Adjustable Focus, Intensity, and Gradient Light for Commercial Photography

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Abstract

The adjustable light for commercial photography is intended to be a mobile light bar that allows a photographer freedom to create light effects while shooting long exposure photographs. The ability to move a light as well as customize its output allows a photographer to "paint with light."

Our light is powered by a rechargeable battery which gives the photographer the freedom to move and position the light as needed without being restrained by cords. Additionally the output of our light can be customized using four inputs to create fades of different styles, intensities, and sizes.

Contents

1 Introduction

The concept of "painting with light" has existed as long as photography. By taking long exposure shots of still objects while moving the light source, photographers can quickly achieve complex lighting effects that would take hours to create in photoshop. Commercial photographer Rick Kessinger has requested a photography light that is purpose-built for this technique. We addressed this problem by designing a LED light bar with controllable focus, intensity, and gradient. With our solution, the photographer will be mobile and in full control of the lighting for a photo shoot. This control will allow for fast adjustment and turnaround between and during photo shoots.

The light bar is comprised of sixteen LED arrays arranged along a forty-eight inch bar, two DC/DC converters, a battery, battery charger, and control circuitry. The light bar can operate from the internal battery or from a commercial wall adapter. When plugged in to the wall adapter, the charger circuit charges the battery. The battery or wall adapter powers the two DC/DC converters, which step down the battery voltage to a level usable by the LED arrays and control circuitry. The control circuitry produces sixteen four-bit signals that dictate the intensity of each LED array based on the user input. User input is controlled by three encoders that can be set to describe the desired intensity, focus, and gradient settings of the light bar.

As a result of the niche use of a LED light bar that is controllable by focus, intensity, and gradient, a retail product does not exist. Rick Kessinger has been able to use custom-made filters for individual photo shoots and change out the filters depending on the effect desired. However, this technique is time-consuming and requires new filters be made in order to achieve new light effects. Additionally, his solution is not battery powered so his light bar must be plugged in to a power source. This presents a safety hazard in the dark environments required by light painting. Our product is a portable alternative that allows for easy and safe control of the lighting effect.

1.1 Block Descriptors

The block diagram of the system is shown in Figure 1 on the next page. The design was split into three main subsections. The power circuitry includes the battery, charger, and DC/DC converters. The LED arrays include the LEDs and LED pulse width modulation (PWM) circuitry. The digital controller includes the circuitry to map the user input to the intensity of the individual LED arrays.

