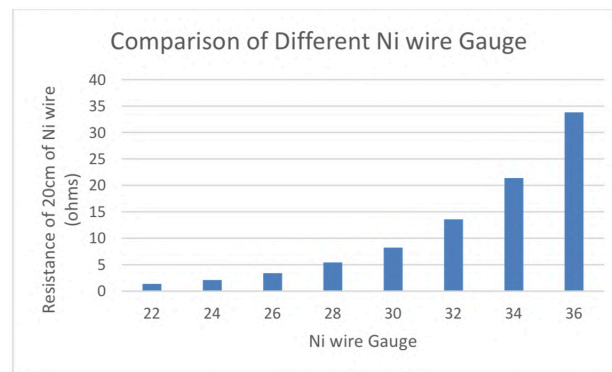


Figure 5. Nichrome Wire Resistance vs Gauge

In order to achieve faster ramp-up rates, it is essential that the wire's resistance is as large as possible, thus, it only makes sense to choose the one with the higher resistance, thus the larger gauge. As can be seen in Figure 6, from the measurements made using a 20cm piece of nichrome wire, the one with the fastest ramp-up rate was the 36g wire which would allow the 30° - 35°C thermochromic to be fully active within 5 seconds.

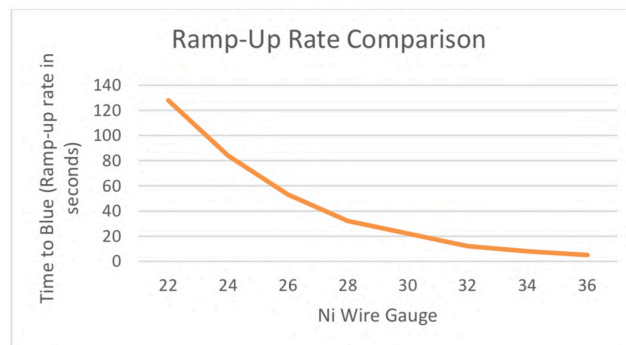


Figure 6. Nichrome Wire Gauge vs Pixel Ramp-Up Rate

5.1.1.3 Foam

This layer is necessary due to the fact that the wire needs a supporting material and cannot be glued to the thermochromic paper as in that case the project would not be modular any more. It is essential that the project is modular so that in case a pixel breaks, it can be easily replaced by a new one.

5.1.2 OVERALL DESIGN

The project will need a case made out of three parts, a front frame to hold the thermochromic paper in place, a top layer to be able to easily access the interior, and a bottom frame that will hold the components, PCBs and cables.

Figure 7 shows a front view of the case and its dimensions in millimeters, the overall dimensions will be 27 cm in width, 18.8 cm in height and 30 cm in depth. The actual display will have 22.5 cm in width and 15.2 cm in height. A 3D side view of the case can be found in ANNEX A.

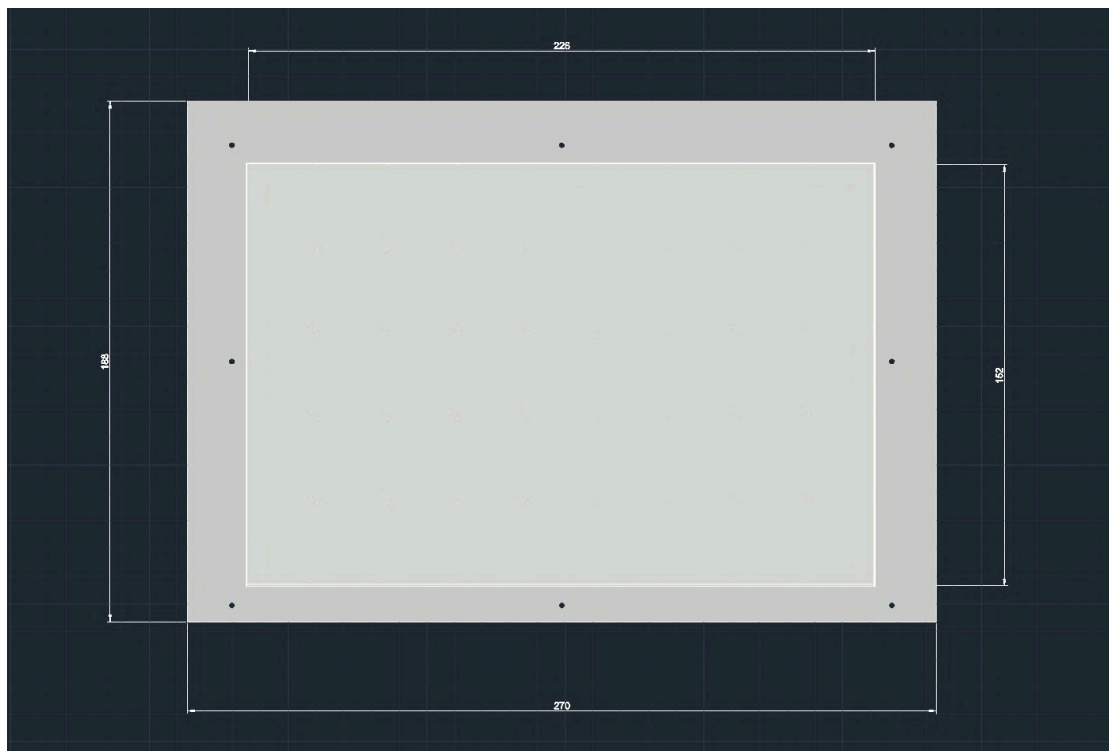


Figure 7. Front View of the Case

5.2 BLOCK DIAGRAM

The whole project can be summarized by the design of a block diagram that explains how each component or sub system of the project works and interacts with the others. Figure 8 shows the project's block diagram.

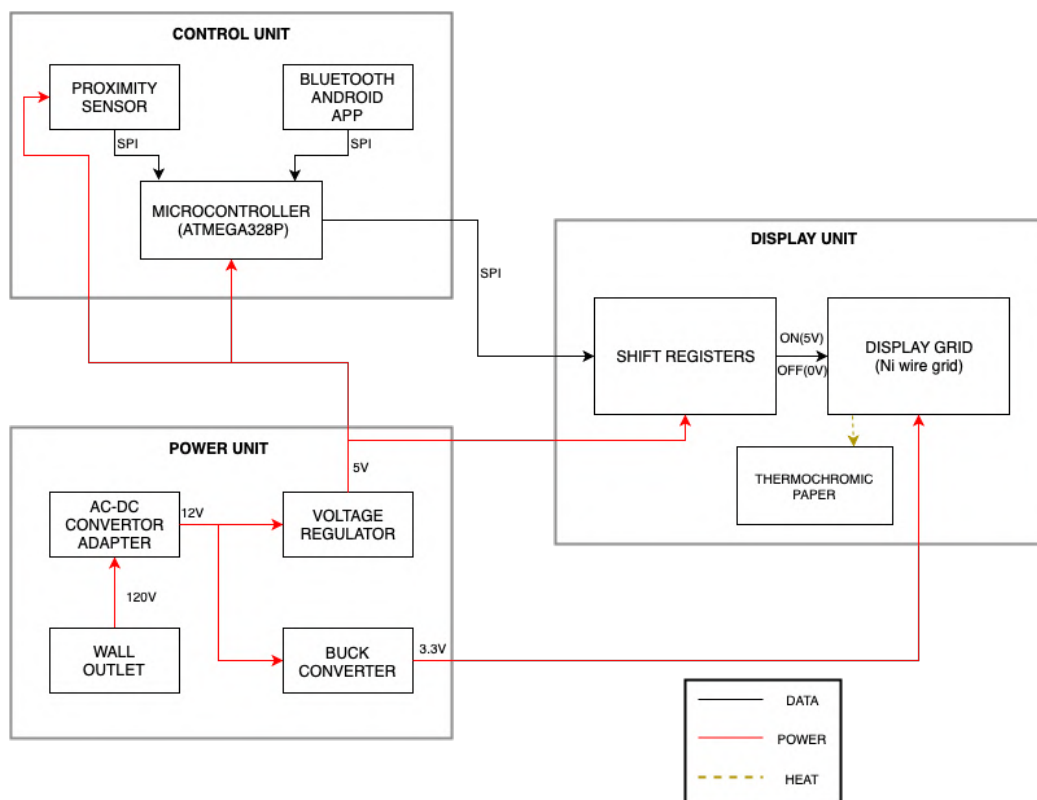


Figure 8. Block Diagram

The design is made up of 3 primary components: Control Unit, Power Unit and the Display Unit. The Power Unit takes input from the wall outlet and sends 5V via the Voltage Regulator to the Proximity Sensor, Microcontroller and the Shift Registers. The Buck Converter in the Power Unit sends 3.3V to the Display Grid (made up of Nichrome wires and N-Channel MOSFETs). The Control Unit has a Microcontroller which stores the program for controlling individual pixels in the display grid, to display letters. It takes input ideally from a Bluetooth app that tells it which 3-letter-word to display. The proximity sensor sends the proximity data to the Microcontroller. The Display Unit takes input from the

Microcontroller, which sends 2 sets of 8-bit data to the shift registers. The shift registers use this data to switch on or off the required individual pixels in the Display Grid. The Display grid uses n-Channel MOSFETs to drive 3.3V through a coil of Nichrome wire when the ‘on’ signal is given by the shift registers for that pixel.

5.2.1 POWER UNIT

The power unit, shown in Figure 9, is comprised of a wall outlet, an AC/DC converter adapter, a voltage regulator, and a buck converter. Figure 9 shows a more detailed block diagram of the power unit. The Wall Outlet provides an input of 120V of AC current to the AC/DC converter. This adapter converts 120V AC to 12V DC current. This 12V DC current is fed as input to a buck converter and a voltage regulator. The buck converter converts it and provides an output of 3.3V to the Display Grid and the voltage regulator provides 5V to all the components in the thermal display.

