# LED Flow Sensor

# Preliminary Proposal


**Gavynn Breed**

**Ryan Schuster**

**Yixiang Zhang**

**Hengling Zhu**


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**Project Sponsor: Northern Arizona University**

**Faculty Advisor: David Michael Willy**

**Sponsor Mentor: Dr. Zhongwang Dou**

**Instructor: David Michael Willy**

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# 1. BACKGROUND

## 1.1. Introduction

This project is based on flow visualization technology to design and produce an LED matrix to realize the light source supply of the particle image velocimetry (PIV) system. The purpose of this project is to create a red, green, blue (RGB) light system in order to illuminate flow so that a camera can detect the flow. The system has three separate channels that control the different colors individually and must operate within a $1000 budget. This project provides the same functions of laser equipment with less money, which saves the sponsor a high cost and makes the marginal benefit increase significantly.

## 1.2. Project Description

Following is the original project description provided by the sponsor:

"Light source is a critical component for flow visualization and diagnostics. This project aims at designing and implementing a high-speed high-power pulsed RGB LED light source for volumetric particle image velocimetry (PIV) system. A group of LEDs will be integrated together as a LED matrix. In this LED matrix, three different colors, namely red, green, and blue will be controlled independently, using a home designed circuit board. Furthermore, it requires the following specifications to be met:

- Trigger input: TTL
- Minimum light pulse width: 0.5us
- Frequency: 1Hz – 60 KHz
- Energy per pulse per channel: 0-30 mJ
- Trigger to light pulse min. delay: 500ns
- Trigger to light pulse jitter: 5ns
- Trigger to Sync output min. delay: 100 ns
- Trigger to Sync output jitter: 5ns
- Channels: Red, Green, Blue

Knowledge, skills, and expertise required for this project:

- Strong interests in engineering design and problem solving.
- Familiarity with basic CAD software.
- Familiarity with basic circuit board design.
- Familiarity with basic machine shop.
- Good communication skills and teamwork.

Budget: $1000"

# 2. DESIGN SPACE

This chapter mainly introduces Customer Requirements, Engineering Requirements and House of Quality. Customer Requirements are weighted according to the actual needs of customers and the reasons for weighting are explained. Engineering Requirements gives Justifications on engineering standards based on the target value provided by the sponsor. Based on the first two requirements, House of Quality has made a comprehensive calculation to obtain the evaluation criteria of absolute and relative importance.

## 2.1. Customer Requirements (CRs)

The customer requirements for this project are a bit unique. This is the case because our client gave us the engineering requirements. The customer requirements in Table 1 were derived from the engineering requirements. The weights for each one as well as the reasoning behind each requirement can also be found in Table 1.

Table 1. Customer Requirements

| Customer Requirements | Weights | Interpretations |
| --- | --- | --- |
| High Frequency | 4 | High Frequency, as a secondary factor that affects the visualization effect, is not as important as the primary factor. So its weight is of secondary importance. |
| Short Pulses | 4 | Customers will care about the duration of a single pulse, because too long exposure time will cause blurring of the visualization. Based on the secondary influence, its weight is of secondary importance. |
| Adjustable Intensity | 5 | The intensity of the light effect will directly affect the flow visualization, so it has the highest weight. |
| Reliability | 3 | This product will not suffer huge external impact or load during normal use, so customers are least concerned about its reliability. |
| Durability | 3 | This product does not have too many mechanical devices, and customers will not pay too much attention to its fatigue durability. |
| Adjustable Color | 5 | It is the most important for being able to switch between the three light colors of RGB according to the needs of customers, so the weight is the highest. |
| Minimal Jitter and Delay | 4 | Jitter and Delay will cause blurring of the visualization, so weight is the second highest. |
| Cost | 3 | This product has a narrow audience, not many similar products, and obvious marginal effects. Therefore, customers do not pay attention to price. |

## 2.2. Engineering Requirements (ERs)

Many of the engineering requirements were given by our client. The requirements that were derived on our own are the Light wavelength, the Temperature of the system and the LED Lifespan. These requirements help to round out the system as well as match the customer requirements for reliability and safety.

Table 2. Engineering Requirements

| Engineering Requirements | Target Value | Justifications |
|---|---|---|
| Pulse Width(us) | Minimum 0.5us | The pulse width is modulated to ensure the intensity of light. Pulse Width should be at least 0.5us. |
| Frequency(kHz) | 1Hz – 60 kHz | The pulse frequency is the number of effective discharges in the discharge gap per unit time. Frequency is between 1Hz and 60 kHz. |
| Energy Per Pulse Per Channel(mJ) | 0-30 mJ | Measure the radiant energy contained in a pulse. Pulse energy is between 0 and 30 mJ. |
| Trigger Delay(ns) | Minimum 500ns | Clarify the switch trigger delay time of the pulse power device is no lower than 500ns. |
| Trigger Jitter(ns) | 5ns | Ensure the Trigger jitter of one pulse cycle is 5ns. |
| Output Delay(ns) | Minimum 100 ns | Make sure the output delay is 100 ns at minimum. |
| Output Jitter(ns) | 5ns | Determine the output Jitter is 5ns. |
| Light Wavelength(nm) | 622-770nm for Red<br>492-577nm for Green<br>455-492nm for Blue | The wavelength of light directly reflects the corresponding color on the spectrum. The specific wavelength comes from the visible light spectrum. |
| Temperature(°C) | Maximum 65 °C | Temperature affects reliability. Excessive temperature will cause the resistance value to decrease, thereby affecting the failure rate of the circuit board. 65 degrees Celsius is the critical value. |
| LED Lifespan(hr) | Maximum 10^5 hrs | The lifespan of the LED light determines its durability. The theoretical life of the LED is a maximum of 100,000 hours. |

## *2.3. House of Quality (HoQ)*

The house of quality is a product planning matrix that is used to discuss customer requirements and engineering requirements. In the customer weights section a scale of one to five is used to measure the importance of the customer requirements. A one being of little importance and a five being of high importance. Then the engineering requirements were compared to each customer requirement and rated as a one, three, nine, or left completely blank. One means it has some relevance, three being a good amount of relevance, and nine being of most relevance. The Absolute Technical Importance (ATI) is the scores under each engineering requirement multiplied by their weight and then added up to get a score. The higher a score the more important that engineering requirement is. The Relative Technical Importance is the average of that ATI over the sum of all the ATI's. This is to show the importance of the engineering requirement in percentages.

The House of Quality helped the team realize that the cooling system will be an integral part of the system since its ATI was 15.8%. This cooling system will need to control the temperature enough so that the LED's work efficiently and are not self destructive. LEDs lifespan at 12.6% ATI shows the importance of purchasing a good LED that can last long enough for many experiments. A cheap LED would not work as efficiently and be as durable. An upside to quality LED's is that they will save money in the long run, but will cost more up front. With light wavelength as the lowest ATI score it shows that worrying about the wavelengths is not as important. This is because red, green, and blue a;ready have their set wavelengths and there is not much to do about it, other than to try and increase light intensity. Trigger delay really had no effect on our design choices other than implementing it correctly. The TTL trigger was already chosen for the team. The House of Quality showed the team what were the most important design factors to focus on first which as explained previously is mainly cooling and frequency of the light source.

Table 3: QFD

| **Customer Requirement** | **Customer Weights** | Pulse Width (us) | Frequency (KHz) | Energy Per Pulse Per Channel (mJ) | Trigger Delay(ns) | Trigger Jitter (ns) | Output Delay(ns) | Output Jitter(ns) | Light Wavelength (nm) | Temperature(degree C) | LED Life Span (hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. High Frequency | 4 | 3 | 9 | | | | | | | 3 | 1 |
| 2. Short Pulses | 4 | 9 | 3 | | | | | | | 3 | 1 |
| 3. Adjustable intensity | 5 | 9 | 9 | 9 | | | | | | 3 | 1 |
| 4. Reliability | 3 | 1 | 1 | 1 | 9 | 9 | 9 | 9 | | 9 | 9 |
| 5. Durability | 3 | 1 | 1 | 1 | | | | | | 9 | 9 |
| 6. Adjustable Color | 5 | | | 3 | | | | | 9 | | |
| 7. Minimal jitter and Delay | 3 | | | | 9 | 9 | 9 | 9 | | | |
| 8. Cost | 4 | 1 | 1 | 9 | 1 | 1 | 1 | 1 | | 9 | 9 |
| **Absolute Technical Importance (ATI)** | | 103 | 103 | 102 | 58 | 58 | 58 | 58 | 45 | 129 | 103 |
| **Relative Technical Importance (RTI)** | | 12.6% | 12.6% | 12.5% | 7.1% | 7.1% | 7.1% | 7.1% | 5.5% | 15.8% | 12.6% |
| **Target ER values** | | 0.5us | 1Hz-60KHz | 0-30mJ | 400ns | 0ns | 75ns | 0ns | 380-700 nm | 70C | 5*10^5 hrs |
| **Tolerances of Ers** | | - | - | 5mJ | 100ns | 5ns | 25ns | 5ns | - | 5C | 1*10^4 hrs |
| **Testing Procedure (TP#)** | | | | | | | | | | | |

# 3. DESIGN SPACE RESEARCH

Chapter 3 covers the research done on the topic of the project to gain a necessary understanding of what is to be done. This includes literature reviews on necessary subsystems, including the circuit design, control elements, cooling system, and the LEDs. Next the design requirements were benchmarked against existing designs on the market in order to evaluate benefits and negatives of each. Finally the system was broken down into a functional decomposition to gain a further understanding of the necessary components and subsystems.

## *3.1. Literature Review*

The literature review will include up to 20 sources on circuits, LEDs, control signals, and the cooling system. Each of these topics are an integral part of the design and making of the LED system. Without knowledge of each the system could easily fail.

### 3.1.1. Student 1 (Ryan Schuster)

This literature review covers the design of the circuit. Specifically covering how to use pulse width modulation on a scale of nanoseconds to power a large quantity of LEDs . The goal is to have a circuit that operates at roughly 300 W and contains at least 3 color channels for Red, Green, and Blue.

**Electric Circuits [1]**

This textbook is a good source of information for the analysis and design of circuits. Specifically chapters 2 and 3 as well as section 4.12 and 5.5. The textbook is mostly just a baseline resource to reference for equations and conditions as well as examples that can be used when designing the circuit. Chapters 2 and 3 review basic analysis equations for power, voltage, current and resistance. Section 4.12 discusses the maximum power transfer within a system which is important in developing a system designed to run at the max power. While Section 5.5 covers non-inverting amplifier circuits which may be an option to increase the voltage and current outputted by the pulse input allowing for a wider range of development options.

**Pulsed operation of high-power light emitting diodes for imaging flow velocimetry [2]**

This article covers the operation of a single LED emitter that is utilized for flow velocimetry. There are a few major differences between the purpose of this circuit and the one needed in the design project. The first among these is that the circuit controls a single LED that emits the light into a fiber optic cable that converts the light into a single plane of light. Due to being a single LED it is much larger and pulls much more current and voltage than the system that we must design. The most interesting aspect of this circuit is that it utilizes the TTL input through a driver to control a gate mosfet which allows the current to flow through the circuit to power the LED in timing with the pulse signal.