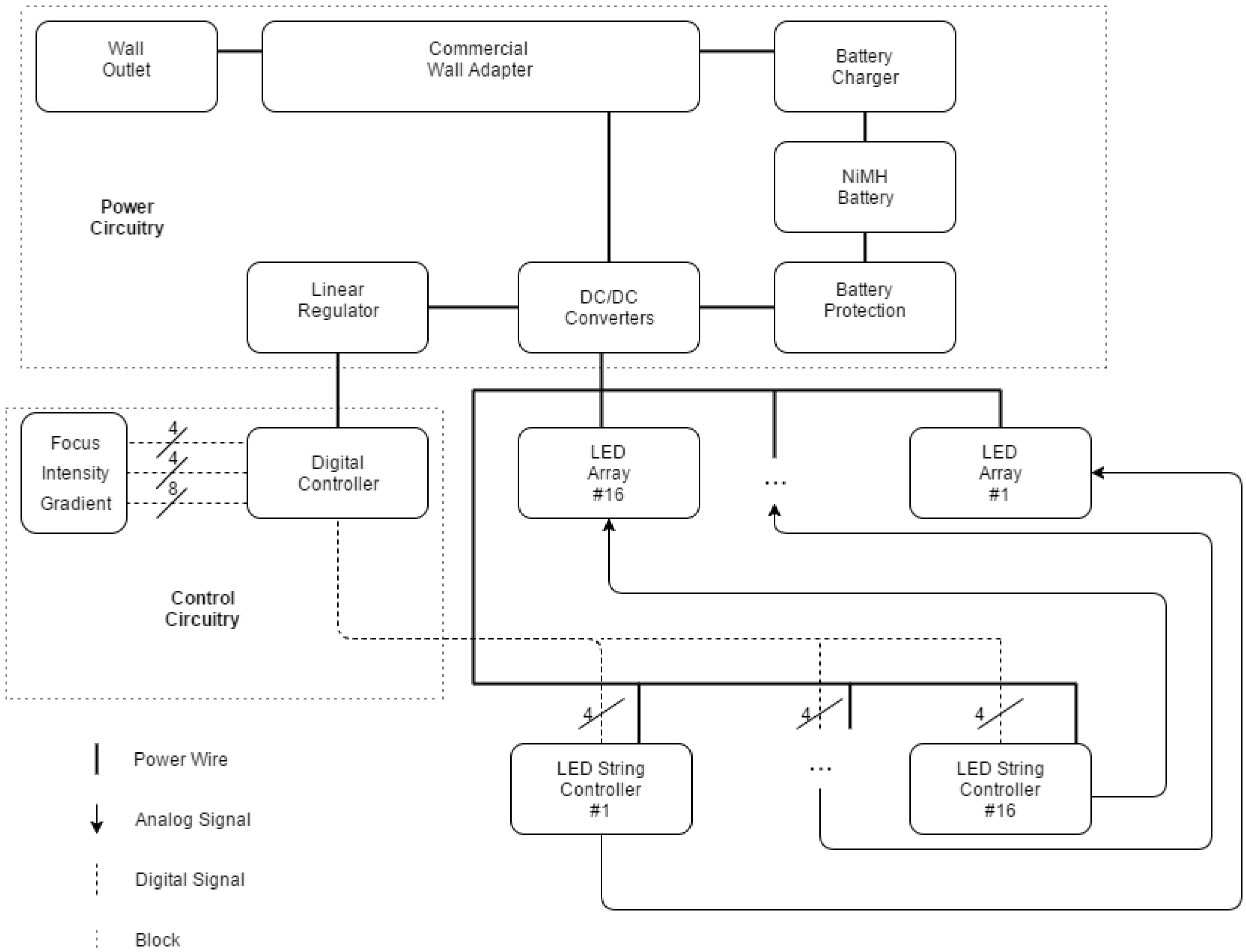

Figure 1: System Block Diagram

- **Digital Controller:**
  The control unit decides the intensity setting based on the three user inputs from the encoders. The control unit is made entirely of digital logic implemented by complex programmable logic units to create a simple, low power design. The control unit interfaces with the LED string controllers using sixteen four-bit signals to describe the output intensity of each array.

- **LED Arrays:**
  The LED arrays consist of 6 Cree MLC LEDs in parallel per array. The maximum luminous output of all 16 arrays is 2500 lumens which is a suitable light intensity for photography.

- **LED String Controllers:**
  These modules take the four-bit signals from the digital controller and use them to determine the duty cycle of the PWM for each LED array. By controlling the duty cycle of the LEDs as they are rapidly switched on and off, the human eye will perceive a level of light proportional to the duty ratio of the PWM. This ratio can range from 0% for fully off to 100% for fully on.

- **DC/DC Converters:**
  The DC/DC Converters are two buck converters that step down the wall adapter voltage or battery

voltage to a level low enough to be usable by the LEDs. Each converter powers eight LED arrays and string controllers. Additionally, one of the converters provides power to the control unit. Both converters are identical.

- **Linear Regulator:**
  The linear regulator further steps down the DC/DC converter output voltage to the 1.8V required by the CPLD's. This module also smooths out any voltage ripple on the DC/DC output due to the PWM circuits of the LED string controllers in order to ensure proper operation of the control circuitry.

- **NiMH Battery:**
  The battery is expected to be supplying power for the light bar during most photo shoots. When the wall adapter is plugged in, the light bar is powered by the adapter and the battery is charged. Otherwise, The battery sends power to the LED load and control circuitry by way of the DC/DC converter modules.

- **NiMH Battery Charger:**
  This module charges the battery when the light bar is plugged in to the commercial wall adapter. In order to make sure that the lighbar is rechargeable overnight, this module is capable of charging the battery from a fully discharged state to a full charge in less than four hours.

- **NiMH Battery Protection:**
  In order to prevent damage to the NiMH battery caused by under-voltage or over-current, a protection module was implemented. The battery can be damaged if the pack voltage drops below 8.0V or if the output current exceeds twice the rated capacity of 4.2A. The protection circuit disconnects the battery from the rest of the circuit before either of these events occur.

- **Commerical Wall Adapter:**
  The purpose of this module is to generate the power required to charge the battery and operate the LEDs when the battery has been discharged. Note that this module is an off-the-shelf power supply.

2 Design

2.1 Power Circuitry

In order to meet the minimum specification of 2500 lumens on the LED output, it was expected that the LEDs would consume 40W of power. The CPLDs were expected to consume no more than 0.5W of power. This results in a total of 40.5W consumed when operating from the battery. The battery pack was required to store enough energy to supply 40.5W for at least 30 minutes of operation. Additionally, when operating from the wall outlet, the battery must also be charged. The worst cast power consumption of one NiMH battery pack of at most 13.2V charging at a rate of 2.25A was estimated to be 29.7W. As a result, the AC/DC stage must be able to supply at least 70.2W.

2.1.1 Commercial AC/DC Supply

Inputs: Standard US Wall outlet voltage at $120V_{rms}$
Outputs: 15V ± 0.75V at 6.0A
Description: A DC voltage is required to power all circuitry inside of the light bar. Standard wall outlets output AC voltage. The Delta Electronics MDS-090AAS15 BA [13] was chosen to convert the wall outlet output to a DC voltage usable by the battery charger and DC/DC Buck Converters. The datasheet for this module shows a maximum output power of 90W with 114mV peak-to-peak of output ripple. This is more than sufficient for the application.