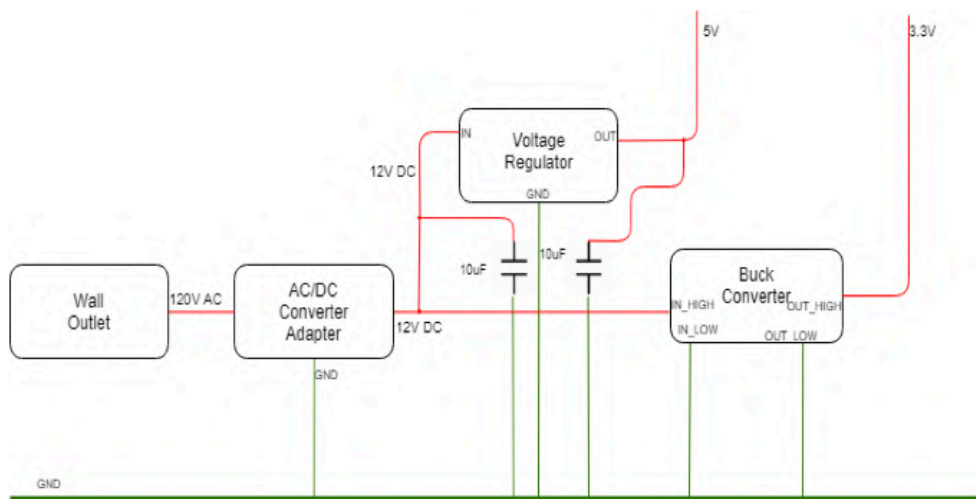


Figure 9. Power Unit

The total power consumption and maximum current draw are calculated as follows:

$$Power = i^2R \times n$$

Where ‘*i*’ is the current flowing through each pixel, ‘*R*’ is the resistance of the Nichrome wire in each pixel and ‘*n*’ is the total number of pixels. The current will be set to 0.09 A to

allow the desired ramp-up rates, the resistance of 10 cm of Nichrome wire is 35Ω , and the number of pixels will be 45, which gives the following power:

$$Power = 0.09^2 \times 35 \times 45 = 12.76W$$

The total power consumption by the display grid when all the pixels are activated is 12.76W.

$$Total Current = i \times n = 0.09 \times 45 = 4.05 A$$

The maximum current draw when all the pixels are activated is 4.05A.

5.2.1.1 Wall Outlet

The entire system will be powered from a wall outlet. This will provide enough power to heat up the heating coils to a temperature of about 35°C and for the microcontroller and sensors to run indefinitely.

5.2.1.2 AC/DC Converter and Adapter

The converter converts 120V AC current to 12V DC current and is rated for 5A current and a maximum power output of 60W. This is important as it may have to provide up to 4.05A at a time. The converter used requires a 2.5 mm DC power jack to provide output to the circuit.

5.2.1.3 Voltage Regulator

The voltage regulator used is the MCIGICM 7805 linear voltage regulator [REFERENCE <https://www.sparkfun.com/datasheets/Components/LM7805.pdf>]. This voltage regulator can step down input voltage from 7-35V to 5V and maintain the potential difference with 2% regulation. This chip takes an input from the AC/DC converter at 12V and outputs a 5V current to the different microchips used in the project.

5.2.1.4 Buck Converter

Buck converters are known for their high current rating while dividing voltages by a factor of D ($0 < D < 1$) [8]. A DC-DC adjustable step-down Buck converter is used to step down voltage from 12V to 3.3V. The converter used is the ‘LM2596 buck converter’ and can handle a total output power of 75W. It is rated for 5A of current and therefore will be safe to use for the project which has a maximum current draw of about 4.05A.

5.2.2 CONTROL UNIT

As seen in Figure 10, the control unit comprises of 3 main components: The microcontroller, the ultrasonic sensor and the Bluetooth module. The microcontroller houses the code for controlling the shift registers in the display unit, to heat individual pixels as required. The ultrasonic sensor communicates with the microcontroller via SPI protocol and provides the distance of the user from the screen. The Bluetooth module receives data from an android app that sends it the text data to be displayed on the screen. Using the input from the ultrasonic sensor and the Bluetooth module, the microcontroller decides which pixels to activate to display the required text. It then sends out this data to the shift registers via the respective ‘latchPins’ and ‘dataPins’.

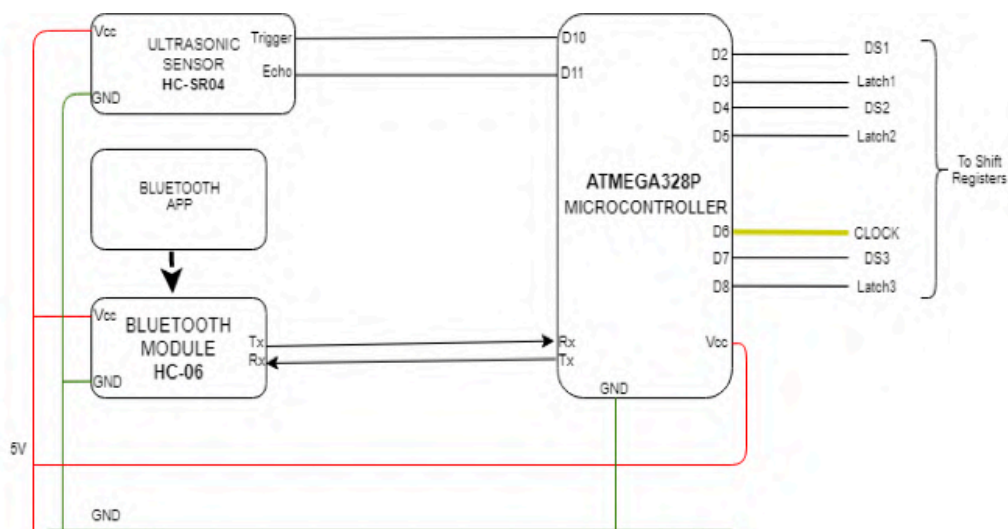


Figure 10. Control Unit

5.2.2.1 Ultrasonic Sensor

The sensor used is the HC-SR04. It has a working frequency of 40Hz, with a max range of 4m and a min range of 2cm [9]. The sensor requires a supply of a short 10uS pulse to the trigger input to start the ranging, and then the module sends out an 8-cycle burst of ultrasound at 40kHz and raises its echo. The distance can be calculated using the time interval between sending the trigger signal and receiving the echo signal.

$$distance (cm) = \frac{time (\mu s)}{58}$$

5.2.2.2 Bluetooth Module

The Bluetooth module used is the HC-06 module. It receives data from an Arduino app via Bluetooth and then sends it to the microcontroller over an SPI protocol [10]. The module receives instructions from the Microcontroller through the RXD pin on the module and sends data to the microcontroller via the TXD pin. It works at power levels between 3.6V-6V and has a Bluetooth range of up to 9m. An android app on the phone allows the user to send a 3-letter-word text to the Bluetooth module which is then sent to the microcontroller and is used to display the required word on the display.

5.2.2.3 Shift Registers

The microcontroller used is the ATMEGA328P as it is one of the standard Arduino Uno Microcontroller chips with more than enough processing power and I/O ports. Figure 11 shows the schematic of the microcontroller in detail. Furthermore, it communicates with the ultrasonic sensor using the SPI data protocol and has a clock speed of 10MHz. Such speeds are necessary for the controller to process proximity sensor data quick enough to provide a seamless user feedback when the user waves his hand in front of it. Also, the number of i/o ports are necessary to implement the display grid using the shift registers and control each pixel independently.

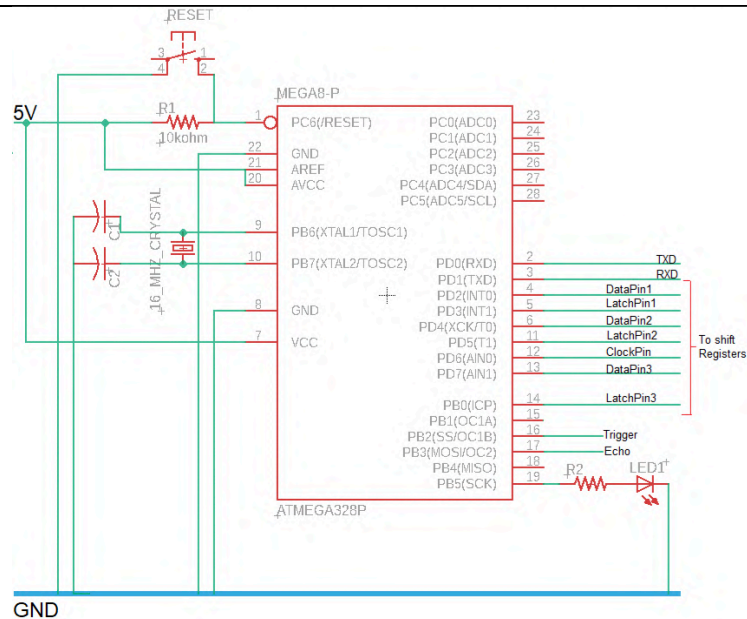


Figure 11. Detailed Schematic of ATMEGA328P

5.2.3 DISPLAY UNIT

The Display unit consists of shift registers, a grid of Nichrome wires connected to them via n- Channel MOSFETs and a thermochromic paper screen. Figure 12 shows how the 3 letters are controlled in parallel by 2 cascaded shift registers each. Each letter is displayed using a matrix of 5x3 Nichrome wires in a row first order. 2 cascaded shift registers control the output through each shift register via n- Channel MOSFETs which, when activated (5V signal), run a current of 0.09A at 3.3V through each Nichrome wire pixel. The Nichrome wires are pressed against the thermochromic paper, which when heated, changes color in the heated regions.

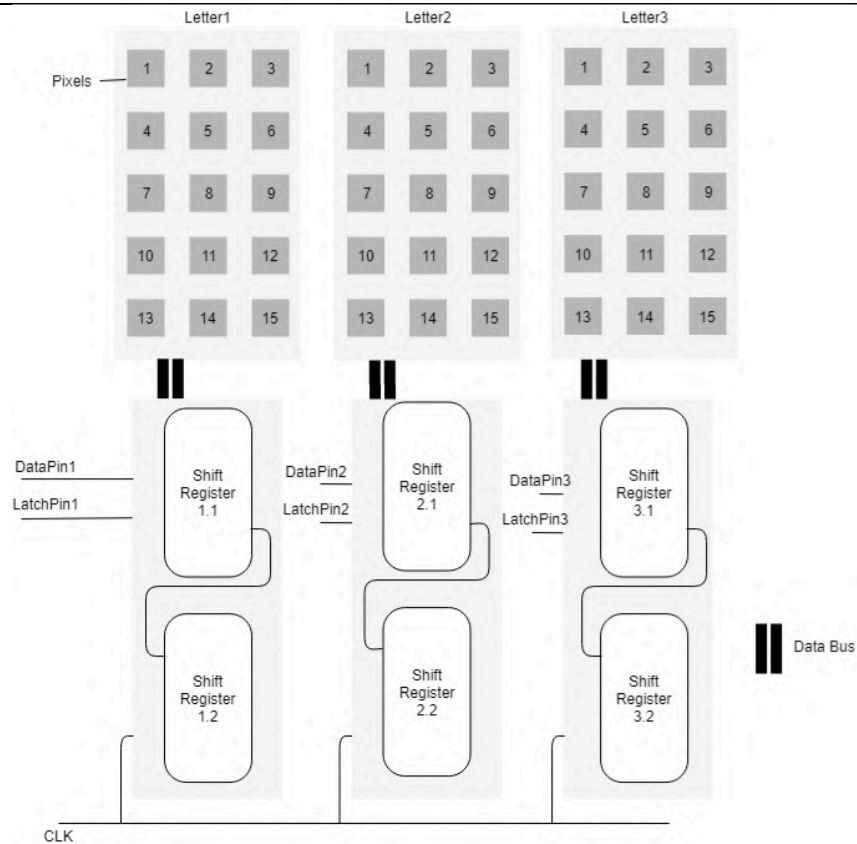


Figure 12. Display Unit Arrangement

5.2.3.1 Shift Registers

The shift registers used are the SN74HC595N 8-bit shift registers. Figure 13 shows a detailed view of how the Nichrome wires for each letter are connected to the two cascaded shift registers. The cascaded shift registers share the same Latch Pin and Data Pin on the microcontroller. All the shift registers share the same clock pin.