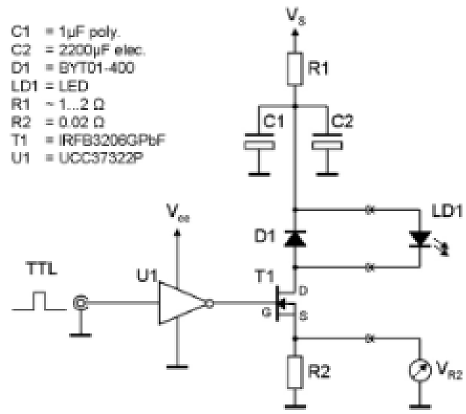



Figure 1: Flow Velocimetry Circuit [2]

**Characterization and Evaluation of PIV Illumination System Using High Power Light Emitting Diodes for Water Tank Applications [3]**

This next article is very similar to the previous one. As with the previous article the 2 LEDS are directed into fiber optic cables then converted to a single plane of light, an important differentiation between our project and this article. However in comparison to the previous article this circuit gives a much better idea of how to set up our own circuit due to having LEDs in parallel. As with the previous circuit the TTL pulse signal is utilized to control a mosfet gate which will open the circuit powered by a controllable voltage source. The capacitors help to keep a steady flow within the circuit. The biggest take away from this article is that a 5 v pulse signal can be split to control multiple gates and a single voltage source V+ can be used to power the circuit. This article also goes into specifics about the reasoning behind each component used, especially the gate types allowing to see the reasoning in the selection and how they can be adapted.

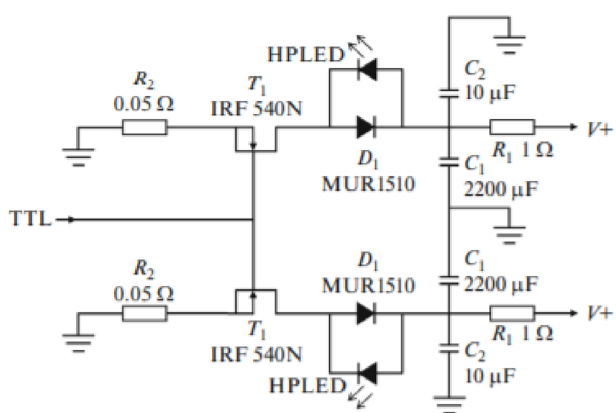



Figure 2: Water Tank Circuit [3]

### Pulsed Over-Current Driving of Cree XLamp LEDs: Information and Cautions [4]

Since the LEDs we selected are the Cree XLamp XM-L Color, it is important to understand how this line of LEDs function under overcharged pulsing. This can be seen within table X. Another thing to note is that this document discusses the reduction of lifespan of these LEDs on the scale of tens to hundreds of thousands of hours. The final note is that LEDs have reduced output when temperature is increased. Cree argues that this makes pulsed operation ineffective due to the increases in temperature within the system. However with a proper cooling system this effect should be avoided creating an effective system when used with pulsed operation.

Table 4: Xlamp Power Table [4]

| Current (mA) | $V_f$ (volts) | Average Power |
|---|---|---|
| 175 | 2.84 | 0.100 |
| 350 | 2.99 | 0.209 |
| 700 | 3.21 | 0.449 |
| 1000 | 3.35 | 0.671 |
| 1500 | 3.56 | 1.067 |
| 2000 | 3.74 | 1.494 |
| 2500 | 3.89 | 1.944 |
| 3000 | 4.04 | 2.422 |
| 3500 | 4.17 | 2.920 |
| 4000 | 4.30 | 3.442 |

### High speed, high current pulsed driver circuit [5]

The final literary source that was reviewed is a patent on a pulsed LED driver, by Sandia Corporation. This patent is a more advanced version of the goal of this project. It is the driver for an array of LEDs similar to what we are looking to do, however these leds are larger than what we are looking to use. This system is also much more complex than this project needs, essentially there is much more digital control involved within this system. Another interesting aspect of this system is that it uses large capacitor banks to supply the power to the system. Figure X shows the control circuit and Figure X shows another example circuit within the patent.

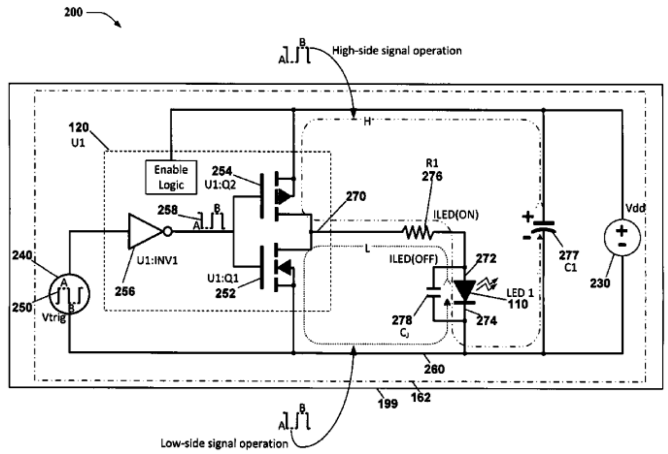



Figure 3: Patent Circuit controller [5]

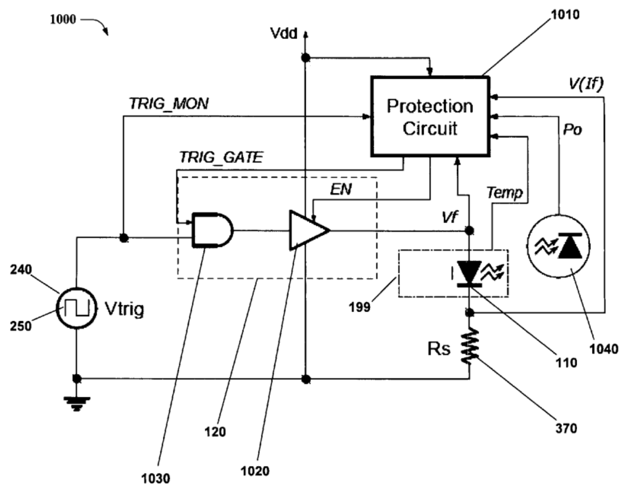



Figure 4: PatentCircuit [5]

### 3.1.2. Student 2 (Gavynn Breed)

[Explain what technical aspect of the project this student focused on and then list the 5+ relevant sources with summaries and discussions. Cite all textual information and figures.]

This literature review contains the information and aspects of an LED and how it can be incorporated into the system. The LED's in the system need to have a high illumination for the flow tracking, must be able to handle pulses at high rates, be placed in a certain array for collimating particles, not be overdriven to the point of destruction, and every color must be separate from one another.

The basis of using RGB LEDS is to use it for measuring fluid flow in a system. In depth "In a backlit configuration, liquid droplets appear as shadows in each color channel" , which allows for "Color reversal and color cross-talk correction yield a series of three frozen-flow images that can be used for further analysis" [1]. This shows that droplet velocity can be measured with particle tracking to show exactly how a fluid is flowing with the reflection of the colors.

The five articles helped the team understand how the LED system needs to be set up and what will need to be done for it to work.

**Multi-Pulse [6]**

This article particularly explains the use of the LEDS and how they were set up to measure each color's frozen pictures for particle velocity. The illumination of the particles is very important. Since the colors need to be alternated "each color's pulse duration and the delay between the pulses were independently adjusted with a digital delay generator" [6]. This will be very important towards the success of the project. This can be done with coding so we are not receiving mixtures in the light sources being outputted. This article also gives information on the maximum power for operation of LEDs. The article says "The maximum power used to operate LEDs is limited by the mean energy dissipation in the device" [6]. The mean energy dissipation is how much of that energy going into the device is being lost to the surroundings. This is basically used to calculate the efficiency of how much energy is going to be transferred to light and how much is going into the surroundings such as heat. The article provides information on how one can put more power into their LEDs without them being affected. To do this the LEDs can be put into a "pulsed" mode [6]. A pulsed mode is when the LEDs are turned on and off in quick succession, instead of being continuously run. One good note to have is that the green diode will need to be driven in longer pulses to achieve the same per-pulse output as the red and blue diodes [6].

### High-power LED [7]

This article describes what light sources are available for multi-led emitters and the light projection from each color. The systems using the LEDs are mainly designed for surface emitters with constant intensity distribution per unit area. To do this it is achieved through " photonic lattice bonded to the surface of the emitter which channels the light through micron-sized, surface-normal holes" [7]. This means that the system is able to collimate particles more easily. This can be useful towards the project, just in case our particles are not collimating effectively. In this article it provides information on relative LED-radiant power distribution as seen in figure one.

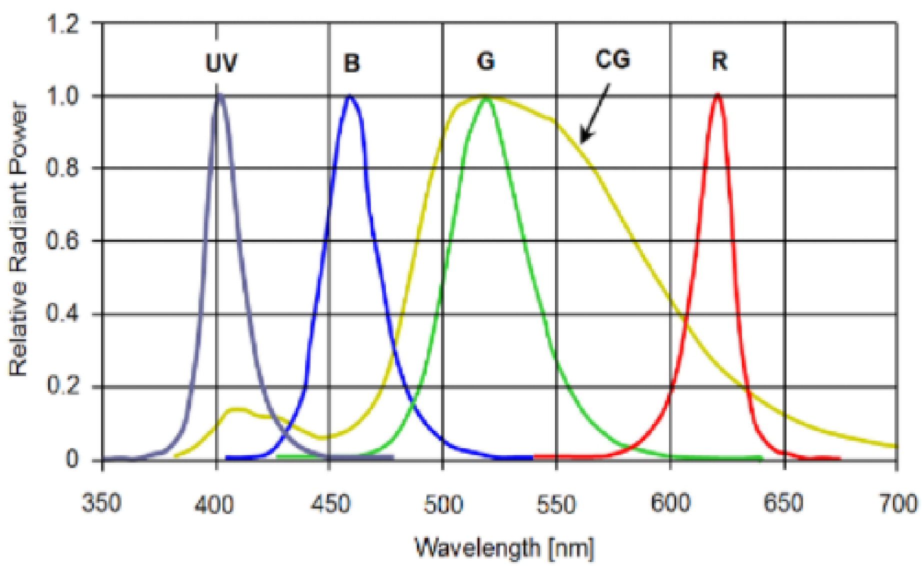



Figure 5: Relative LED-radiant power distribution [7]

This graph shows the wavelengths of each color compared to radiant power. This is important for the team to realize at what wavelengths the light gives off more power. This can help us decide the pulses for each color. This article also provides information of how the nominal operating current can be exceeded when used with a pulsed current. As shown in figure the LED pulse current in amps exceeds the max CW current when run in a pulsed operation.

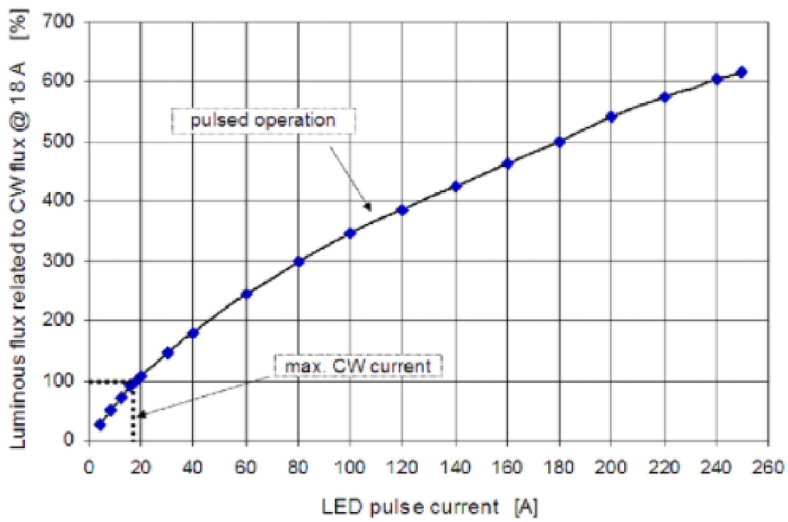



Figure 6: CW vs Amps [7]

## Performing Calibration [8]

The main information taken from this article is the information provided about the RGB light-emitting diode. To get a better light illumination a huge number of LEDs are required [8]. Using the data from the article we can determine how many LEDs the team might need for the illumination scaled down to the size of the control that is going to be illuminated. This article also shares the importance of the different light sources. Different fluids being measured will require different wavelengths. The article also describes how the light intensity of the LEDs is more useful for measurement. The article explains "spectral width, which is defined as the wavelength range that presents an emission intensity greater than/equal to 50% of the maximum value. So, wavelengths located below that threshold have a lower influence on the samples" [8]. This shows that the light intensity matters to getting accurate measurements.This is shown in figure 3.