2.1.2 DC/DC Buck Converters

Inputs: 15V ± 0.75V from the AC/DC Supply or 9.6V ± 1.6V from the batteries
Outputs: 4.0V ± 0.1V
Description: A schematic of one of the converters is shown in the Figure 2 below:

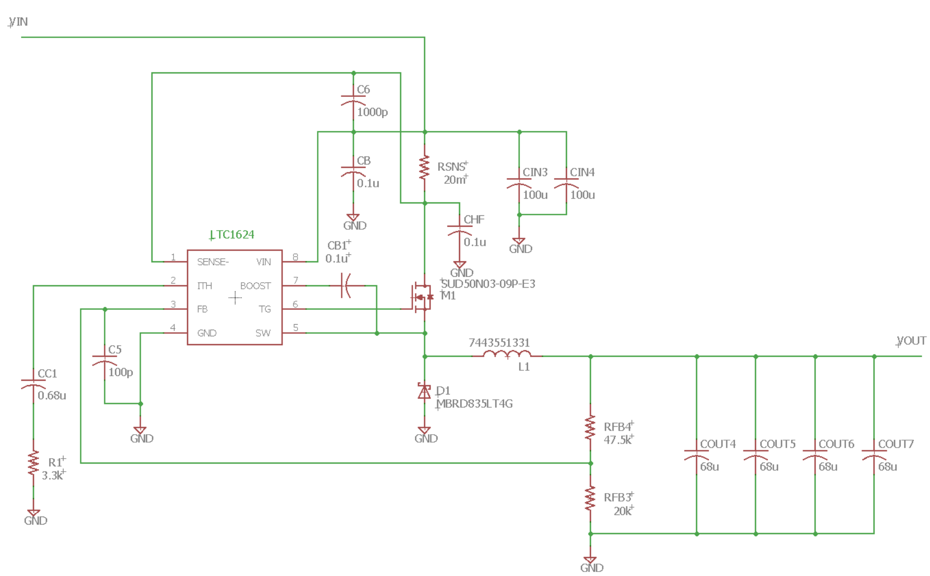

Figure 2: Single DC/DC Buck Converter Schematic

The battery voltage can range from 8.0V to 13.2V depending on the level of charge. In order to regulate voltage to a consistent 4.0V that the LED's require, two buck converters were used. One buck converter provides power to LED modules 0 through 7 and the control circuitry. The other converter provides power to LED modules 8 through 15. The LTC1624 IC was chosen to control the converters. Note that this controller has a set switching frequency of 200kHz. Using the formula for the duty cycle of the duty cycle of a buck converter, the maximum duty cycle that this converter will operate at is:

$$V_{out} = DV_{in} \tag{1}$$

$$D = \frac{V_{out}}{V_{in}} = \frac{4.0V}{15V} = 0.27 \tag{2}$$

A $\Delta I_{L_{pp}}$ of 0.75A was allowed. Using volts-seconds balance on the inductor when the MOSFET is conducting:

$$V_L = V_{in} - V_{out} = L\frac{di_L}{dt} \tag{3}$$

$$L_{min} = \frac{(V_{in} - V_{out})D}{\Delta I_{L_{pp}} f_{sw}} = 19.57\mu H \tag{4}$$

The inductance was increased to $33\mu H$ as a near value. For an output voltage ripple of 0.1V:

$$\Delta I_{L_{pp}} = \Delta I_{C_{pp}} = 0.75A \tag{5}$$

$$C = \frac{\Delta Q}{\Delta V} = \frac{\Delta I_{L_{pp}}}{8 f_{sw} \Delta V_{out}} \tag{6}$$

$$C_{out} = \frac{\Delta I_{Lpp}}{8 f_{sw} \Delta V_{out}} = 11.719\mu F \tag{7}$$

For an input voltage ripple of 0.30V, when the MOSFET is conducting:

$$I_{in} = I_c + I_{out} \tag{8}$$

$$I_c = 5.5 - 9.6 = -4.1A \tag{9}$$

because average current in the capacitor must be zero in periodic steady-state:

$$C = \frac{\Delta Q}{\Delta V} = \frac{\frac{I_c D}{f_{sw}}}{\Delta V} \tag{10}$$

$$C_{in} = \frac{I_c D}{f_{sw} \Delta V_{in}} = 18.45\mu F \tag{11}$$

The LTC1624 has an upper limit on the output ESR of $2R_{sns}$ in order to maintain control loop stability. Including the effects of ESR:

$$\Delta V_{out} = \Delta V_{out,capacitor} + \Delta I_{out} ESR \tag{12}$$

After several iterations, it was determined that four $68uF$, $70m\Omega$ ESR capacitors will be used on the output and two $100uF$, $85m\Omega$ capacitors will be used on the output in order to meet the requirements. A simulation of the output voltage ripple at full load of one this converter is plotted in Figure 3 on the next page