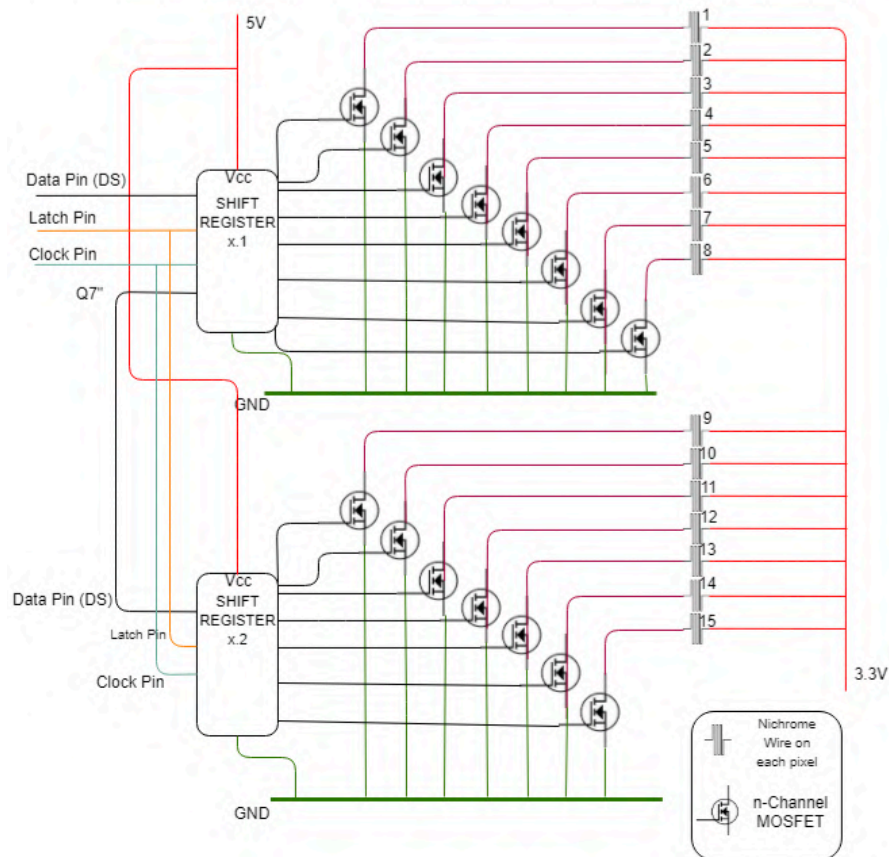


Figure 13. Detailed Schematic of Display Unit

5.2.3.2 Display Grid

The display grid consists of a grid of tightly wound Nichrome wires placed as individual pixels that are made as explained in 5.1.1.

5.2.3.3 Thermochromic Paper

A single sheet of thermochromic paper will be placed in front of the pixels to allow the display to show characters.

5.3 SOFTWARE

The software can be classified into two major parts. First, the code necessary to print character on screen and second, the code to decide what character to print on the screen.

For the first part, a library will have to be built that maps each ASCII character to two 8-bit numbers that will be the inputs of the shift registers for a specific letter.

For the second part, the code will take an input either pre-programmed or through the Bluetooth interface and based on the input from the ultrasonic sensor, it will decide what to print.

Figure 14 shows a flowchart for the example where the words “HEY” and “BYE” are coded into the microchip such that when a hand is placed within 10 cm of the sensor, the words will change.

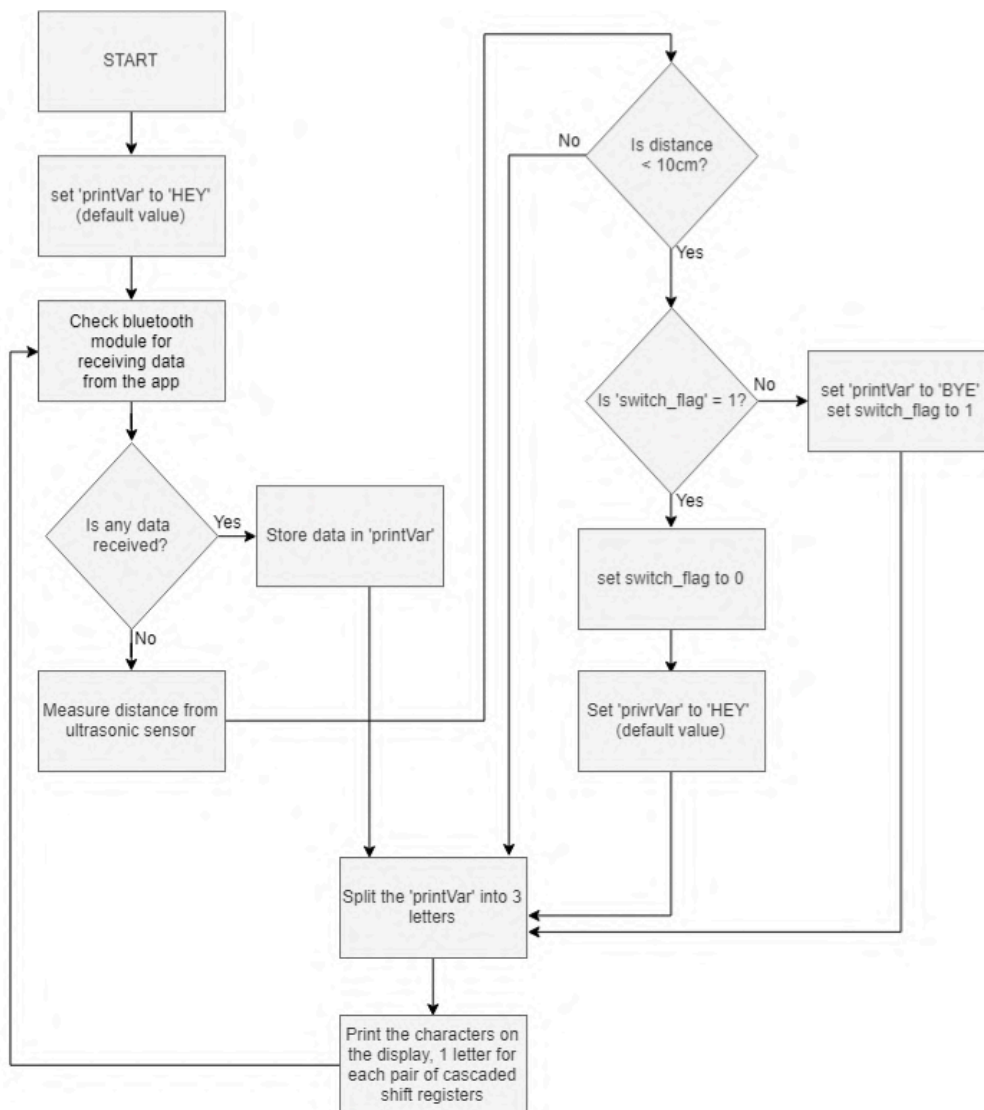


Figure 14. Software Flowchart

5.4 PCB DESIGN

One of the core parts of the project is its PCB as it's the platform used to connect all of its electronic components with the peripherals such as the ultrasonic sensor and the pixels.

The display will have two different PCBs, one with the microchip and other core circuitry and components, and a second PCB used to connect the pixels that will be individual for each letter. This second PCB will be identical for all three letters and will have the shift registers, connections to the pixels and transistors. Finally, the main PCB will connect to the three PCBs used for the letters through header pins.

5.4.1 DESIGN OF THE MAIN PCB

The main PCB will hold the microcontroller ATMEGA328P, the components and circuitry it needs to work, and the header pins that allow the PCB to connect to the voltage regulator, the ultrasonic sensor, the three other PCBs for the letters, and an extra header pin with additional connections to the empty I/O pins of the microprocessor, just in case they are needed.

So, in order for the microprocessor to work, it needs voltage that comes from an input jack that then goes into a voltage regulator that brings it down to its operating voltage of 7 Volts, it also needs some capacitors, resistances and a status LED.

Figure 15 shows the schematic made using Eagle Software to design and manufacture the PCB. In the schematic it can be seen all of the above mentioned components, the header pins JP1 to JP5 that connect to the peripherals and components previously mentioned, the voltage regulator IC17905T that brings the voltage down to 7 Volts from the input that comes at 12 Volts from the jack J1, and the ON/OFF switch PJ-002.