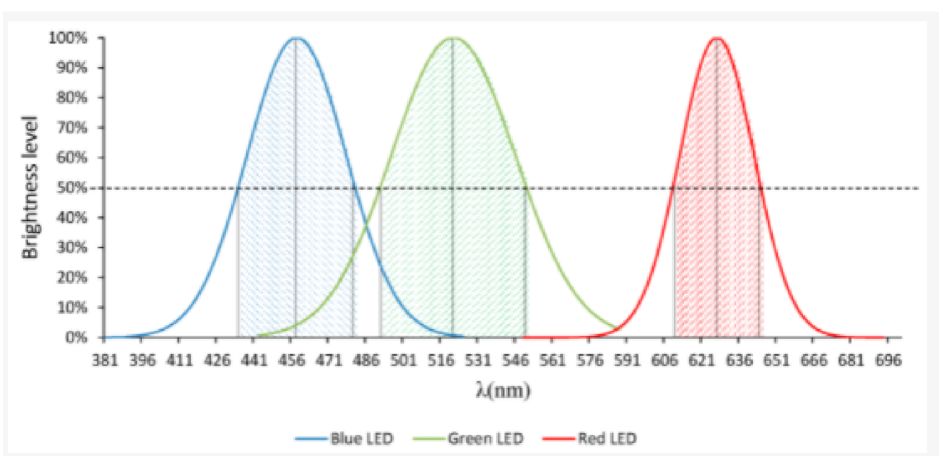



Figure 7: Intensity Vs Wavelength [8]

The information in this article will help determine how many LEDs the team can implement into the system. It also teaches how LEDs work to provide particle measurement at different wavelengths to get the right amount of light intensity for measurement of particles.

## LED Color Control [9]

This article describes many benefits for light emitting diodes (LED) and how to obtain the right color for measurement, and how to set up the systems. One important factor for the project is that each light source needs to be controlled independently and also contain color mixing. When mixing colors it can be determined by ratios of each diode's light intensity and can be controlled linearly by a PMW dimming technique [9] . PMW is an abbreviation for pulse-width modulation, which changes the cycle of the diodes and will adjust the current proportionally.  This article provides a block diagram to show how a system could be set up to control each diode as seen in figure 4.

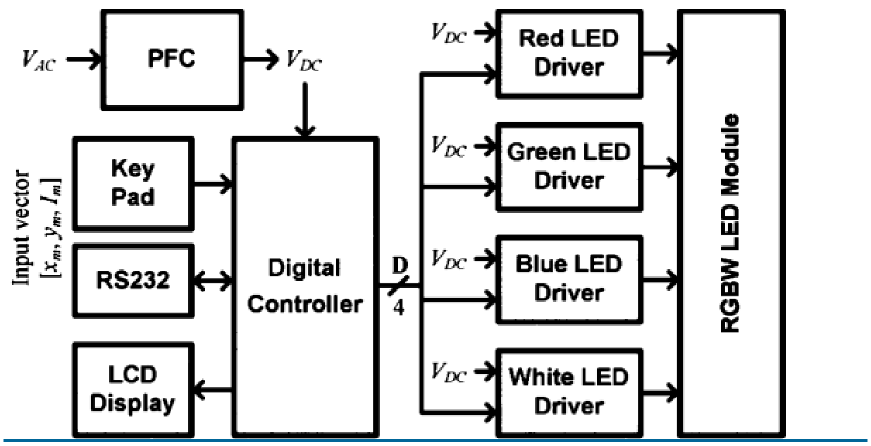



Figure 8: color controllable LED System [9]

The team also needs to know how to set up the color temperature and illuminance so that our system gives off the desirable amount of light from the diodes. The color mixing theory is important to determine the relationship between each LED. Color mixing theory is " the chromaticity coordinate of the mixed light is a weighted linear combination of the individual chromaticity coordinates". The equations for discovering the values of the light sources are in the Appendix.

## RGB LED Driver [10]

This article provides information on a LED driver and its technique to track the required driving voltage for LED strings to improve efficiency of the LEDs by decreasing power loss in the system. Firstly a LED driver is an electrical device whose purpose is to regulate the power output to a string of LEDs. LEDs are mainly used over lasers for lighting and backlighting due to their lifespan, efficiency, and reliability. Even though LEDs are more efficient than lasers, there are still ways to make them even more efficient. This article will talk about using adaptive driving voltage and energy-saving technique. The power loss from this technique can decrease up to 58% [10].  The article provides the layout of the technique as seen in figure 6.

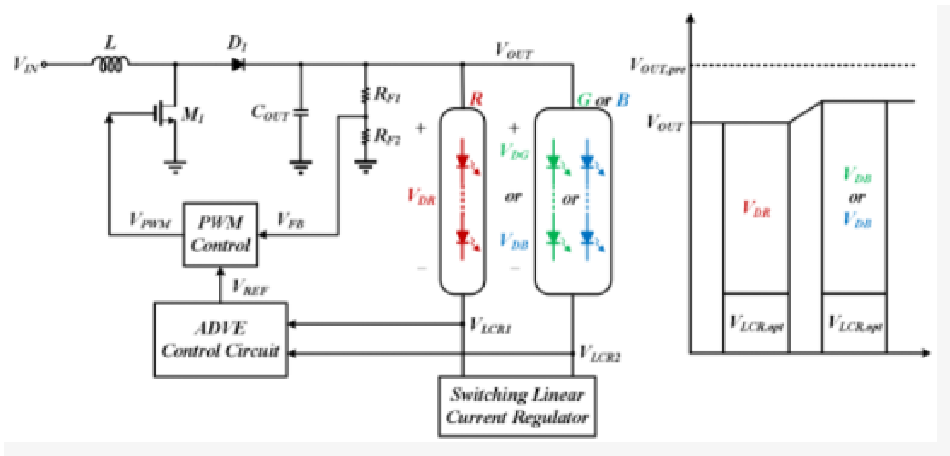


Figure 9: LED Driver (ADVE) [10]

In summary this article provides plenty of calculations that can be used for setting up the LED driver such as frequencies, voltages, and the power loss. This is important towards the project because we can create our system to be more efficient and give off less heat. The important calculations are in the appendix.

### 3.1.3. Student 3 (Yixiang Zhang)

This literature review clarifies TTL triggering and its application in this project. TTL trigger is a kind of Transistor-Transistor Logic, which is used for waveform transformation and converts triangular waves, sine waves and other irregular signals into rectangular pulses[11], and it is convenient for the reading of the subsequent circuit system.

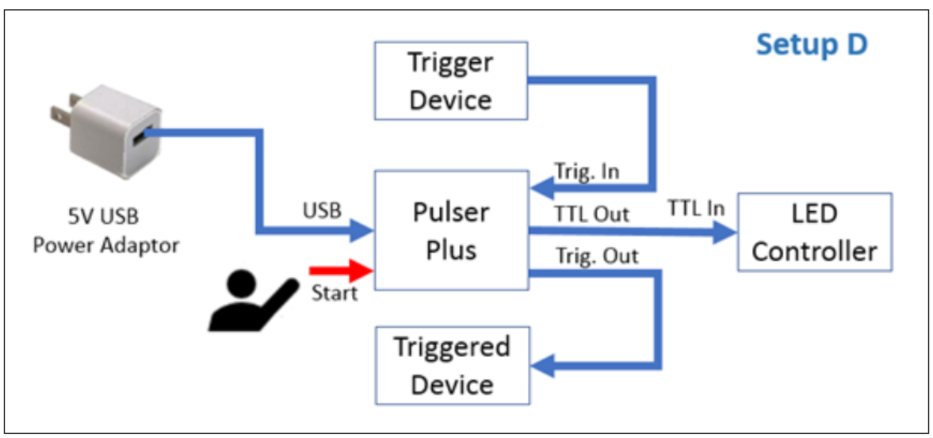



Figure 10: Manually activated trigger model[11]

**TTL interface overview[12]**

TTL is transistor-transistor logic, and TTL level signals are generated by TTL devices. The TTL interface is an interface that transmits data in parallel.[12] When using this interface, it is not necessary to use a dedicated interface circuit in the LED matrix, but the TTL data signal output by the main control chip of the driver board is directly transmitted to the input interface of the circuit board through the cable.

**TTL output signal[12]**

The TTL output interface of the driver board generally contains three types of signals: RGB data signals, clock signals and control signals.[12] To realize the reception and control of the RGB digital signal, the TTL output signal directs the RGB signal to be transmitted in order and ensures the correctness of the data transmission.

**TTL Applications and Advantages[13]**

The advantages of TTL include high speed, reliability, and low power.[13] Since this project requires fast pulses, low delay, and control current, TTL is suitable for use as triggers and controllers.

**TTL Circuit Design[14]**

The TTL circuit is composed of a series of logic gate circuits. To realize the control of excitation and pulse delay, it is necessary to integrate the time oscillation circuit, the adjustable timer and the manual gear control switch into the TTL circuit.[14]

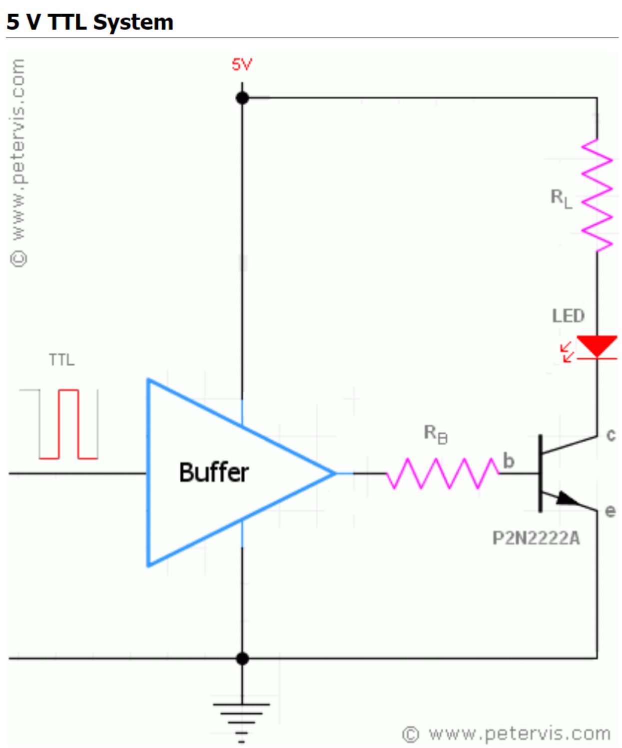



Figure 11: The TTL System for LED[15]

### 3.1.4. Student 4 (Hengling Zhu)

This literature review mainly focuses on the cooling system of the LED array. The temperature of an LED array is very important because the optical output and lifetime of LEDs is greatly affected by the temperature of LEDs. Also we can increase the reliability of LEDs by efficient thermal management with a cooling system.

**Thermal Analysis of LED Arrays for Automotive Headlamp With a Novel Cooling System[16]**

This article introduces the designed air flow cooling system, and then gives the thermal analysis between cooling systems with and without fins, how pin numbers and flow velocity affect the temperature.