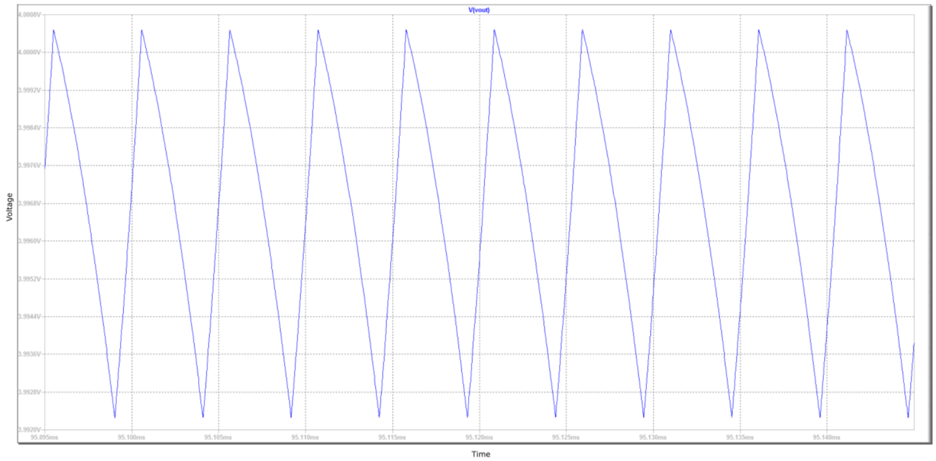

Figure 3: SIngle DC/DC Buck Buck Converter Full Load Output Voltage Ripple

2.1.3 NiMH Battery

Inputs: 2.25A charging current from the battery charger
Outputs: 9.6V ± 1.6V
Description: In order to function throughout the entirety of a photo shoot, the batteries were required to sustain the light bar for at least 30 minutes of operation. The components that draw the most power are the LED arrays, which can draw up to 100mA each when the light bar is fully illuminated. The Panasonic HHR-450AB21L2X4 nickel metal hydride battery pack operates at 9.6V nominal with a capacity of 4.5mAh for a total of 43.2Wh of stored energy in the pack. A pack is made up of 8 cells at 1.2V nominal. The discharge characteristic of one of the cells in the pack is shown in Figure 4 below.

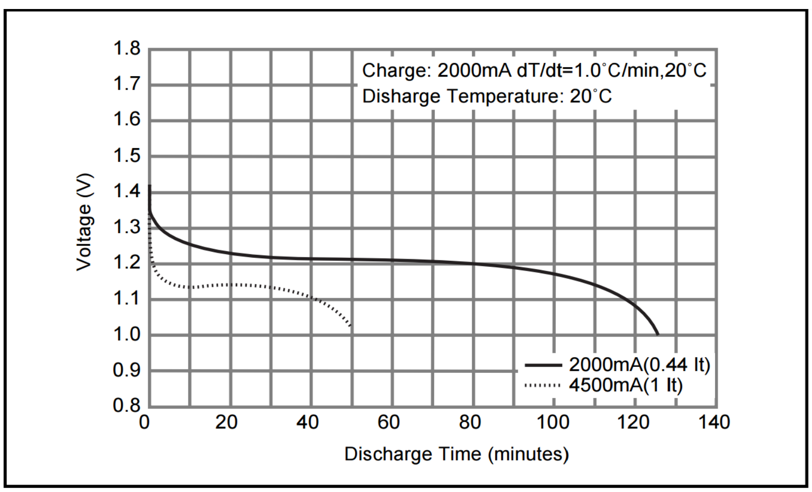

Figure 4: Typical Discharge Curve of a single NiMH Cell

The dotted curve represents a 1C (4.5A) discharge, which was the expected discharge rate for the battery under maximum load. It was estimated from this curve that the batteries would be able to supply the light bar for at least 40 minutes.

2.1.4 NiMH Battery Charger

Inputs: 15V ± 0.15V from the AC/DC Supply
Outputs: 2.25A fast charge current to the batteries
Description: The Maxim DS2715 battery charger IC is a standalone charger for the NiMH battery. The battery is fast-charged at 0.5C (2.15A) for no more than 200 minutes. Fast-charge is terminated by the dT/dt method using a 10k NTC thermistor mounted to the battery pack. When the cell pack's temperature rate of change exceeds $0.5C^{\circ}$ per minute, fast-charging terminates. After fast-charge ends, the charger begins a topoff charge of 580mA in order to fully charge the battery. This terminates after 50 minutes or if the battery temperature is above 50°C. After the batteries reach full charge, a maintenance charge of no more than 0.033C (148mA) offsets any battery leakage. A schematic of the charging circuit is shown in the Figure 5 below:

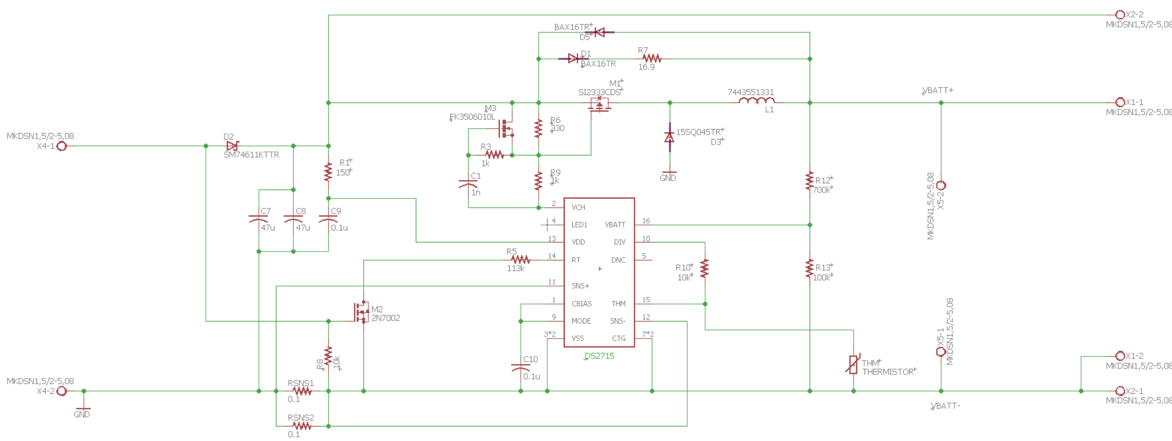

Figure 5: NiMH Battery Charger Schematic

The DS2715 controls current through the inductor L1 and into the battery by switching on and off the transistor M_1. First, the V_{ch} pin is pulled low, turning on M1 and allowing current through the inductor to ramp up. Once the voltage across the sense resistor reaches $|V_{FC}| = 121mV$, the V_{ch} pin goes high impedance, turning off M1 and allowing current in the inductor to ramp down as it freewheels through the diode D3. V_{ch} holds at high impedance until the sense resistor voltage drops to $V_{FC} + V_{HYS-FC} = 93mV$, at which point V_{ch} pulls low again and the cycle repeats.