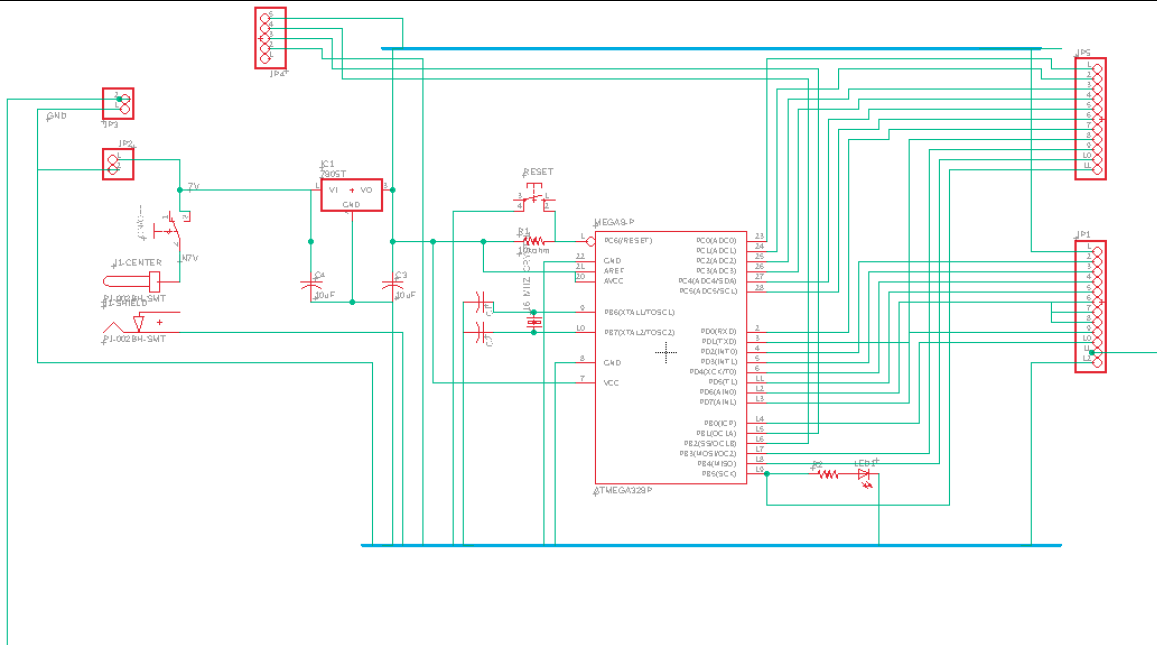


Figure 15. Schematic of the Main PCB

5.4.2 PIXEL PCB

Each Pixel PCB will hold all the circuitry needed to connect the 15 pixels needed to show one letter, meaning, 15 N-Channel MOSFET transistors, two shift registers and 30 header pins, 15 of them connected to the drain of the transistors, and the remaining 15 connected to +3.3 V.

Figure 16 shows the schematic of a Pixel PCB made using Eagle Software. As can be seen in the schematic, the header pins are located in ports JP1, for the +3.3 V, and JP2, for the transistor's drain, the two 74HC595N shift registers connected in series, the IRF512 transistors, and the inputs from the main PCB in JP1.

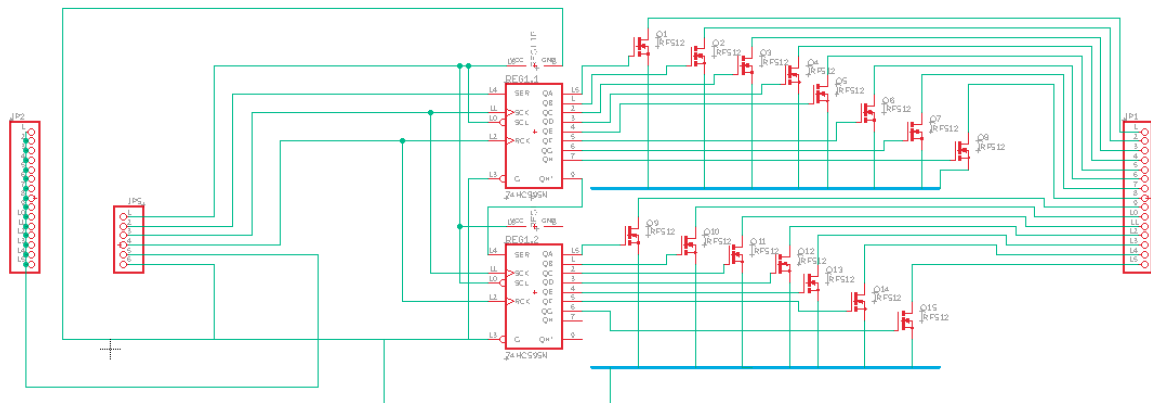


Figure 16. Schematic of the Pixel PCB

Part 6. BUILDING THE DISPLAY

Once the design of the project is finished, it is time to start building it. This process can be split into three parts. First, manufacturing the PCBs, second, making the pixels, and third, printing the case and fitting everything in.

6.1 MANUFACTURING THE PCBs

The PCBs are manufactured by a company called PCBWay, which simplifies the process as they ship them and all there is left to do is solder the components on them. In order for PCBWay to be able to print the PCBs, the connections in the PCB have to be drawn using Eagle Software by creating a .brd file. ANNEX B shows the resulting board layouts with the connections drawn.

PCBWay allows for a two layer board configuration, meaning that the PCB is made up of two layers so that the connections don't overlap each other as they would short-circuit. As can be seen in the board layouts, there are two different colors used for the connections, red and blue. Red shows the connections on the upper layer, and blue those on the lower layer. It takes around one week for the boards to be made and shipped, in the meantime, the pixels were made.

6.2 PIXEL MAKING

The first and hardest step in the pixel making process is to coil 10 cm of nichrome wire. In order to speed up and automate this process, a mold was 3D printed, as shown in Figure 17. Nichrome Wire Mold. By using this mold, the time it takes to coil one pixel went from 1 minute to just 10 seconds, making it 80% faster.

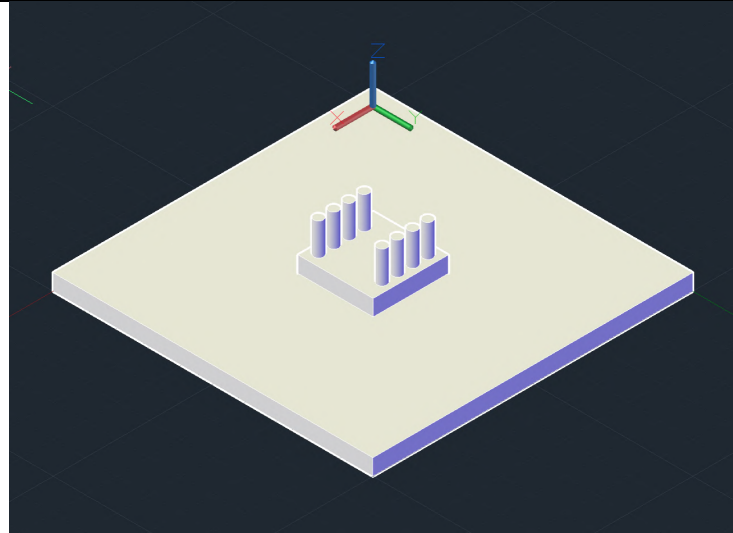


Figure 17. Nichrome Wire Mold

Once the nichrome wire had been coiled, it has to be glued to the adhesive foam, the result is shown in Image 1.

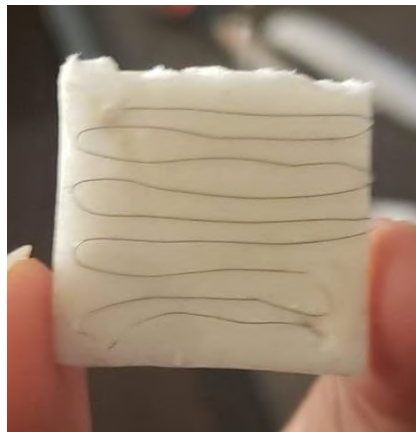


Image 1. Step 2: Nichrome Wire Adhered to Foam

The last step in the process is to solder the nichrome wire tips to regular wire that will allow the pixels to connect to the PCB.

6.3 PUTTING EVERYTHING TOGETHER

After printing the three parts of the case it is time to wire the PCBs, place them inside the case and proceed to connect the pixels to the PCB. It's important to be careful when connecting the pixels to the PCB as the nichrome wire is very thin and might break or short-circuit if it touches another pixel, making both pixels useless until fixed. The result of this

process can be seen in, it looks very messy due to the fact that there are over 100 cables in a very small volume.

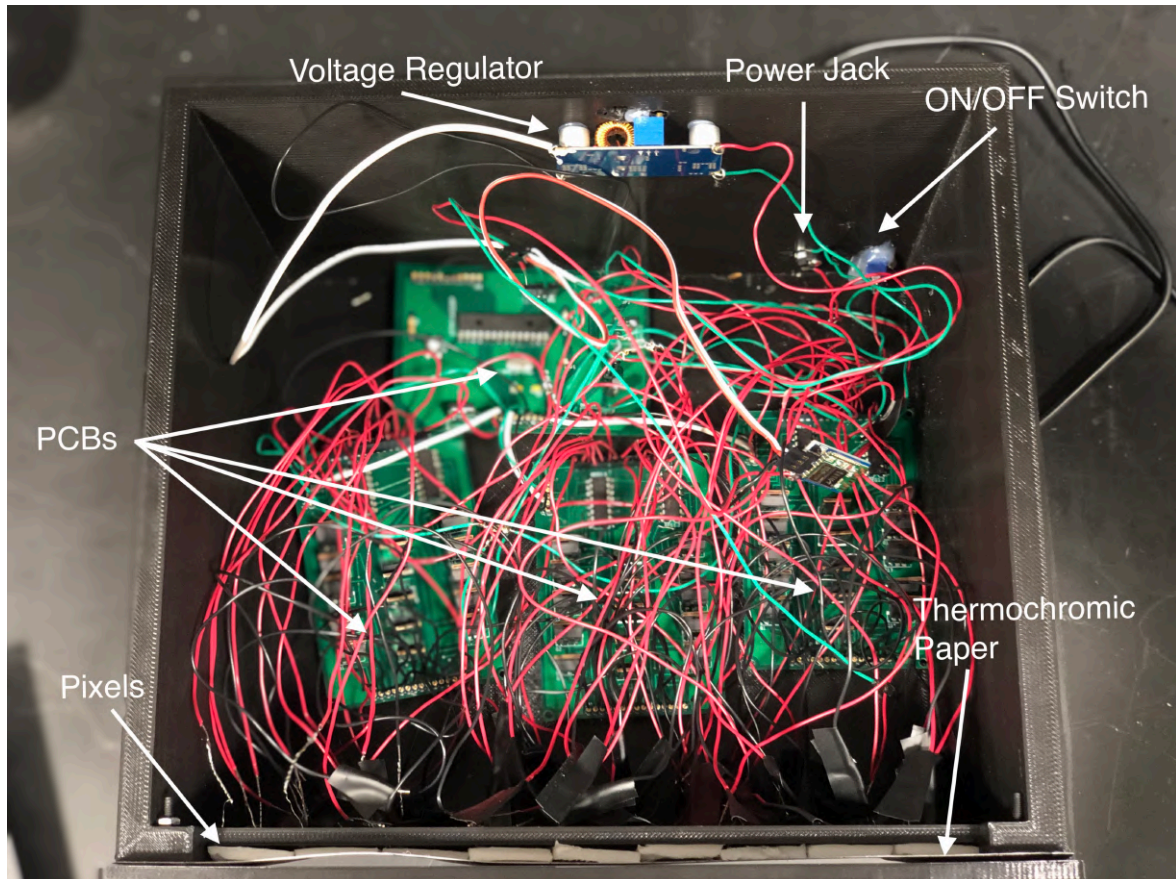


Image 2. Inside look of the Case

6.4 FINAL PRODUCT

After wiring the PCBs to the pixels and the other peripherals, everything was assembled and the final result can be seen in Image 3.