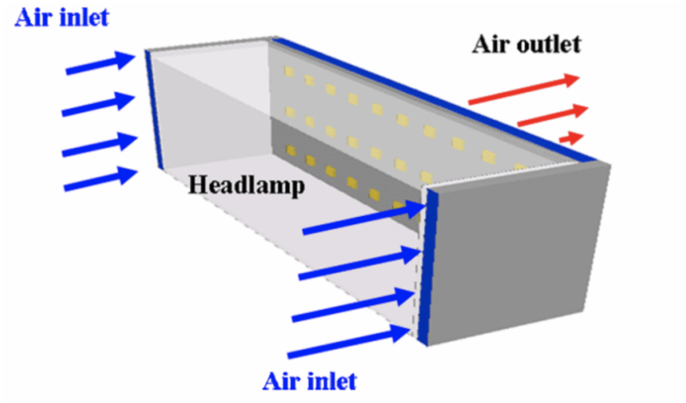
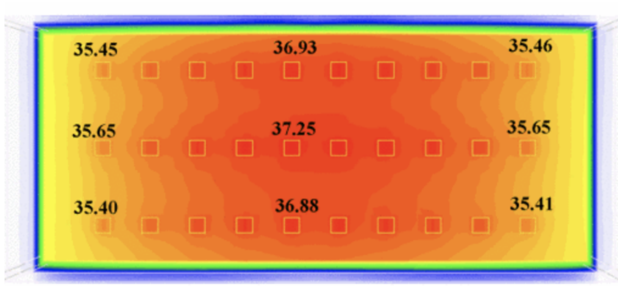



Figure 12: Isotropic View of the Air Flow Cooling System[16]



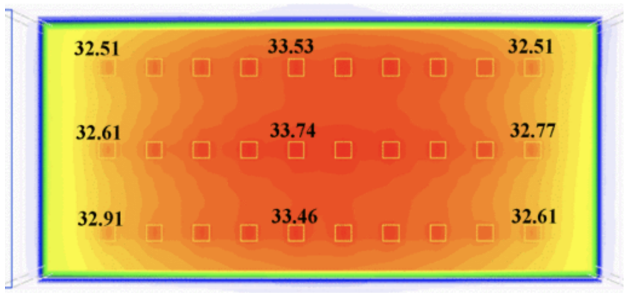




Figure 13: Temperature Distribution Without Fin[16] Figure 14: Temperature Distribution With Fins[16]

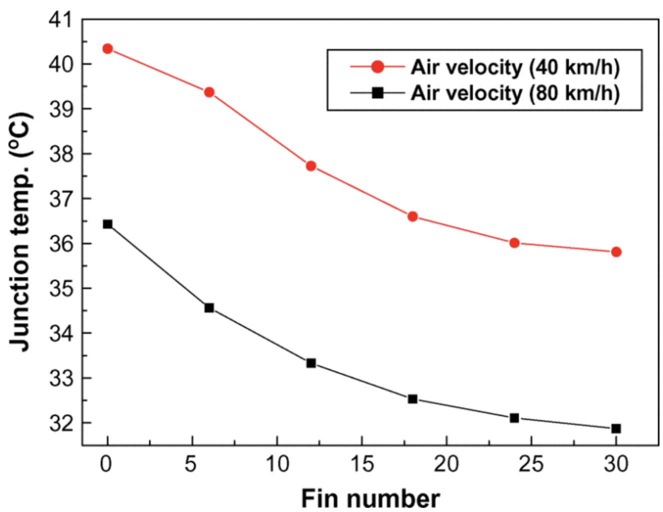



Figure 15: Temperature With Different Fin Numbers and Air Velocities[16]

The result comes out that we should try to use more fins and provide as high flow velocity as possible to keep the temperature at a low level.

**A Microjet Array Cooling System for Thermal Management of High-Brightness LEDs[17]**

In this paper, there is a microjet-based cooling system which is a little bit complicated because they created multiple microjets and builded a closed-loop cooling system with a micropump. They analysed temperature with 2 different flow rates, 2 different microjet diameters, and 2 different metal shell materials.

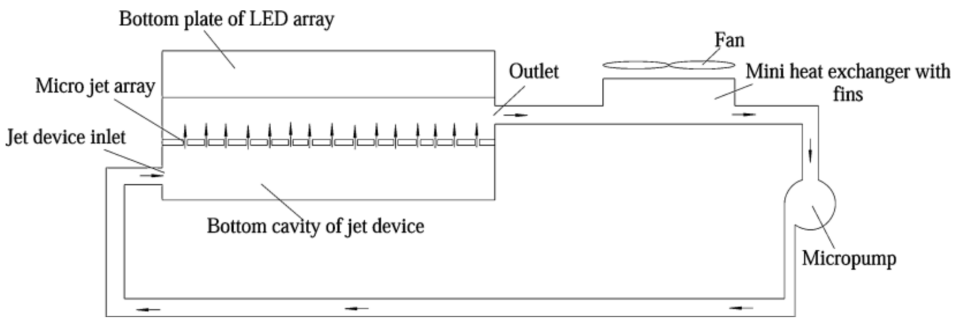



Figure 16: The Closed-loop Microjet Array Cooling System[17]

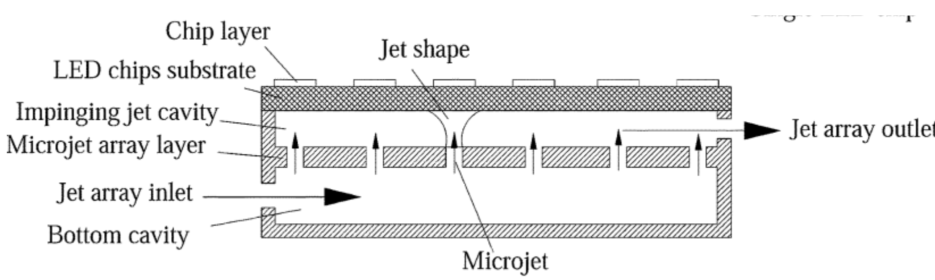



Figure 17: Detailed Microjet Design[17]

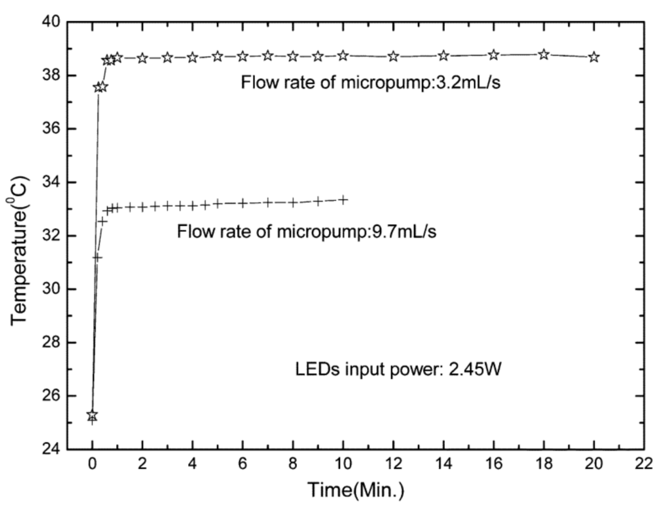



Figure 18: Temperature With Different Flow Rate[17]

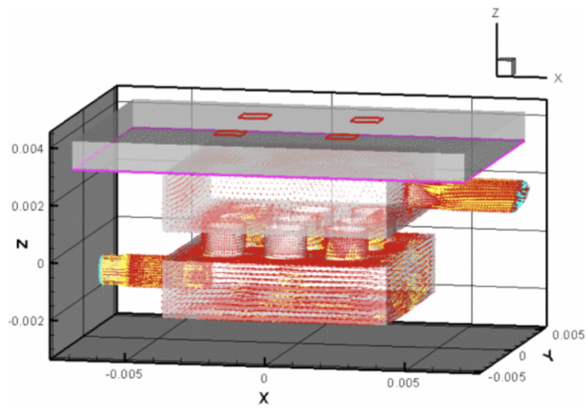



Figure 19: Flow Distribution With 1.5mm Jet Diameter[17]

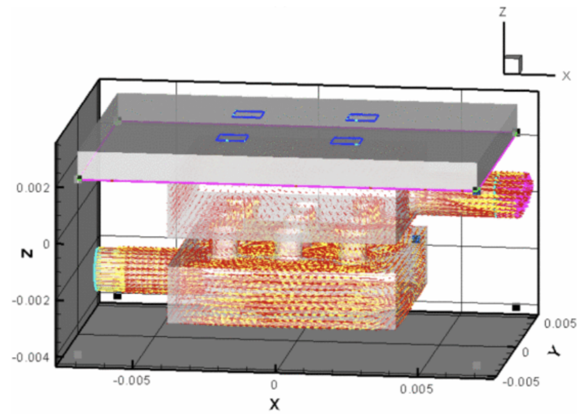



Figure 20: Flow Distribution With 1mm Jet Diameter[17]

Table 5: Temperature With Different Metal Shell Materials[17]

| Shell material | Maximum temperature of LED chips(℃) | Flow resistance (Pa) |
|---|---|---|
| Aluminum | 48.63 | 18928.83 |
| Copper | 45.84 | 18493.31 |

The flow velocity result keeps the same with last paper that higher flow velocity comes with lower temperature. And 1mm diameter jets are stronger than 1.5mm diameter jets. Copper is the better metal material for heat transfer.

**[3]Structural optimization of a microjet based cooling system for high power LEDs[18]**

The same cooling system as the last paper is used for thermal analysis because both of these papers are from the same authors and this paper is a continuation of the previous work. So, they analysed how different inlets and outlets affect the flow and temperature distributions.

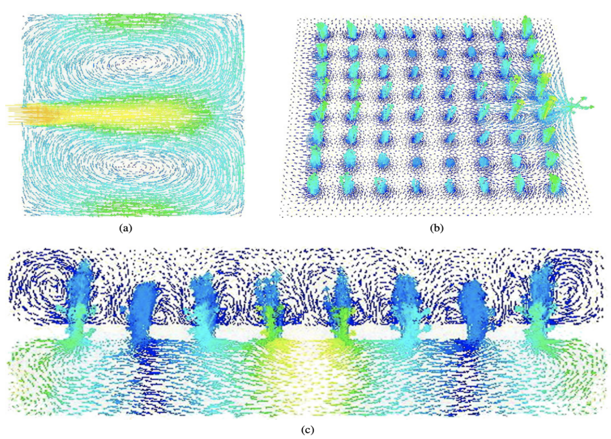



Figure 21: Flow Temperature Distributions with Rectangular Housing,1 MidInlet, 1 MidOutlet[18]

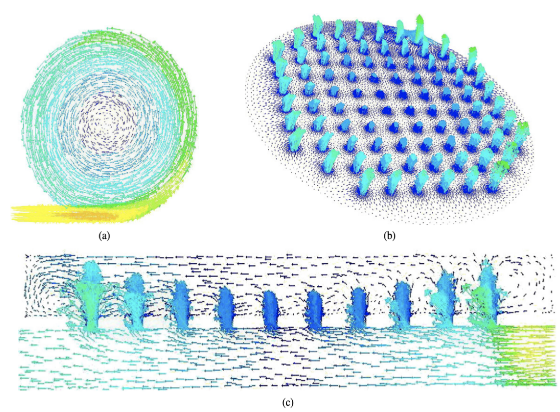



Figure 22: Flow Temperature Distributions with Circular Housing, 1 BotInlet, 1 TopOutlet[18]

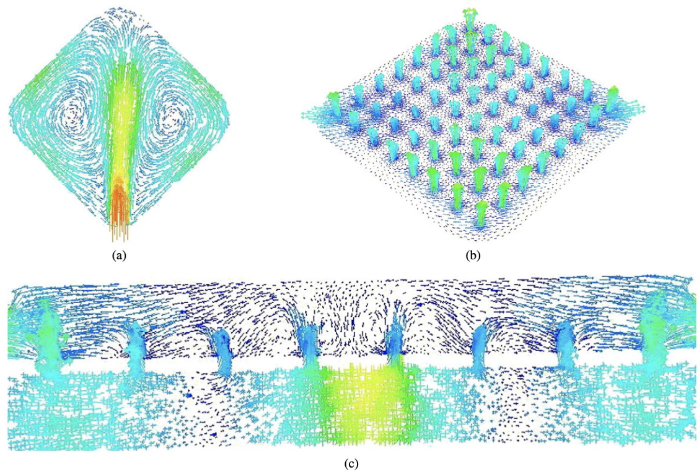
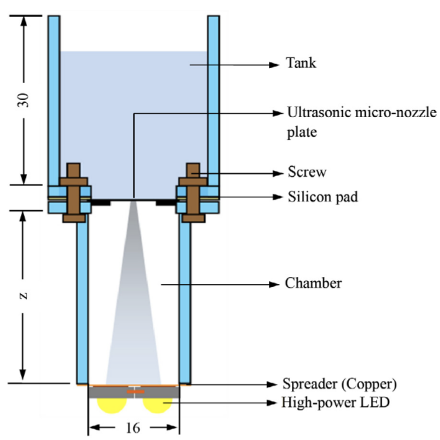



Figure 23: Flow Temperature Distributions with Rectangular Housing, 1 BotInlet, 2 TopOutlets[18]

For the closed-loop microjet cooling system, design with one inlet and two outlets can achieve the best cooling performance. More outlets may help lower down the temperature.