The DS2715 measures the charging current through the battery back using a sense resistor in series with the battery pack. By choosing the resistance of the sense resistor, the current that the DS2715 regulates to can be controlled. The sense resistor was determined using the equation given on page 11 of [7] to be $50m\Omega$ for a charging current of 2.15A Once the battery is deemed to be fully charged, its enters done mode. The DS2715 remains in this state until it detects that the battery has begun to discharge, at which point it turns on M1 to allow current to flow out of the battery.

The transistor M1 was chosen for its small source drain capacitance of 350pF in order to all ow for fast switching. Additionally, the bootstrap circuit composed of C1, M3, R3, R6, and R9 was added to speed up the turn off of M1 by helping to discharge M1's gate-source capacitance through the drain-source resistance of M3.

2.1.5 NiMH Battery Protection

Inputs: 9.6V ± 1.6V from the battery
Outputs: No less than 8.2V at no more than 5.5A to the DC/DC Buck Converters
Description: In order to protect the batteries from under-voltage or over-current, the LTC-4356 surge stopper was used to provide under-voltage lockout at 8.2V and over-current protection at 5.5A. Below 8.0V, continued discharge of the battery could damage the cells. At the lowest battery voltage allowed by the protection circuit the LED arrays were expected to draw no more that 5.0A of current, the upper limit on battery current was set to 5.5A to allow for some extra margin. A schematic of the battery protection circuit is shown in Figure 6 below:

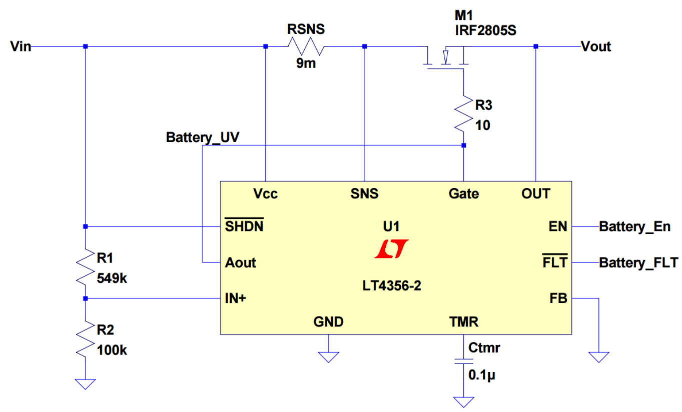

Figure 6: NiMH Battery Protection Circuit Schematic

The safest and most efficient route to implementing undervoltage and overcurrent protection for the battery was to use an IC specifically designed for this purpose. The LT4356-2 surge stopper was chosen. Undervoltage lockout is set by a resistor divider on the IN+ pin as:

$$V_{limit} = \frac{1.25V(R_1 + R_2)}{R_2} \tag{13}$$

for the lower limit of 8.0V required by the battery packs, R2 was chosen to be 100kΩ and R1 was chosen to be $540k\Omega$. For any voltage on the VCC pin lower than this, the LT4356-2 will pull the gate of the MOSFET M1 low, disconnecting the load from the battery. Overcurrent protection is set by the sense resistor R_{sns}. If the voltage across this resistor is greater than 50mV, the surge stopper will pull the gate of the MOSFET M1 low, disconnecting the load from the battery.

$$I_{limit} = \frac{50mV}{R_{sns}} \tag{14}$$

$M1$ and R_{sns} power ratings were chosen to be several times the maximum rating of 5.5A in order to ensure that the components could survive the large currents expected during an overcurrent event.

2.1.6 4.0-to-1.8V Linear Regulator

Inputs: 4.0V from the DC/DC Buck 14.5-to-4.0V converter
Outputs: 1.8V to the CPLDs
Description: Some form of conversion was necessary to create the 1.8V needed by the digital logic. A linear

regulator was selected to step down the 4.0V from the DC/DC converter down to 1.8V for this purpose. The CPLDs consumed relatively little power, so the small power loss inherent to a linear regulator was considered acceptable. The LT1963 Linear Regulator was chosen for this task. $10\mu F$ capacitors were added to the output as per the datasheet specification in order to prevent oscillations [6]. A schematic of the linear regulator is shown in Figure 7 below:

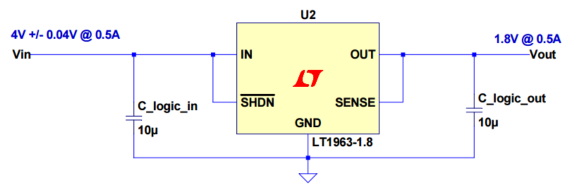

Figure 7: Linear Regulator Circuit Schematic

Worst case power dissipation in the regulator was estimated to be:

$$P = I_{out,max}(V_{in} - V_{out}) = 500mA(4.0V - 1.8V) = 1.1W \tag{15}$$

given that the package has a thermal resistance of $55°C/W$ the part will have a temperature rise of:

$$T_J = P(55°C/W) + T_A \tag{16}$$

$$T_J = 1.1W(55°C/W) + 40°C = 100.5°C \tag{17}$$

this is less than the maximum rating of $125°C$ for this package and so is acceptable.