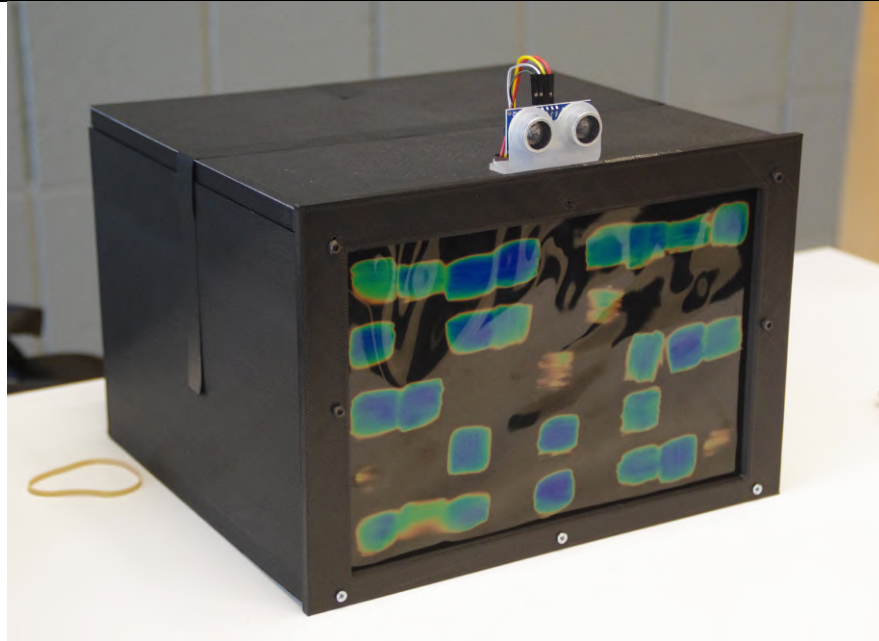


Image 3. Thermal Display

The display has been programmed to display two different words, first “HEY”, shown in Image 4, and once a user interacts with it by placing their hand within 10 cm of the ultrasonic sensor, shown in Image 5, the display changes to show the word “BYE”, shown in Image 6.

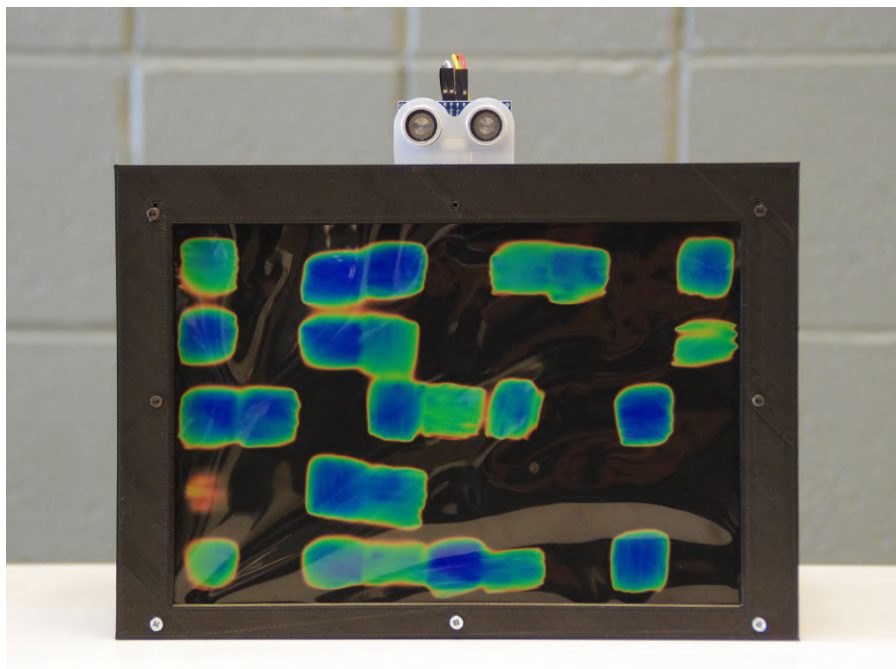


Image 4. Thermal display showing "HEY"

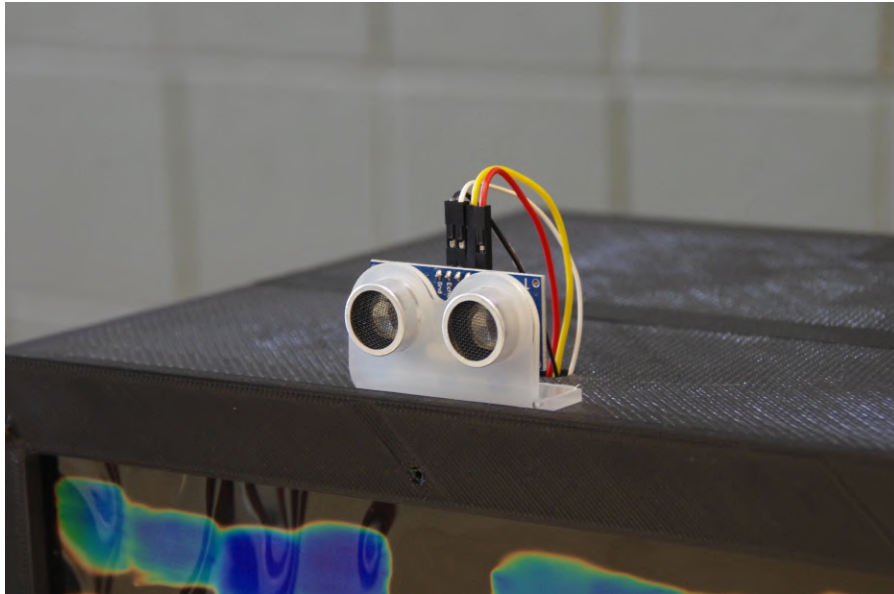


Image 5. Ultrasonic Sensor HC-04

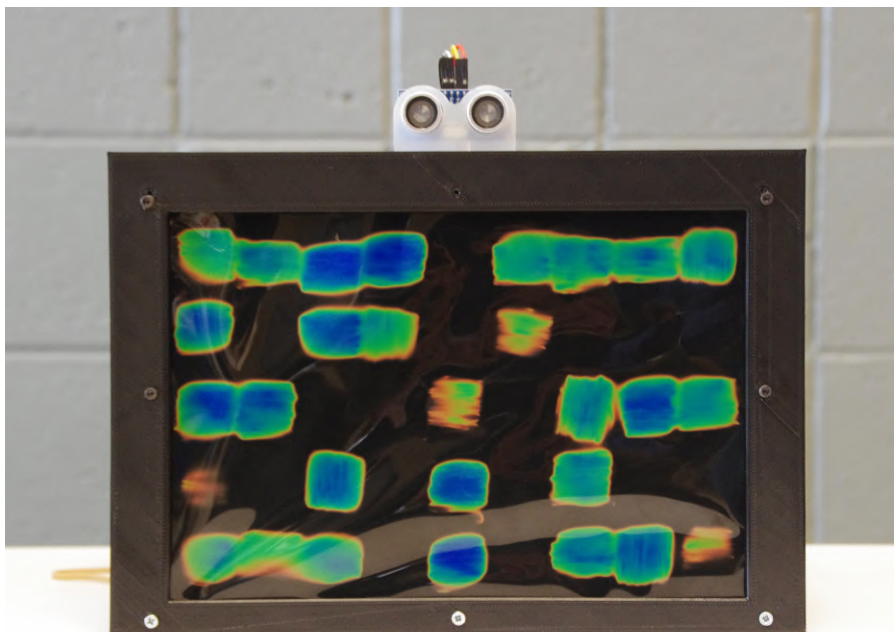


Image 6. Thermal Display showing "BYE"

Part 7. RESULTS VERIFICATION

Testing and checking results is an essential part of any project as it allows to make sure that the project's components and sub systems are working prior to finishing it, and that once finished, the project works as expected.

7.1 PIXEL RAMP-UP RATES

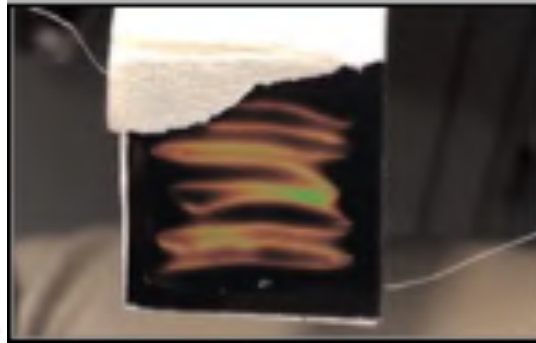


Image 7. ON Pixel

Before beginning to work on the project, the first thing to do was to pick out the correct materials and their amount for each pixel to achieve the required ramp-up rates. The amount of material was determined by the size of each pixel that we wanted to build, which was about 2.54cm x 2.54cm. To achieve a uniform heat spread, the material had to be tightly wound, and thus we decided to use about 20cm of the heating element. This heating element was tightly wound on a piece of sticky foam sheet of 2.54cm x 2.54cm and then pressed against a cut-out of the 30-35°C thermochromic paper of the same size. Figure 3.1 shows the prototype pixel made for testing the pixel's ramp-up rates. The heating element was then connected to the breadboard by soldering wires to its ends and then a variable power supply was connected to the breadboard in series with the pixel. Then, the power supply was increased until the measured current draw was about 0.1A. The voltage was noted and once the heating element cooled down, it was provided with 0.1A of current and the time for the thermochromic paper to turn to blue was measured. This measurement was performed four times and the average was noted. The different elements used were PTC heating element and

Nichrome 80 Alloy wires of gauge 22 to 36. The ramp-up rate of 36-gauge Ni 80 alloy wire came out to be 5 seconds, which was within the desirable ramp-up rate.

Once all the pixels were connected to the display, their initial ramp-up rate was on average 25 seconds, but after they had been active for one cycle, their ramp-up rates were of 6 seconds, on average. This difference is due to the fact that the pixels during the first cycle have to warm up from room temperature (21°C) to their activation temperature (35°C), but during the following cycles they only had to warm up from around 29°-30°C to 35°C, which is why they took less time to activate after the first cycle.