**[4]A microspray-based cooling system for high powered LEDs[19]**

In this paper, the author used a water spray to cool the LED chip. Also compared different sprays' characteristics.



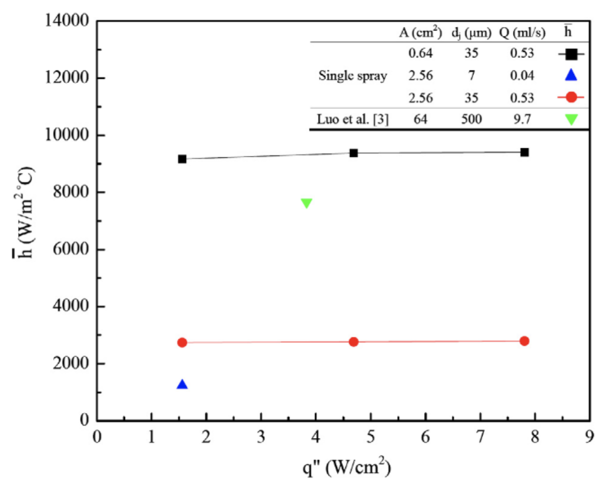




Figure 24: Water Spray Cooling System[19]

Figure 25: Heat Transfer Coefficient with Different Spray[19]

As a result, spray with a bigger diameter can cool the system better than the smaller one.

**[5]A liquid metal cooling system for the thermal management of high power LEDs[20]**

In this paper, liquid metal is used as the coolant for an active cooling solution.

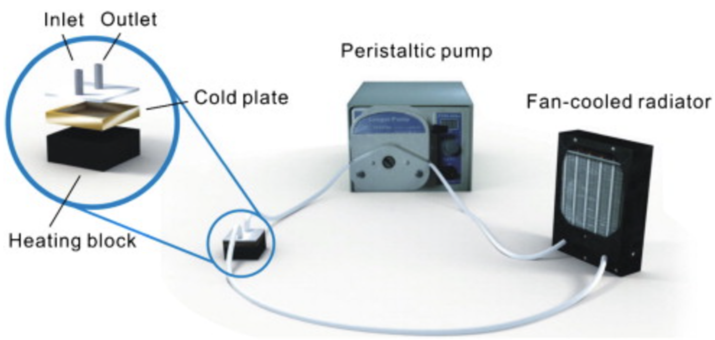



Figure 26: Liquid Metal Cooling System[20]

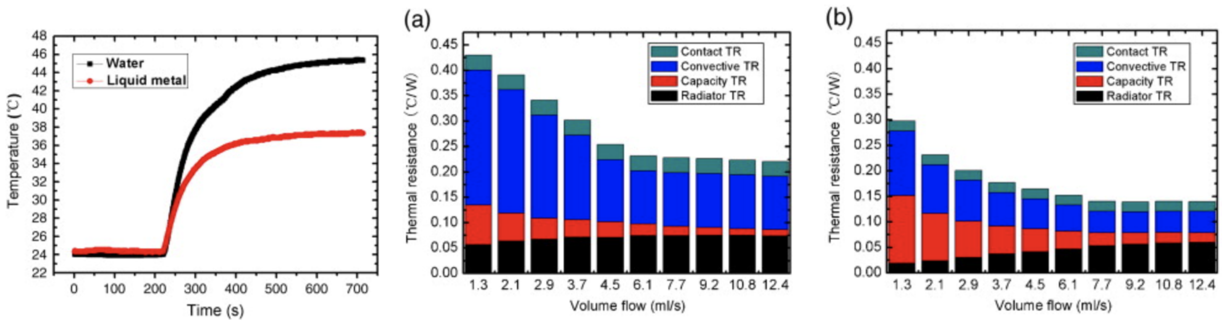



Figure 27: Liquid Metal and Water Cooling Performance with Different Flow Rate[20]

Result from the chart above is liquid metal cooling is better than water and higher flow rate, lower temperature.

## *3.2. Benchmarking*

The benchmarking is generally finished online including the articles shared by Dr. Dou and Google. Existing LED arrays in the market are really similar and we are trying our best to figure out the new design and the way to create cheaper products. So, analysing the whole system and subsystems are necessary. Basically, we decided to go through 3 different subsystems-LED housing, Cooling, and Circuit, which are easy to research and analyze.

### 3.2.1. System Level Benchmarking

#### 3.2.1.1. *Existing Design #1: A mini-LED illuminator*

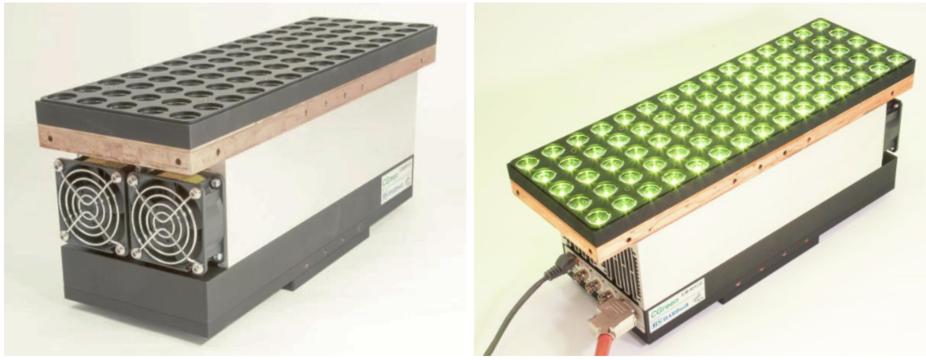


Figure 28: A mini-LED illuminator[21]

Multiple LEDs with rectangular LED housing, tight packing and metal heat sink with two fans.

Benefits:

- Good light intensity

Disadvantages:

- N/A

#### 3.2.1.2. *Existing Design #2: A single-LED illuminator*

Figure 29: A single-LED illuminator[21]

One single powerful LED with fans cooling system.

Benefits:

- Light can focus on one single point.

Disadvantages:

- Irradiate areas may not be enough.

#### 3.2.1.3. *Existing Design #3: LED-Flashlight 300*

Figure 30: LED-Flashlight 300[22]

Similar to Existing design#1, the only difference is the position of fans.

Benefits:

- Good light intensity

Disadvantages:

- N/A

### 3.2.2. Subsystem Level Benchmarking

#### 3.2.2.1. *Subsystem #1: LED Housing*

The housing of the system is what will hold the LEDs. The housing variants can change the overall light intensity, cost, durability, and assembly. This LED housing is the most important component when first trying to design a system because the rest of the system will have to complement it.

##### 3.2.2.1.1. Existing Design #1: Rectangular

Figure 31: Rectangular LED Housing[21]

Normal packing used in the labs. Meets the light intensity requirement.

Benefits:

- Good at light intensity requirements.
- Avoid repeated waste of light, reduce light loss and simplify the structure

Disadvantages:

- Not so good for the size requirement.

- Less effectively reduce weight and decrease safety.

#### 3.2.2.1.2. Existing Design #2: Circular

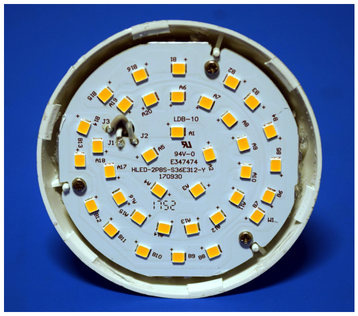


Figure 32: Circular LED Housing

The most commonly used packing for family lighting.

Benefits:

- Best light intensity
- Size requirement

Disadvantages:

- Hard to packing LEDs
- If the heat sink is not done well, it is easy to cause safety problems

#### 3.2.2.1.3. Existing Design #3: Triangular

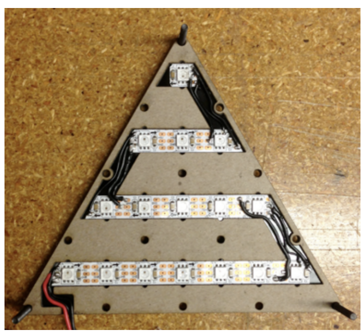


Figure 33: Triangular LED Housing

Weird housing which may attract people’s attention.

Benefits:

- The triangle LED housing has an attractive shape, which is charmful.
- Screen utilization is greatly improved

Disadvantages:

- The triangle LED housing will have some limitations in shape condition.
- Limited by the honeycomb arrangement of pixels, the dot pitch cannot be too small.

- Software writing is also more troublesome.

### *3.2.2.2. Subsystem #2: Cooling*

The cooling of the system is a top priority. The system will need to be cooled or the LEDs can overheat and cause damage to the overall system. These cooling components will be mainly used to cool the heat sink if needed. This subsystem will only be needed in the final design if the heat sink doesn't fulfill its job.

#### 3.2.2.2.1. Existing Design #1: Fans

Figure 34: Cooling fans[21]

Most commonly used cooling method. Fans are.

Benefits:

- No technical problem will appear.
- Cost is lower than other cooling systems.
- Don't need much maintenance.
- Easy to set and safe

Disadvantages:

- Cooling performance is not so impressive.
- The use of many fans may produce louder noise..

#### 3.2.2.2.2. Existing Design #2: Water Spray

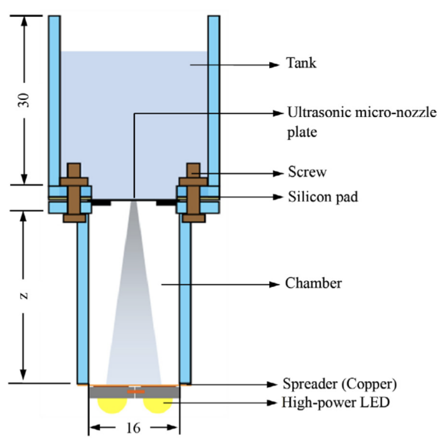


Figure 24: Water Spray Cooling[19]

Strange way to cool with water spray..

Benefits:

- Cooling fast.

Disadvantages:

- Not safe because leakage can cause huge safety problems.
- Complex to build and hard to do the maintenance because of rusty.