2.2 Control Circuitry

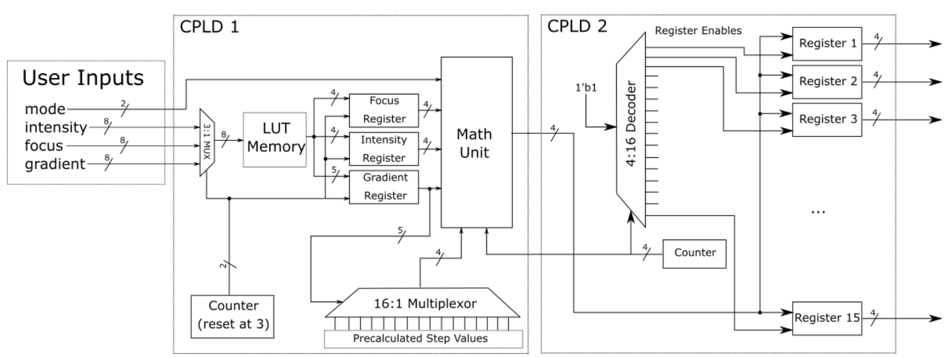

Figure 8: Block Diagram for Digital Controller

Inputs: Focus (8-bit binary signal), Intensity (8-bit binary signal), Gradient (8-bit binary signal), Mode (2-bit binary signal)
Outputs: 16 4-bit Intensities
Description: The Digital Controller takes the user inputs and output 16 4-bit signals, one for each string controller, describing the intensity each light should be outputting. The output intensity of the controller ranges from 0% (4'0000) to 93.75% (4'1111). The controller is made entirely from digital logic rather than a microcontroller to create a simple, low power design. The most efficient way to actualize the digital logic was to use CPLDs which allows all of the circuitry to be on two chips rather than the 60 chips we would

need to implement it with other integrated circuits. This also allowed us to design and test the circuitry in Verilog.

On the CPLDs, the main blocks are the registers and the math unit. The registers are 4 bit synchronous registers. These hold the intensity data for each LED string. Each register has a data input from the math unit and an enable signal from the 4:16 multiplexer. The math unit is responsible for determining the intensity that should be stored in each register. It uses information from the user inputs to calculate a four bit intensity value for each of the 16 LED strings.

The first CPLD also contains circuitry to decode the inputs. The encoders used for user input output a unique 8 bit value for 128 different positions. These patterns needed to be decoded to be useful. This problem was solved by instantiating flash memory on the CPLD to act as a look up table for the encoded output.

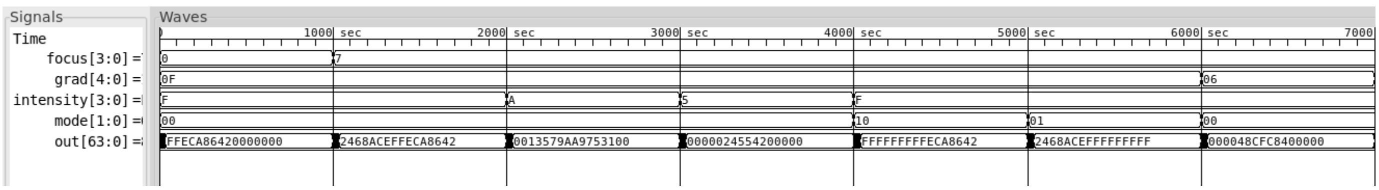

Figure 9: Digital Controller Verilog Simulation

In this waveform simulation of the digital logic the output can be seen relative to various inputs. Inputs focus, gradient, and intensity are displayed as hex values and the mode input is displayed as a two bit binary number. The output is a string of 16 hexadecimal values. Each value represents the digital logic's 4-bit output to that respective LED string. The first 1000 seconds of the waveform are to show an example gradient. The next section shows that the center of the gradient can be moved. The third and fourth section show that the intensity can be lowered while still maintaining a consistent gradient. The fourth and fifth section show the two alternative modes of light output. The sixth section shows that gradients of different sizes can be made by the controller.

2.3 LED String Controller

Inputs: 4-Bit Binary Control signal from Digital Controller at 1.8V
Outputs: Pulse Modulated Square Wave at 4.0V at 1.0MHz
Description: The LED String Controller uses a PWM (Pulse-Width-Modulation) control circuit that takes the 4-Bit control signal from the master digital controller and alters the duty cycle of a clocked square wave based on this 4-bit control signal. The LED string controller takes the 4-bit digital signal and converts it to an analog voltage level which the LTC6992-1 chip maps to a pulse-modulated square wave output at 4.0V max level. The 4-bit control signals will be stepped down from 1.8V to 1.0V because the LTC6992-1 PWM chip's modulation input can only range from 0-1V[10]. This is accomplished with a voltage divider consisting of a 80kΩ resistor in series with a 100kΩ resistor. Each bit of the 4-bit control signal is routed through this voltage divider and then connected to an R-2R ladder. This R-2R ladder's base resistance R will be 1kΩ which generates an output which is only 0.5% off from the actual value of 0.875V as shown in the simulation in Figure 21 .