7.2 SHIFT REGISTER INDIVIDUAL PIXEL CONTROL

Shift registers are used to control each pixel individually i.e. to be able to activate an individual pixel independent of the other ones. Since we are using 45 pixels, and the project is to be scaled further to hundreds of pixels, we decided to use shift registers. To test if the shift registers could control the pixels properly, we performed 4 tests. First, a single shift register was connected to an Arduino on a breadboard and had an LED connected to each of its output pins. A program to turn on one LED at a time till all of them turn on was stored in the Arduino Uno and the output was noted. The LEDs turned on in the required pattern and the test was successful. Next, two shift registers were cascaded together and had a total of 16 LEDs connected to their output pins. A similar program was run on the Arduino Uno and the pattern was noted. The expected pattern was observed, and the test was successful. Next, two shift registers were connected to the Arduino in parallel. The registers shared both clock pins and latch pins but had their separate data Pins. A program to run the same pattern was run on the Arduino but it failed. Only one set of LEDs were showing the expected pattern. The test had failed and thus, the latch Pins were then separated as well. The test was repeated, and the observed pattern matched the expected one, thus, passing the test.

7.3 PIXEL RELIABILITY

Due to the difficulty behind the pixel making process that involved many steps with manual labor which led to uncertainty in their reliability, some pixels' connections were loose. This led to those pixels either being unable to activate fully, due to insufficient

current, or not activate at all due to no current running through them. An example of this is shown in Image 8.

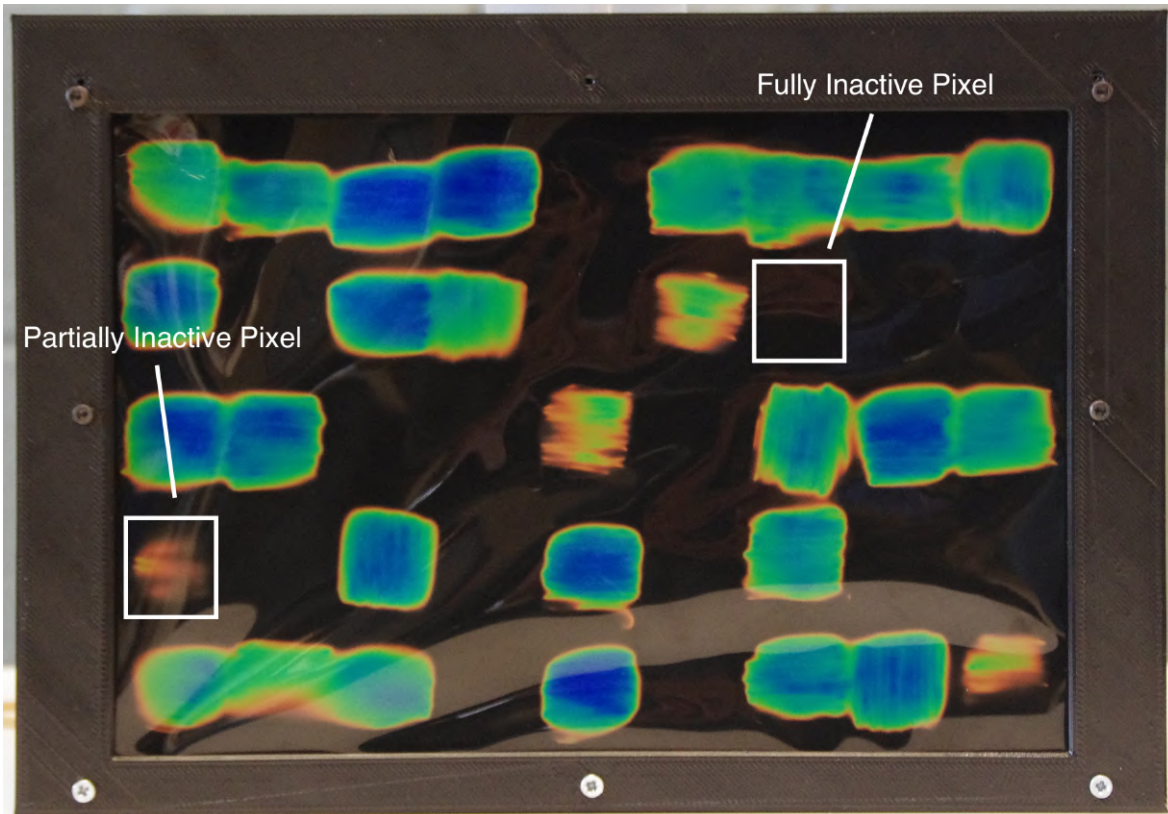


Image 8. Example of Malfunctioning Pixels

The solution to this would be to automate the pixel making process in a way that allows to have a more reliable connection between the pixel (nichrome wire) and the board, as the current connection was made by soldering the nichrome wire to a regular cable and then to the PCB. This caused some problems due to the fact that the nichrome wire has a coating that repels partially the solder. Furthermore, this coating only melts at temperatures higher than 250°C and the available soldering irons could only reach up to 190°C. A solution to avoid soldering the nichrome to the wire could be to use crimps which would make the project even more modular and the pixels easier to fix, but it would also take more time to make each individual pixel.

7.4 USING THE TRANSISTORS AS SWITCHES

N-Channel MOSFETs are used for delivering current to each pixel because each pixel requires about 0.09A of current but the shift registers cannot provide that high amount of current. Additionally, the shift registers provide an ‘ON’ signal with an output of 5V that we use as the transistor’s base signal to activate them when necessary.

To test the n-channel MOSFETs, two tests were carried out. First, a single n-channel MOSFET was connected to the prototyped pixel and an input of 3.3V. Then, the current passing through the pixel was measured using a multimeter and the ramp-up rate checked. The current passing came up to approximately 0.09A with the expected ramp-up rate.

Next, the MOSFETs were introduced in between the shift registers on the breadboard and the LEDs connected to them. The same test for shift registers was then conducted and the expected pattern was recorded. The test was successful.

7.5 BLUETOOTH CONNECTIVITY

Bluetooth connectivity was not achieved as the Arduino code was written and appeared to work, as well as a simple prototype of the App designed using “MIT App Inventor 2.0”, but when testing the data transfer it didn’t seem to work as expected as characters were not being received properly.

7.6 PROXIMITY SENSOR MEASUREMENT

The proximity sensor used is the Ultrasonic Sensor “HC-SR04”. In order to test the sensor, it was connected to an Arduino using a breadboard, its output was used to calculate distance and then printed on the Serial Monitor. An object was placed in front of the sensor at a distance of 10 cm the output was recorded. The distance displayed was on average 10 cm ± 0.2 cm. The error range was 2% which is acceptable for the project. The test was successful, and the proximity sensor was verified.

7.7 FINAL COST OF THE PROJECT

In 4.4.2 an economic forecast for the project, including prototyping was shown. XXXX shows the actual costs of making the display along with the potential costs in case it were to be mass produced. It is important to note that the bulk production costs are 48% lower than the cost of producing a single unit, at just \$60,53.

<i>Part</i>	<i>Manufacturer</i>	<i>Q</i>	<i>Bulk Cost</i>	<i>Actual Cost</i>
30-35°C Thermochromic Paper	Education Innovations Inc.	1	\$6,5	\$7,95
Nichrome 80 36 Gauge	Master Wire Supply	450 cm	\$2,1	\$3,29
5A DC-DC Adjustable Buck Converter	d-Planet	1	\$3	\$3
ATMega328P	Atmel	1	\$1,14	\$1,44
CONN PWR Jack Connector	CUI Inc.	1	\$1,44	\$1,7
SWITCH 0.05A 24V	Omron Electronics Inc- EMC Div	1	0,27	\$0,49
L7805 Voltage Reg.	MCIGICM	1	\$0,89	\$1,16
12. 5A 60W Power Supply	CHANZON	1	\$15,84	\$15,84
IRF510 Transistors	Vishay Siliconix	45	\$12,83	\$43,8
SN74HC595N Shift Registers	Texas Instruments	6	\$4,54	\$4,54
PCB Board	PCBWay	4	\$9,2	\$29,6
HC-SR04 Ultrasonic Sensor	Baumer	1	\$2,78	\$3,86
Total			\$60,53	\$116,67

Table 2. Actual Cost of the Display

Part 8. CONCLUSIONS AND FUTURE WORK

8.1 ACCOMPLISHMENTS

In section 4.2 three essential objectives were defined for the project along with a reach goal. In this section the accomplishment of those goals will be assessed.

First, the display has a ramp-up rate of 6 seconds and a cool down time of 3 seconds, meaning that the text displayed could be reconfigured within 9 seconds which is under the 10 second objective that was set for the project. Second, if all the pixels were working on the display, the characters would be clear and legible, but due to the fact that some pixels would either not activate fully or not activate at all, the characters are not as clear as expected, but they are legible. So, this goal was not fully accomplished with this version of the display, but could be easily accomplished once the pixels that were malfunctioning were fixed or the pixel making process is automated. Lastly, the ultrasonic sensor identifies a user and allows to change the text in the display alternating between a series of words that can be pre-programmed, making this objective a successful one as there is a feedback mechanism.

The reach goal was to be able to choose the text displayed using an Android app that communicates with the Microcontroller via a Bluetooth module. Unfortunately, it was not possible to accomplish this objective due to the fact that there were some errors in the transmission of data.

Overall, this project fully satisfies all of the key objectives and the reach objective partially. It can be confirmed that this project sets solid grounds for future studies and work in the field of thermal displays, making it successful.

8.2 *UNCERTAINTIES*

The project mainly deals with uncertainties in power and current draw. Currently, each Nichrome wire draws about 0.09A of current to generate an average ramp-up rate of 6 seconds to blue. However, if a pixel is left turned on for too long, the resistance of the wire could change and this would change the current draw accordingly. Other uncertainties arise for future work on the project, such as, if the display were to be scaled from the current 45 pixels to a larger number of pixels, the current draw would be very high depending on the number of pixels used. Thus, it may become difficult to provide such a high amount of current at a low potential difference of 3.3V as electrical components rated for such high current are difficult to come by.

8.3 *ETHICAL CONSIDERATIONS*

The project does not infringe upon the privacy or require any form of user information and therefore does not have any ethical issues. As the IEEE Code of Ethics state [11], it holds paramount the safety, health, and welfare of the public.

8.4 *FUTURE WORK*

The first improvement that could be made would be to increase the number of pixels in the display to allow for better resolution. In order to achieve this, new ways to optimize the power consumption would need to be studied and tested.

The second improvement would be to improve the connections between the pixels and the PCB. Currently, the pixels are connected to wires which are then plugged into the PCB board to allow for the user to replace any pixels if they burn out. However, this causes the product to have a very messy wiring arrangement. To fix this, a PCB board could be used which would be the size of the display screen, with through-holes in places for the pixels to simply 'plug' in. This would reduce the number of wires to be used by an exponential amount.