#### 3.2.2.2.3. Existing Design #3: Liquid Metal

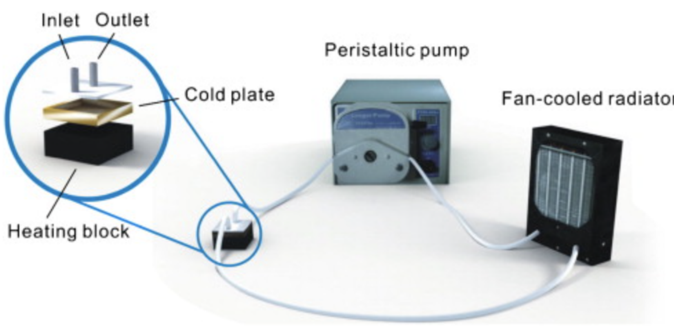



Figure 26: Liquid Metal Cooling[20]

Using liquid metal to cool.

Benefits:

- Leakage won't cause big safety problems.
- Higher thermal efficiency than water.

Disadvantages:

- Liquid metal may be unstable at times.

### *3.2.2.3. Subsystem #3: Circuit*

The circuit subsystem focuses on the design of the circuit powering the LEDs, the minimum requirement for this subsystem is for the TTL control system to control the pulse width modulation for the LEDs.

#### 3.2.2.3.1. Existing Design #1: Generate High Current Pulse Circuit

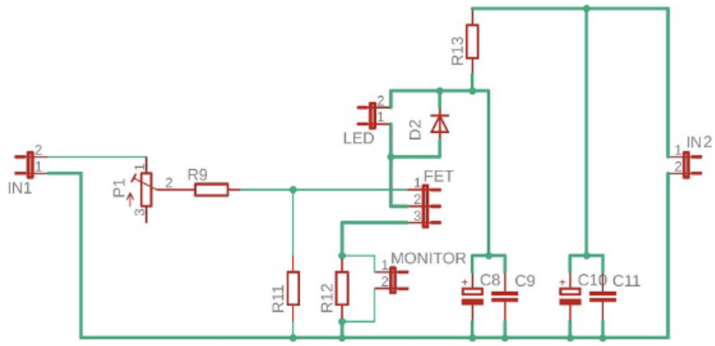



Figure 35: [23]

The high current pulse circuit controls a single LED, it has 2 inputs one being a control input and the other being a voltage source. The circuit also contains a capacitor bank to ensure steady flow within the circuit. Finally there is a serial monitor built into the circuit to view it in real time. This circuit has the advantage of being easily analyzed while it's running, however is much more complex than the other designs. It also only supports a single LED operating at high voltages

#### 3.2.2.3.2. Existing Design #2: Flow Velocimetry Circuit

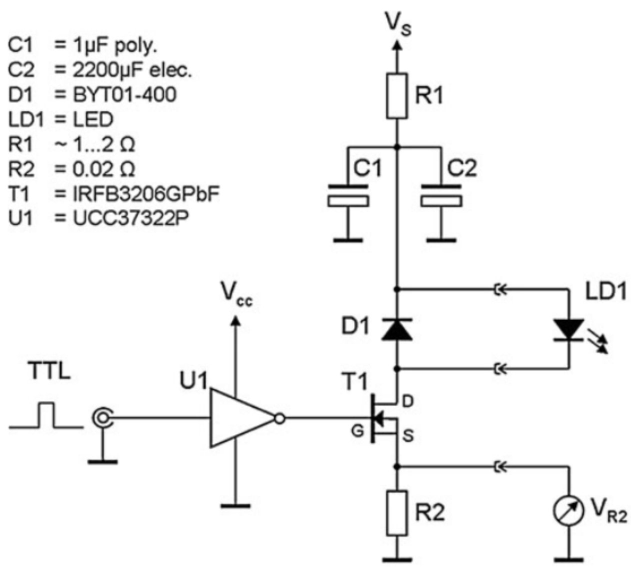



Figure 1: Flow Velocimetry Circuit [2]

As mentioned in the literature review above the Flow Velocimetry Circuit pulses a single LED which has its light converted into a single plane of light. The circuit is controlled by a TTL input signal to a gate enabling and disabling the flow from a voltage source that is kept constant by a capacitor bank. While this circuit is easier to manufacture than the one above it suffers from the same problem that it supports only a single LED. Another Benefit is that the circuit accepts a TTL control input.

#### 3.2.2.3.3. Existing Design #3: Water Tank Circuit

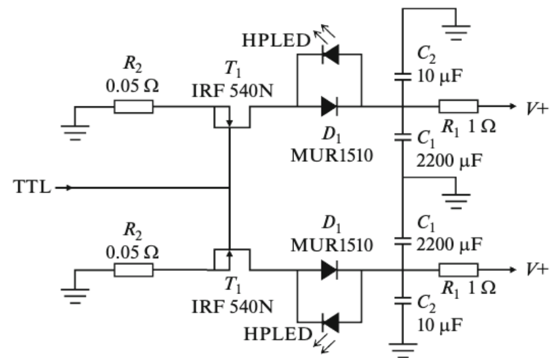



Figure 2: Water Tank Circuit [3]

The final benchmarking circuit was also taken from the literature reviews above. The Water Tank Circuit has the advantage of running 2 LEDs in parallel. It also uses a capacitor bank to keep the voltage source constant. Finally it uses a TTL input signal into two gates to enable the circuit and power the LEDs. While this design is slightly more complex than the Flow Velocimetry Circuit it enables multiple LEDs in parallel, a requirement of this project.

## *3.3. Functional Decomposition*

### 3.3.1. Black Box Model

The Black Box model is used to describe the inputs that are going into the system and the outputs that occur after the inputs affect the system. The black box model here revolves around the entire LED system. The inputs are electrical energy,the control signal, and the cooling fluid. The electrical energy comes from the system having a battery that supplies the system energy when on. The control signal is what describes how the system is running. The cooling fluid is what is entering the system so it doesn't overheat and get damaged. The outputs occur from the process of the inputs. The outputs leaving the system are light, thermal energy, the control signal, and the cooling fluid. The light is a result from the electrical energy turning on the LEDs. The thermal energy is a result from the electrical energy not having a maximum efficiency and results in losses that are converted to heat instead of light.The control signal is the system telling us the diagnostics of the system. The cooling fluid will then leave the system with the heat it collected. The black box model can be seen in figure #

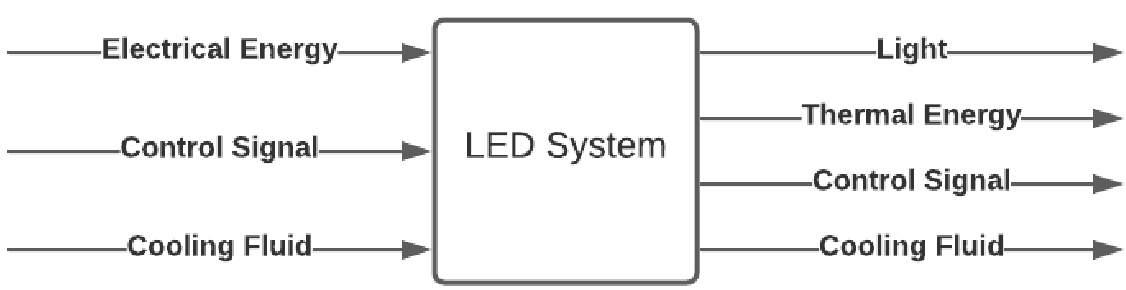



Figure 36: Black Box Model

### 3.3.2. Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional model's importance is to show how a system is structured to work. The functional model includes the inputs of energy and how the system works as a whole. The functional model in this report starts with the input of human energy. The person using the system has to turn on it which needs their energy to start the process. When the system is turned on it provides electrical energy from a battery or electrical source. The electrical energy then travels to three different sections of the device. The first section being the system diagnostics, which gives feedback on if and how the system is running.The second area electricity travels to is the cooling system.The cooling system starts the movement of the fluid that will collect the heat from the heat sink and then it will leave the system. This area that the electrical energy transfers to is the circuit board. The circuit board will then convert the electrical energy into light and heat. The light will be transferred into the red, green, and blue LEDs.

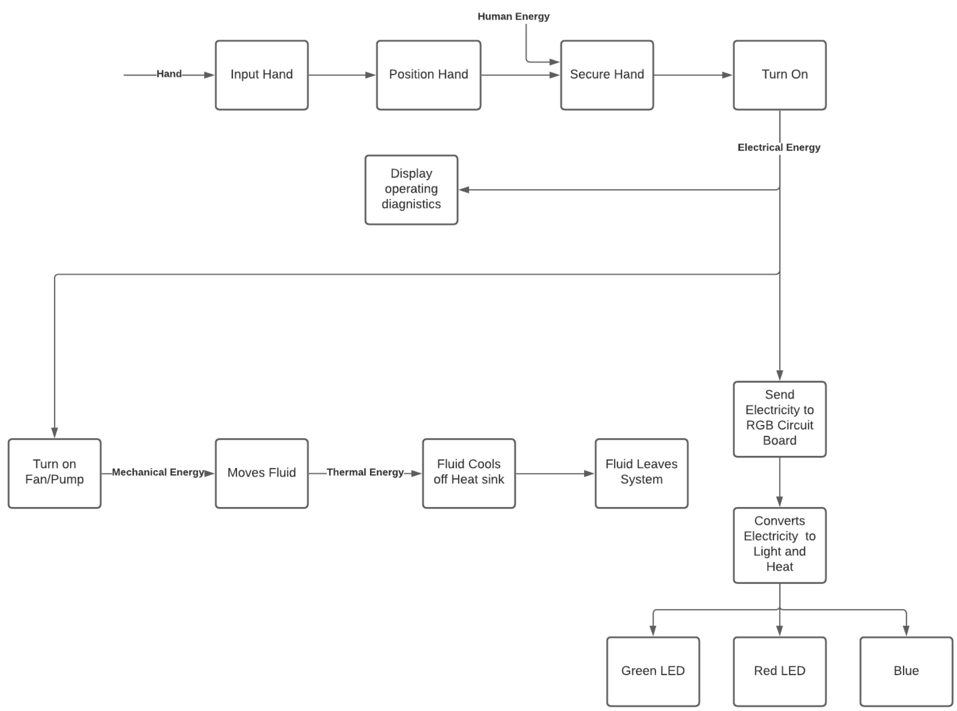



Figure 37: Functional Model

# 4. Concept Generation

Chapter 4 contains five subsystem concepts and 3 full system concepts selected by pugh chart from full 8 concept variants. Both advantages and disadvantages of each subsystem and system are listed. The subsystem concepts were put into a morphological matrix from which the 8 full concept variants were derived.

## *4.1. Full System Concepts*

### 4.1.1. Full System Design #1: Concept Variant 1

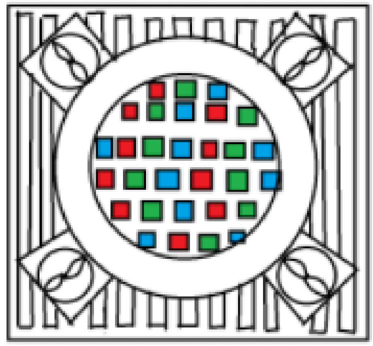


Figure 38: Concept Variant 1

This design is a circular housing with tightly packed LEDs, four medium size fans under a rectangular fin copper heat sink. The LEDs in this system all use the RGB LED chips.These chips allow the team not to worry about the set up of the colors since they contain all of the colors. The circular housing is good for light intensity and directing light such as a flashlight uses circular housing. The downside of circular housing is that it is more expensive to manufacture and the difficulty of manufacturing is a lot harder than rectangular. The LEDs were tightly packed. The four medium sized fans will cool off most of the area under the copper heatsink. The copper heatsink uses rectangular fins because they are more useful than the pin fins when it comes to this set up. No coolant system was needed because the heatsink and fans were assumed to be enough.