After the 4-bit control signal is converted to an analog voltage, The LTC6992-1 chip will take this voltage and map it to a square wave with duty cycle from 0% to 100%. In order ensure the LED flicker is not perceptible to the human eye, the square wave frequency must be above 1kHz. The LTC6992-1 chip has an output frequency shown by equation 18.

$$f_{master} = \frac{1MHz * 50k}{R_{Set}} \tag{18}$$

By using a 50kΩ set resistance, the output frequency will be set to 1MHz. The square wave output will be routed to the gate of a T2N7002AK,LM transistor which will turn on and off the drain source current based on the PWM square wave. However, the LTC6992-1 cannot output a higher than 90% duty cycle, so the 4'b1111 control input is clipped to 100% duty cycle.

2.3.1 LED Array

Inputs: 1MHz PWM'ed Square Wave, 4.0 V Supply Voltage
Outputs: Light from LEDs
Description: Each LED Array will consist of 6 Cree MLC LEDs in parallel with a forward voltage of 3.2V, a current at 100m, and a lumen output around 180 lumens[11]. This is in series with a T2N7002AK,LM transistor with an R_{DS} value of 3.9Ω which is in series with a ballast resistor of 4Ω as in Figure 11 [12]. The entire light bar will consist of 16 of these LED arrays to make a total of 96 LEDs with a total lumen output around 2800 lumen. The schematic in Figure 10 shows one string of 6 LEDs which is the base unit of the LED array.

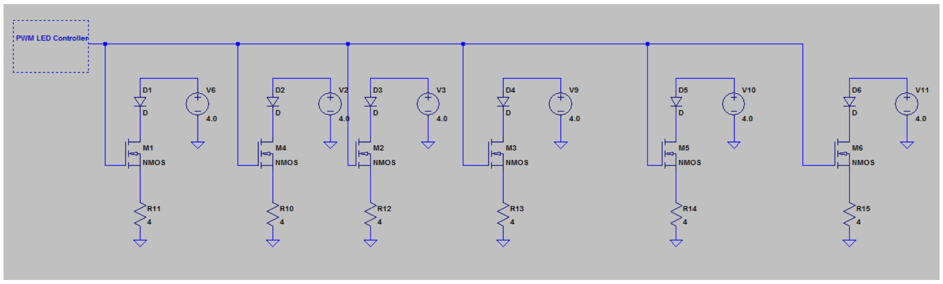

Figure 10: LED string of 6

3 Design Verification

3.1 DC/DC Buck Converters

Figure 11 shows the output current and output voltage of one of the DC/DC buck converters at 4.0A of current output. As seen in the figure, the output voltage is maintained at 4.0V with negligible output ripple. However, the output does have significant ringing on the rising edge of the gate signal.

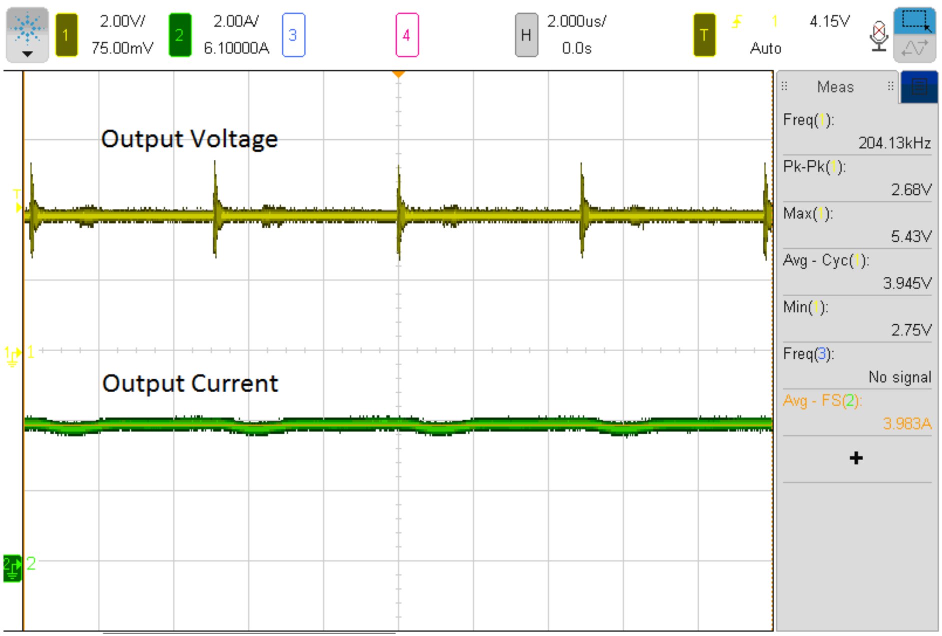

Figure 11: DC/DC Buck Converter Output Voltage Verification

3.2 NiMH Battery

Figure 12 below shows a plot of the battery voltage versus time when a 2.4Ω resistor was attached to the output of the battery through the battery protection circuit. The battery was able to provide power for 65 minutes before the protecion circuit began to enter undervoltage lockout and the battery was disconnected.