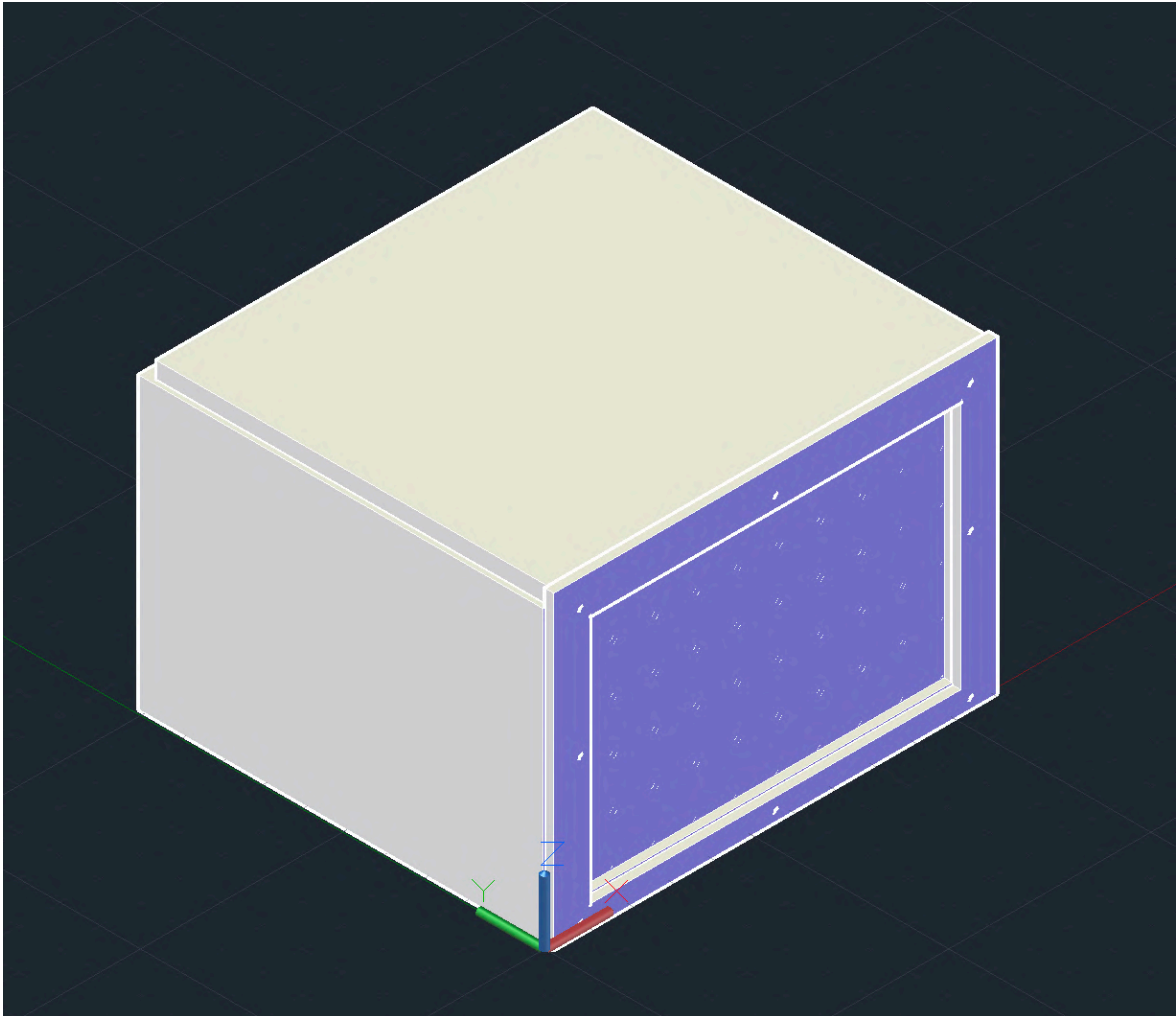
Lastly, another improvement would be to optimize the pixel making process. Currently, all pixels are made by hand and take a large amount of time to make. One way to speed this process could be to make the pixels in a factory using professional machinery that would allow for more standardized and reliable pixels.

Part 9. BIBLIOGRAPHY

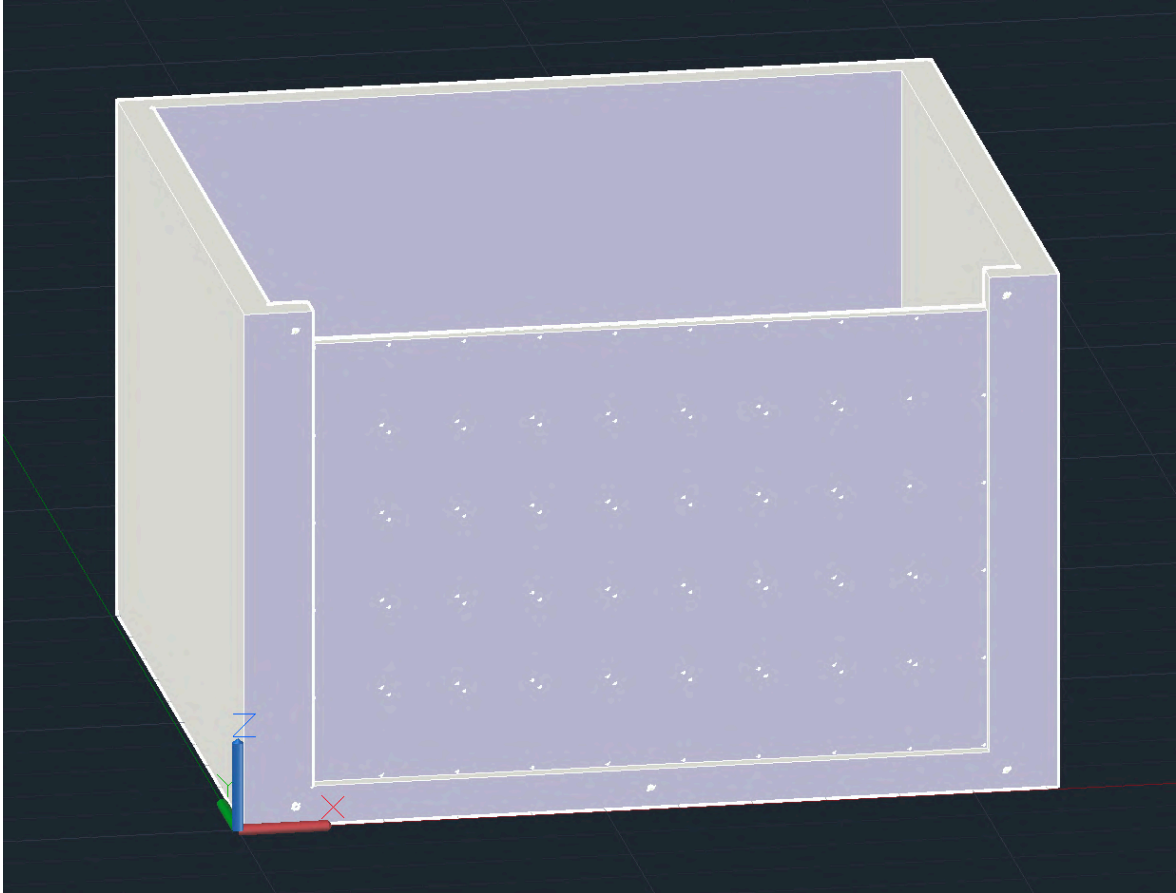
- [1] All about Flexible Macroelectronics. [Online]. Available: <https://macroelectronics.blogspot.com/2007/10/electronic-papers-history-and-future.html>.
- [2] NanoDays. “Exploring Materials-Liquid Crystals.” 2013, http://www.nisenet.org/sites/default/files/catalog/uploads/1989/materialslc_sign_15nov10.pdf.
- [3] *AmbiKraf*. [Online]. Available: <https://cargocollective.com/ambikraf>.
- [4] “Thermochromic Display,” *Vimeo*, 27-May-2019. [Online]. Available: <https://vimeo.com/2616647>.
- [5] “Functional Printing,” *Printed Thermochromic Display Circuits*. [Online]. Available: <http://www.hallcrest.com/our-products/special-effect-pigments/printed-thermochromic-display-circuits>.
- [6] L. L. C. H&H Graphics, “Thermochromic Printing Reveal Example,” *YouTube*, 15-Feb-2017. [Online]. Available: <http://www.youtube.com/watch?v=Dt6Rb1brnZ0>.
- [7] G. Elert, “Temperature of a Healthy Human (Skin Temperature),” *Temperature of a Healthy Human (Skin Temperature) - The Physics Factbook*. [Online]. Available: <https://hypertextbook.com/facts/2001/AbantyFarzana.shtml>.
- [8] B. Hauke, “Basic Calculation of a Buck Converter's Power Stage,” *Texas Instruments*, Dec-2011. [Online]. Available: <https://www.ti.com/lit/an/slva477b/slva477b.pdf>.
- [9] “Ultrasonic Ranging Module HC - SR04,” *Sparkfun*. [Online]. Available: <https://cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf>.
- [10] E. Styger, “Using the HC 06 Bluetooth Module,” *Instructables*, 19-Jun-2013. [Online]. Available: <https://cdn.instructables.com/ORIG/FX1/N43N/IMXQP4WO/FX1N43NIMXQP4WO.pdf>.
- [11] “IEEE Code of Ethics.” IEEE - Advancing Technology for Humanity, www.ieee.org/about/corporate/governance/p7-8.html.