Benefits:

- Stronger light intensity
- Good cooling system

Disadvantages:

- Manufacturing cost
- Manufacturing
- Assembly

### 4.1.2. Full System Design #2: Concept Variant 5

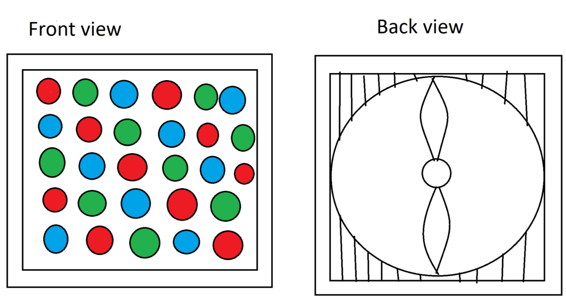



Figure 39: Concept Variant 5

This design is a rectangular housing with loosely packed LEDs, rectangular copper heat sink with one large fan. The rectangular housing is good for light intensity, but the loose packing is not, so the light intensity isn't so good. Both rectangular housing and loose packing make the size of this design large. The large fan cannot cover everywhere, so the cooling performance is bad.

Benefits:

- Easy manufacturing
- Lower manufacturing cost
- Durability

Disadvantages:

- Cooling
- Size
- Bad light intensity

#### 4.1.3. Full System Design #3: Concept Variant 8

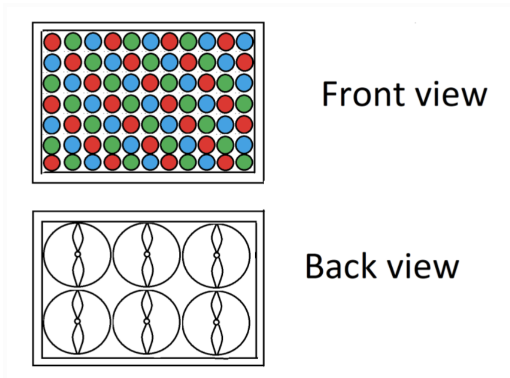



Figure 40: Concept Variant 8

This design is a rectangular housing with tightly packed LEDs, rectangular copper heat sink with many fans. Both rectangular and tight packing are good for light intensity, so the light intensity of this design is over average level. The size of this design will not be too large since tight LED packing is applied. Many fans are able to cool the copper heat sink very fast, so the cooling performance is good.

Benefits:

- Easier manufacturing
- Manufacturing cost low
- Light intensity good

Disadvantages:

- Harder to assemble more fans
- Lower durability

### *4.2. Subsystem Concepts*

#### 4.2.1. Subsystem #1: LED Housing

The housing of the system is what will hold the LEDs. The housing variants can change the overall light intensity, cost, durability, and assembly. This LED housing is the most important component when first trying to design a system because the rest of the system will have to complement it.

#### *4.2.1.1. Design #1: Circular*

The circular design is used in things such as light bulbs and flashlights. The circular housing although would be great for light intensity would require many manufacturing issues. Everything such as the heat sink would have to fit on it correctly.

Pros:

- Best light intensity
- Commonly used for light sources

Cons:

- Manufacturing costs
- Manufacturing difficulty

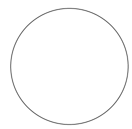


Figure 41: Circular housing

#### *4.2.1.2. Design #2: Rectangular*

The rectangular design was a design that most examples we viewed used. It has the easiest manufacturing and assembly with other equipment. The downside would be that using this type of housing would give up some light intensity.

Pros:

- Easy to manufacture
- Good light intensity

Cons:

- Size

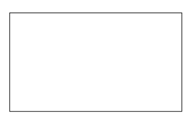


Figure 42: Rectangular Housing

#### *4.2.1.3. Design #3: Triangular*

The triangular design was a design choice due to the variability it could bring. The triangular design would most likely include multiple of them set into a specific configuration. They could also be interchangeable.

Pros:

- Variability
- Good light intensity (multiple)

Cons:

- Hard assembly
- Poor light intensity (single)
- Cost

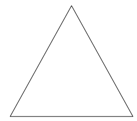


Figure 43: Triangular Housing

#### *4.2.1.4. Design #4: Lego*

The lego design would be multiple housing with each containing a single LED. The housings then will be connected together like legos. So pieces will have to be made differently for where they are placed into the system.

Pros:

- Fun
- Light intensity is descent

Cons:

- Hard assembly
- Hard manufacturing
- Need special circuitry

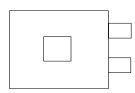


Figure 44: Lego Housing

### 4.2.2. Subsystem #2: Cooling

The cooling of the system is a top priority. The system will need to be cooled or the LEDs can overheat and cause damage to the overall system. These cooling components will be mainly used to cool the heat sink if needed. This subsystem will only be needed in the final design if the heat sink doesn't fulfill its job.

#### *4.2.2.1. Design #1: Many Small Fans*

This design includes using many small fans covering all of the surface of the heatsink.

Pros:

- Good cooling area
- Easily placeable in all regions

Cons:

- Difficult assembly
- Less durable
- Higher occurrence of problems

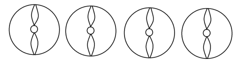


Figure 45: Many Small Fans

#### *4.2.2.2. Design #2: Some Medium Fans*

This design includes a good amount of medium sized fans that cover most areas of the heatsink.

Pros:

- Good cooling area
- Average layout over area

Cons:

- Okay assembly
- Medium durability
- Average amount of problems

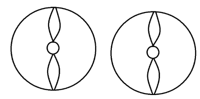


Figure 46: Some Medium Fans

#### *4.2.2.3. Design #3: One Large Fan*

This design is one large fan in the center of the system for cooling. The one fan design will not cover all of space due to circular design.

Pros:

- Durability
- Assembly
- Low amount of problems

Cons:

- Subpar cooling area

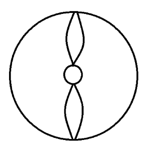


Figure 47: One Large Fan

#### *4.2.2.4. Design #4: Coolant*

Coolant would be in a system that uses a liquid to gather heat out of the heat sink, then be cooled and rerun through. This system will require a pump for the liquid of choice.

Pros:

- Excellent cooling

Cons:

- Assembly
- Cost
- Needs a pump

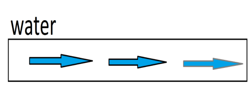



Figure 48: Coolant

### 4.2.3. Subsystem #3: Packing

The packing subsystem details the layout of LEDs that will be encased in the housing. The packing can affect the cost, light intensity,and circuitry/assembly difficulty. This is important because it will have a huge impact on the function of the design.

#### *4.2.3.1. Design #1: Tight*

Tight packing is when the LEDs are prepared closely together. There will be minimal space between them if any.

Pros:

- Excellent light intensity
- Small size

Cons:

- Cost
- Circuit set up

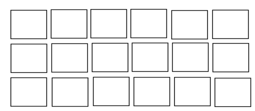


Figure 49: Tight Packing

#### *4.2.3.2. Design #2: Loose*

The loose design will have the LEDs prepared with a distance between them. This means less LEDs will be used.

Pros:

- Cost
- Easier circuitry set up.

Cons:

- Weak light intensity
- Big size

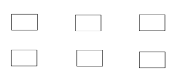


Figure 50: Loose Packing

#### *4.2.3.3. Design #3: Bayer*

The Bayer layout is a design that has been mostly used for cameras and capturing most of the light. There is more green in it because green is in the sweet spot of wavelength for measuring. LEDs will be set up this way if we only have single color LEDs.

Pros:

- Common use/it works
- Easy design layout and assembly
- Circuit setup

Cons:

- Only useful when using separate color LEDs

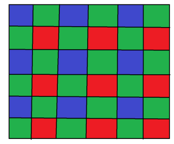


Figure 51: Bayer Pattern

#### *4.2.3.4. Design #4: RGB Chip*

This multicolored chip will include red, green,blue, and white as its light sources. This will make it easier to set up the LEDs since they won't need to be in a special arrangement.

Pros:

- Circuit set up
- Easy Assembly
- Contains all needed colors

Cons:

- N/A

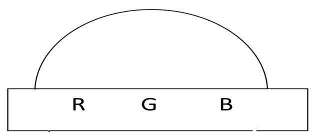



Figure 52: RGB Chip

### 4.2.4. Subsystem #4: Heat Sink

A passive device used to exchange heat produced by an electronic to a fluid or surrounding. This is an integral part of the system since it is what will cool the LEDs keeping them from destroying themselves. The heat sink captures the heat by being made out of a conductive material. The material that we are going to use is copper.

#### *4.2.4.1. Design #1: Pin Fin*

The pin fin heat sink uses multiple cylinders to transfer heat through the heat sink and out the end. This allows the heat to leave the system

Pros:

- Better in situations where the heat sink may be oriented in multiple orientations.
- Cost low

Cons:

- Worst in performance in most situations

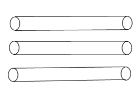


Figure 53: Pin Fin

#### *4.2.4.2. Design #2: Rectangular Fin*

The rectangular fin heat sink is just like the pin fin, except it has thin rectangles that cover more area. The rectangles are parallel to each other. The rectangles reach from one end of the heat sink to the other.

Pros:

- Best performance in most situations
- Cost

Cons:

- Worst performance in multiple orientation situations.

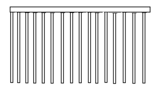


Figure 54: Rectangular Fin

#### 4.2.4.3. *Design #3: Coolant Reservoir*

A coolant reservoir is a pool of liquid that the LED system would sit in. This liquid would absorb the heat out of the LED system.

Pros:

- Quick cooling

Cons:

- Safety
- Durability

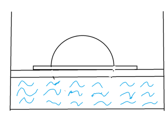


Figure 55:Coolant  Reservoir

#### 4.2.4.4. *Design #4: Fins and Reservoir*

This design involves having a heat sink sitting in the cooling reservoir.The heat sink will collect heat from the electrical system and then the coolant will collect the heat from the heat sink. This concept is not very reliable and more of a hypothetical to our design.

Pros:

- Best cooling

Cons:

- Cost
- Safety
- Durability

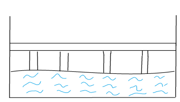


Figure 56: Fin and Reservoir

### 4.2.5. Subsystem #5: Circuit

The circuit subsystem focuses on the design of the circuit powering the LEDs, the minimum requirement for this subsystem is for the TTL control system to control the pulse width modulation for the LEDs.

#### 4.2.5.1. *Design #1 : Single Input Circuit*

One of our clients goals is to only control the system utilizing a pulse generator, this circuit reflects that. Figure X displays a snippet of the circuit, the voltage source represents the input of the signal generator and is the only power source to the system, as such the LEDs are then directly connected to ground. All of the LEDs in a color channel are connected in parallel while each color channel is separate and controlled by an independent voltage source. The benefit of this system is the simplicity in both the design and the control. However a downside is a potential lack of power to the system. Ideally a pulse generator acts as an ideal voltage source, however if this is not the case the system may lack in current due to containing every LED in parallel.

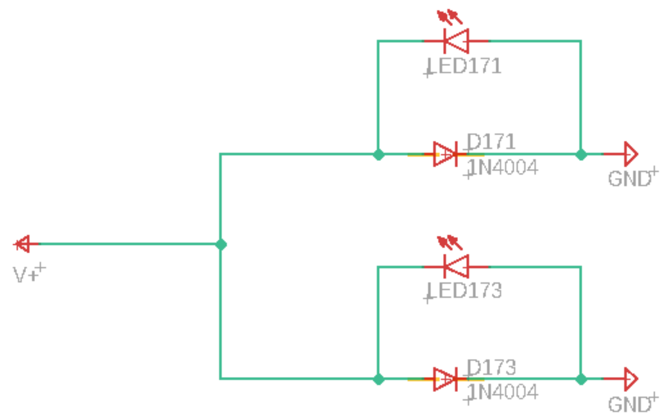



Figure 57: Single Input Circuit

#### *4.2.5.2. Design #2: Gate Controlled Circuit*

The Gate Controlled Circuit is essentially a contingency for the Single Input Circuit. This circuit has an independent voltage source that each LED is connected in parallel to. This voltage source is also connected to two capacitors to ensure a steady flow in the circuit. To control the circuit the signal generator is connected to a N-Channel Power Mosfet that functions as a gate opening and closing the circuit to ground. When the signal generator outputs a high signal the gate will open and the LEDs will turn on, when the pulse lowers it will close the circuit. This design is much more complex to manufacture and has a higher cost. It also could have limitations on speed dependent on the reset speed of the mosfet. It can however be better adjusted to the size of the system for the necessary voltage, because if the system in parallel is too large some of the LEDs can be put in series and the input voltage can be increased above 5 volts.

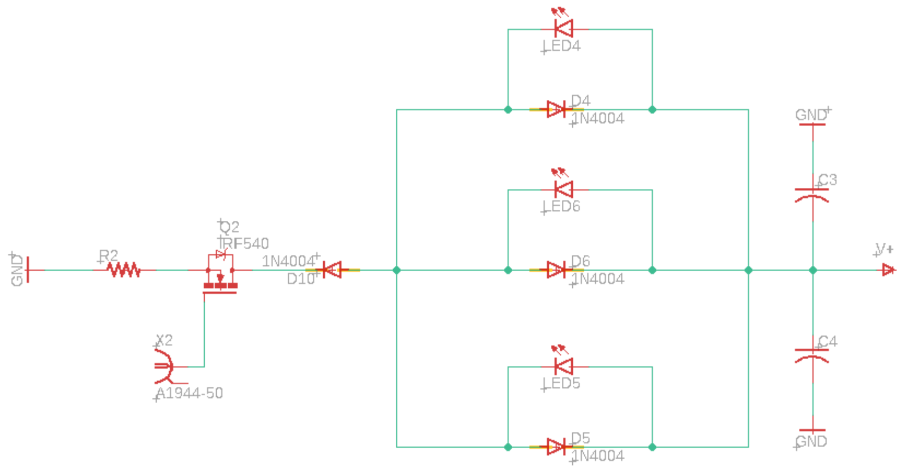



Figure 58: Gate Controlled Circuit

# 5. DESIGNS SELECTED – First Semester

Chapter 5 contains the methods used to select the final designs that will be progressed with through the rest of the project.

## *5.1. Technical Selection Criteria*

To properly evaluate the designs 6 criteria were selected from customer and engineering requirements. They are the cost of the design, the intensity of light produced, the durability of the design, the size of the design, the cooling performance and the overall safety. The most important of these criteria are the light intensity and the cooling performance because they will have the biggest impact on whether or not the design is a success. These specific criteria were chosen because they are a good array of criteria on which the design can be evaluated early on with back of the envelope calculations and do not require advanced simulations or prototypes to test.

## *5.2. Rationale for Design Selection*

### 5.2.1. Pugh Chart

The Pugh chart is a tool that is used to rate and rank all of the concept variants. In a pugh chart the team set a datum concept variant of choice. From that datum the other concept variants are rated with a plus, a minus, or an s. A plus being better, a minus being worse, and a s being equivalent. These ratings are based on the criteria and have values associated with them as seen in the key of the figure. The criteria of the concept variants was the cost, light intensity,durability, size, cooling performance, and safety of the system. After this criteria all of the concept variants were evaluated off of the datum. Once all of the evaluations were completed concept variant 1, concept variant 5, and concept variant 8 were chosen to be the best three designs. The pugh chart can be seen in appendix A.

### 5.2.2. Decision Matrix

The decision matrix is the tool used to evaluate the best three designs from the pugh chart. The decision matrix uses the same criteria from the pugh chart, but instead they are weighted differently to determine what factors of the design are most important. Light intensity was the most important at 30%. Light intensity is the most important because the whole purpose of this system is based on light intensity and measuring through light reflection. Next cost and cooling performance came in second at 20%. Cost is important because the team only has a 1000$ budget. The cooling of the system is important so the system does not overheat. Third place was safety at 15%, fourth was durability at 10%, and last was size at 5%. Safety was not weighted as high because the parts of the system are not all too dangerous from one another, but still weighted decently because the system should not harm anyone. Durability is really low because most of these systems will have very similar life spans. Size is the least important because it does not affect the outcome of what the system is built to do. The criteria are then rated on a scale from one to ten. Then you multiply that raw score by the decimal point value of the percentage to get the weighted score. Weighted score is much more important than the raw score because it takes the weights of each criteria into factor. From the decision matrix it was found that concept variant 8 was the best overall design, concept variant 5 was the second best, and concept variant 1 was ranked third.

Table 6: Decision Matrix

| | | CV 1 | | CV 5 | | CV 8 | |
|---|---|---|---|---|---|---|---|
| | Weights | Raw Score | Weighted Score | Raw Score | Weighted Score | Raw Score | Weighted Score |
| Cost | 20% | 4 | 0.8 | 7 | 1.4 | 6 | 1.2 |
| Light Intensity | 30% | 8 | 2.4 | 6 | 1.8 | 6 | 1.8 |
| Durability | 10% | 6 | 0.6 | 7 | 0.7 | 5 | 0.5 |
| Size | 5% | 6 | 0.3 | 8 | 0.4 | 8 | 0.4 |
| Cooling Performance | 20% | 6 | 1.2 | 5 | 1 | 8 | 1.6 |
| Safety | 15% | 6 | 0.9 | 6 | 0.9 | 6 | 0.9 |
| Total | | 36 | 6.2 | 39 | 6.2 | 39 | 6.4 |
| Relative rank | | | 3 | | 2 | | 1 |

### 5.2.3. Calculations

#### *5.2.3.1. Size*

One of the goals from our client is that the size of the array be less than that of a laptop. However since the circuit is unknown it is difficult to gauge the size of the device. As such each device was calculated to have an area of 0.5 $ft^2$. Since this value is the same the devices were all originally given a score of 6. Due to the rectangular designs being more modular and could potentially be stacked together to increase their size the score was raised to an 8.

#### *5.2.3.2. Light Intensity*

The light intensity of the device can be calculated fairly simply. The selected LEDs operate at roughly 111 Lm/W. Each system is meant to run at roughly 300 W. As such the intensity for each device can be measured with the overall lumen output. This value comes out to 33,300 Lumens. While dividing this over the area comes out to 66,600 Lumens per $ft^2$. However due to the shapes the light will not collimate as well in a rectangular design as in a circular design due to the greater distance between LED chips, since the light does not properly collimate the intensity won't be ; as such the circular design received a score of 8 while the rectangular designs were scored at 6.

#### *5.2.3.3. Cooling*

The cooling in the system is a bit tricky to calculate in depth due to the presence of a multi-finned heatsink. So the first thing that was done was to evaluate the differences between the pin fin and the rectangular fin heatsinks. Simple calculations showed us that the surface area achieved by the rectangular heat sinks as well as their greater ease of acquisition made it the better choice. The preliminary heat transfer evaluation can be seen in Appendix F. Assuming that the LEDs have roughly 50% efficiency the heat rate generated by the system would be equivalent to 150 W. While the calculated heat transfer out of the system without taking into account forced air or fins is 152 W. This value is higher than the expected heat generation while not taking into account the cooling from the forced air flow and the fins. It however also does not take into account any heat generated by the circuit itself. This shows us while the design is feasible a more in depth heat transfer analysis must be conducted on the system as a whole once the design is further finalized.

#### *5.2.3.4. Durability*

Due to the designs being very similar functionally and component wise the difference in durability was mostly decided by the number of moving parts due to an increased number means there is a higher likelihood of a single part failing. Due to this CV 5 with its 6 fans scored the lowest, CV 1 with its 4 scored slightly above CV 5 and CV 8 with its singular fan was scored the highest with an 8. If the system was passively cooled it would score a 9 with the remaining point lacking incase of any electronic malfunctions.

### 5.2.4. Selected Designs

Through the processes mentioned above the original 8 CVs were reduced down to 2. The top design is concept variant 8 while the second best is concept variant 5. Both concept variants have many similarities with their rectangular design, copper heat sink and tight packing of the LEDs. The major difference is the size of the fans being used. Concept variant 8 uses 6 fans on the back plate while variant 6 uses a singular fan. This difference makes variant 6 easier to assemble and maintain due to a lower number of fans but because it is a singular fan there is less forced air flow moving through the system, the opposite is true of variant 8. It was decided that the increased cooling efficiency was more important as a baseline, however as seen in section 5.2.3.3. the cooling system is potentially more than potent enough for the process and later in the design stages the ease of manufacturing and assembly could be prioritized.

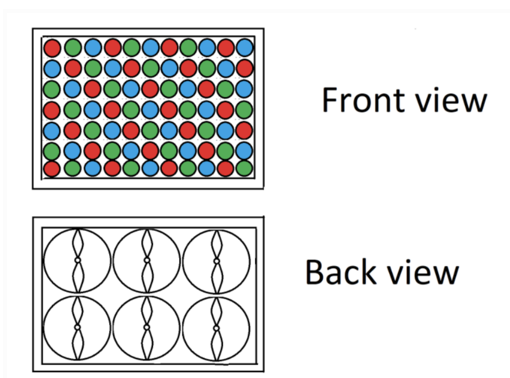



Figure 40: Concept Variant 8

# 6. REFERENCES

[Include here all references cited, following the reference style described in the syllabus. There should only be one Reference list in this report, so all individual section or subsection reference lists must be compiled here with the main report references. If you wish to include a bibliography, which lists not only references cited but other relevant literature, include it as an Appendix.]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# 7. APPENDICES

## 7.1. Appendix A: Pugh Chart

| | | Concepts | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Selection Criteria | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Cost | | Datum | - | - | - | + | - | - | s |
| Light Intensity | | | - | - | s | + | s | - | + |
| Durability | | | - | - | s | s | - | - | s |
| Size | | | - | - | - | + | - | - | + |
| Cooling Performance | | | + | + | + | - | + | + | s |
| Safety | | | + | + | + | s | + | - | s |
| Total + | | | 2 | 2 | 2 | 3 | 2 | 1 | 2 |
| Total - | | | 4 | 4 | 2 | 1 | 3 | 5 | 0 |
| Total s | | | 0 | 0 | 2 | 2 | 1 | 0 | 4 |
| Scores | | 0 | -2 | -2 | 0 | 2 | -1 | -4 | 2 |

| Key | + | - | s |
|---|---|---|---|
| | 1 | -1 | 0 |

## 7.2. Appendix B: Voltage across Linear Current Regulators

$$V_{LCR} = \Delta V_{LCR} + V_{LCR,opt}$$

## 7.3. Appendix C: Unexpected Power Loss

$$P_{Loss} = I_{LED}(\Delta V_{LCR} + V_{LCR,opt})$$

## 7.4. Appendix D: Optimized Power Loss

$$P_{Loss,opt} = I_{LED} \times V_{LCR,opt}$$

## 7.5. Appendix E: Current in ILED

$$I_{LED} = V_{REF}/R_S = V_S/R_S$$

## 7.6. Appendix F: Heat Transfer Calculations

Assumptions:

k=401 W/m*K [23]

h= 100 $W/m^2*K$ [24]

L=10 mm

A=0.0464515 $m^2$

Using Conduction and Convection equations to find $T_2$:

$$- k\frac{DT}{DX} = h(T_2 - T_\infty)$$

$T_2$= 59.92 C

Using the convection equation to calculate the heat rate, q:

$$q = h * A * (T_2 - T_\infty)$$

q = 152.92W