ANNEX A

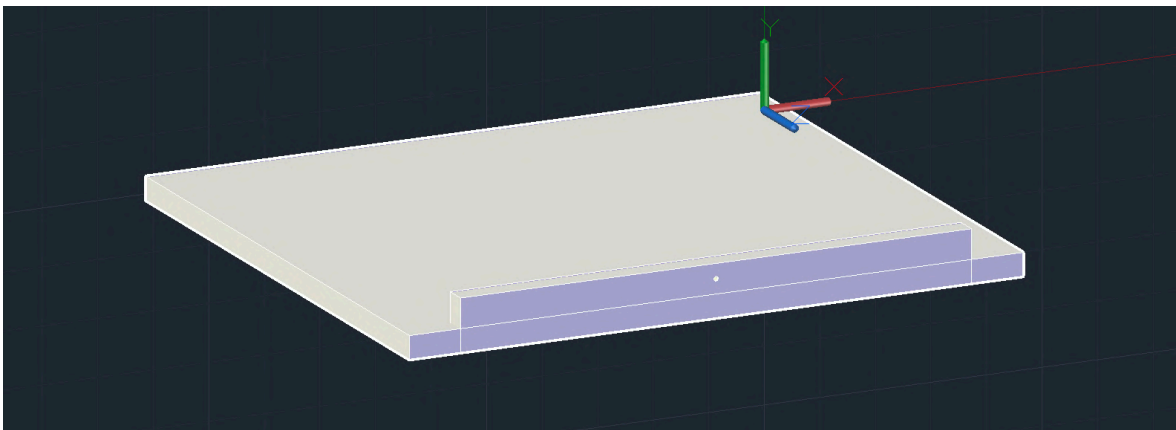
3D Side View of the Case:



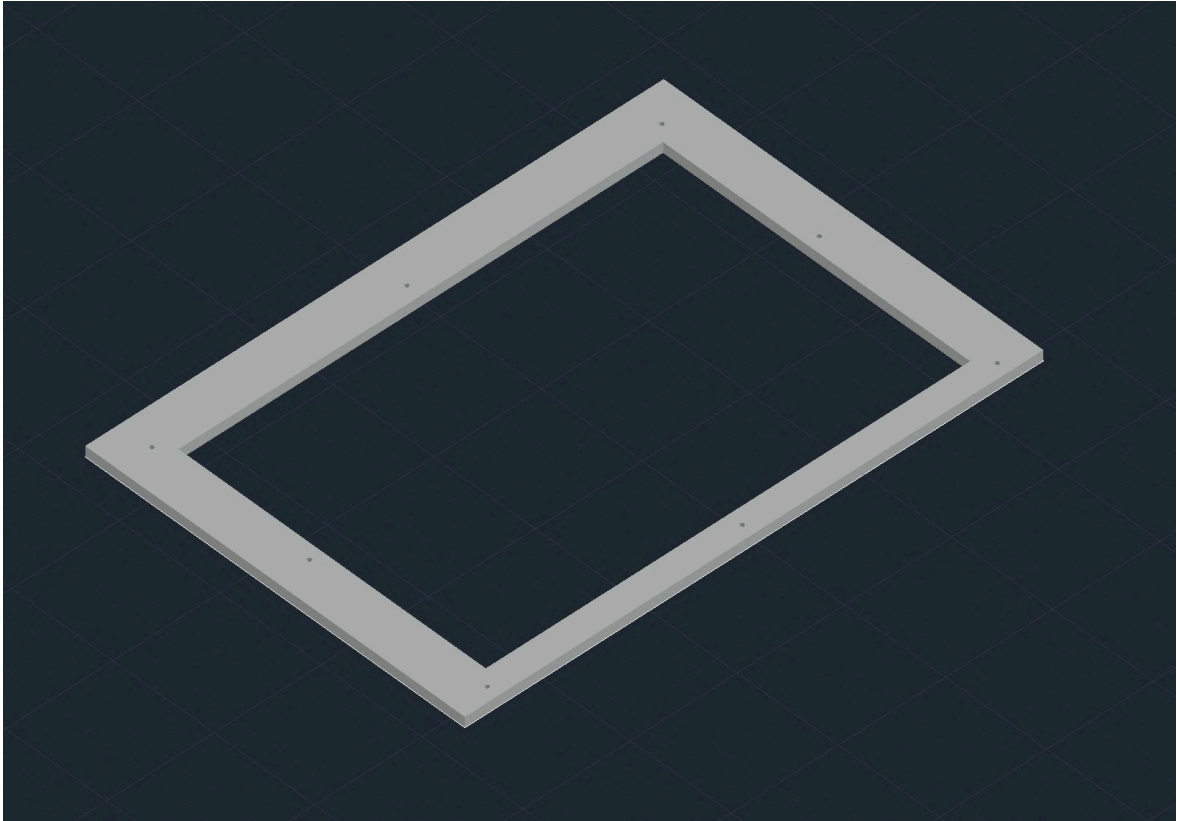
Bottom piece:



Top piece:

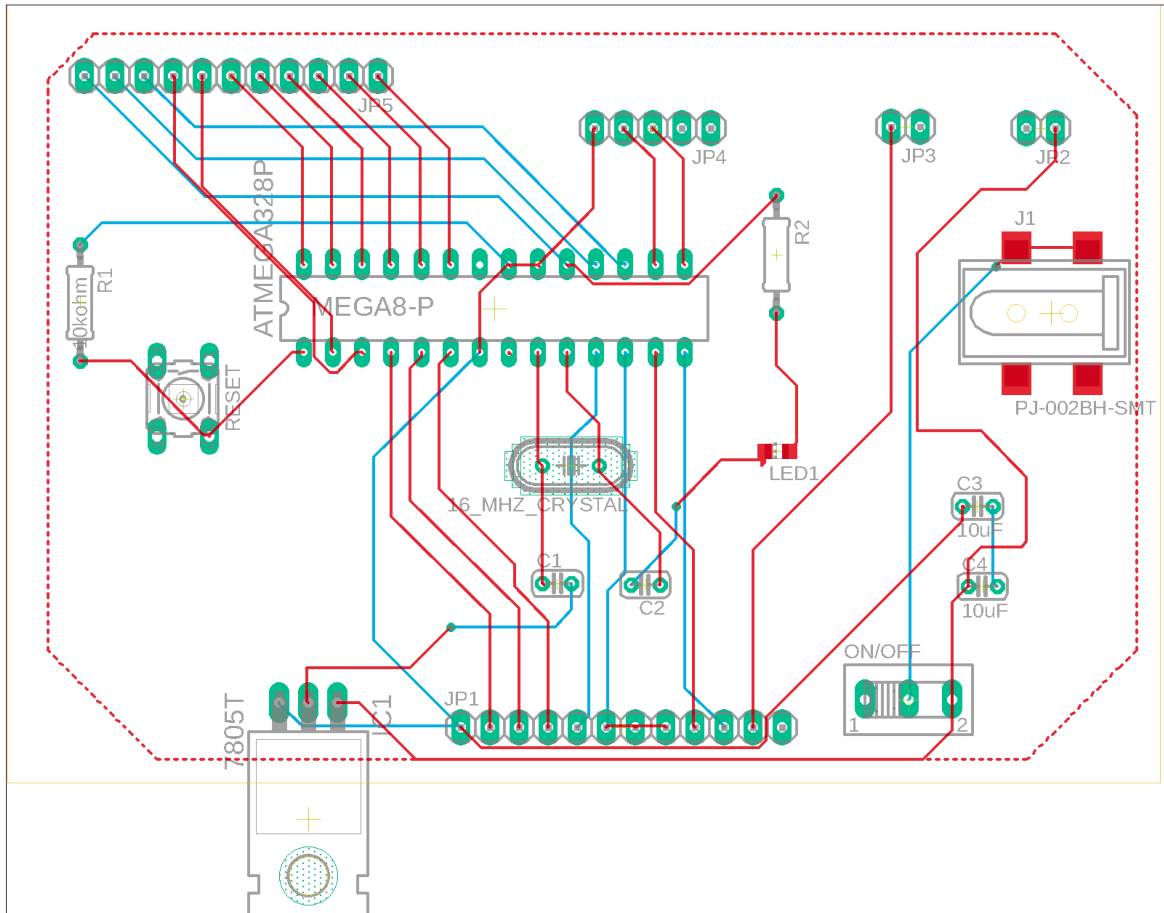


Front frame:



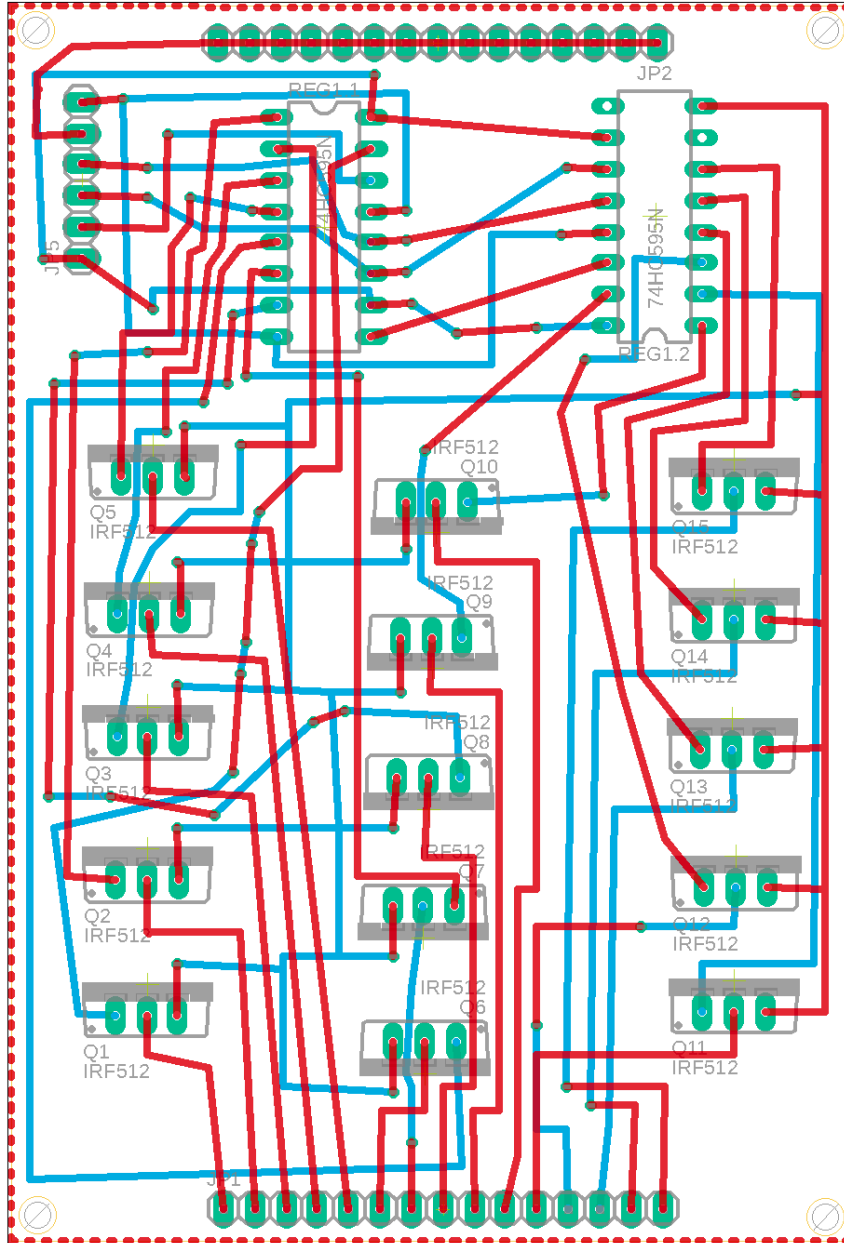
ANNEX B

Main PCB board layout with connections:



Size: 100.6 x 79 mm

Pixel PCB board layout with connections:



Size: 68.5 x 100.5 mm