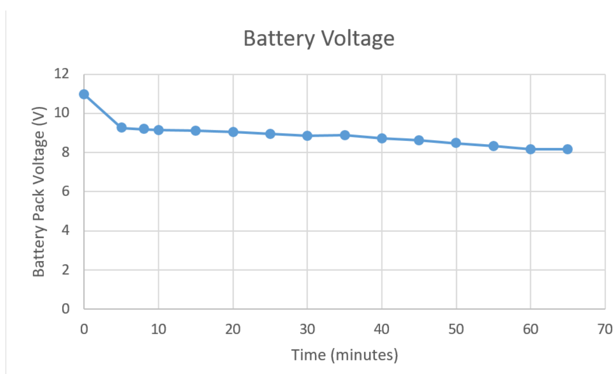

Figure 12: Battery Voltage versus Discharge Time

3.3 NiMH Battery Charger

Figures 15 and 16 in Appendix B show the charger V_{ch} pin voltage and output current during fast charge and topoff respectively. As shown, output current is 2.0A on average for fast charge and 520mA for topoff. While this current is slightly lower than expected, it is still sufficient to charge the battery.

Table 1 shows the pack temperature versus charging time with notes to indicate the transition between charge states. As shown, the charger is capable of charging the battery fully in 150 minutes.

Table 1: Battery Pack Temperature Over Time While Charging

Pack Temperature ($C°$)	25.0	25.2	26.3	27.4	28.6	32.3	35.7	36.6	35.3	36.0	35.4
Time (Minutes)	0	15	30	45	60	75	90	105	120	135	150

3.4 NiMH Battery Protection

The results of the undervoltage and overcurrent tests are shown in Tables 2 and 3 respectively. As shown, undervoltage engages at 8.2V and overcurrent at 5.5A, as required by the specification.

Table 2: Battery Protection Undervoltage Lockout Verification

Voltage Input (V)	15	14	13	12	10	9	8.2	8.0
Voltage Output (V)	14.875	13.835	12.85	11.925	9.47	8.97	8.175	0

Table 3: Battery Protection Overcurrent Protection Verification

Voltage Output (V)	13.91	13.79	13.67	13.51	13.31	0	0	0
Current Output (A)	1	2	3	4	5	5.5	5.6	5.7

3.5 4.0-to-1.8V Linear Regulator

A 3.6Ω resistor was attached to the output of the linear regulator. 4.0V was applied to the input using a DC supply. An output voltage of 1.798V was observed on a DMM, as expected.

3.6 Digital Controller

In order to verify the digital controller, the inputs were sourced through the programming interface and the outputs were measured with a digital multimeter. Results are shown below in table 4.

Table 4: Digital Controller Requirements Verification Table

Requirement Number	Inputs (Decimal)			Outputs (64-Bit Hexidecimal)
	Focus	Intensity	Gradient	
1	7	15	0	0000000F00000000
2	0	15	31	FFEDCBA987654210
3	0	15	0	F000000000000000
3	1	15	0	0F00000000000000
3	2	15	0	00F0000000000000
3	3	15	0	000F000000000000
3	4	15	0	0000F00000000000
3	5	15	0	00000F0000000000
3	6	15	0	000000F000000000
3	7	15	0	0000000F00000000
3	8	15	0	00000000F0000000
3	9	15	0	000000000F000000
3	10	15	0	0000000000F00000
3	11	15	0	00000000000F0000
3	12	15	0	000000000000F000
3	13	15	0	0000000000000F00
3	14	15	0	00000000000000F0
3	15	15	0	000000000000000F

3.7 LED String Controller

The PWM controller and the R-2R ladder were sampled at 4.0V with a 0.001A current with a total power consumption of 4mW which means that that logical overhead is 0.01% of the power consumption of the LEDs. The PWM waveform of 50% is in figure 13 below.

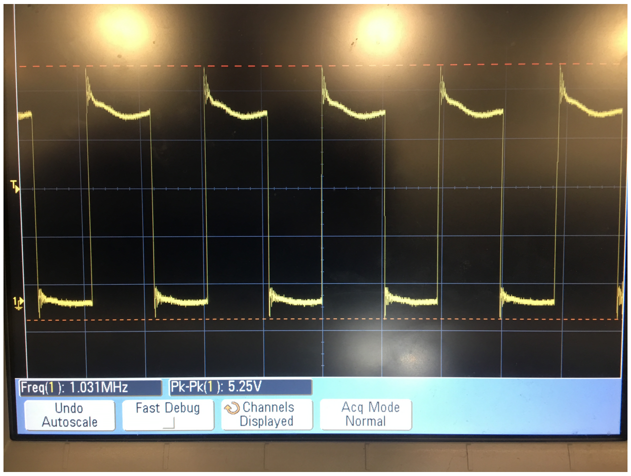

Figure 13: Pulse Width Modulation Circuit Output at 50% duty cycle

3.8 LED Array

A lux meter was used to determine the lumen output of each board. These values were converted using a conversion factor of 0.00101 which was based on the distance that the lux meter was from the light bar [14]. These values were then totaled together to create a total lumen output in the figure below.

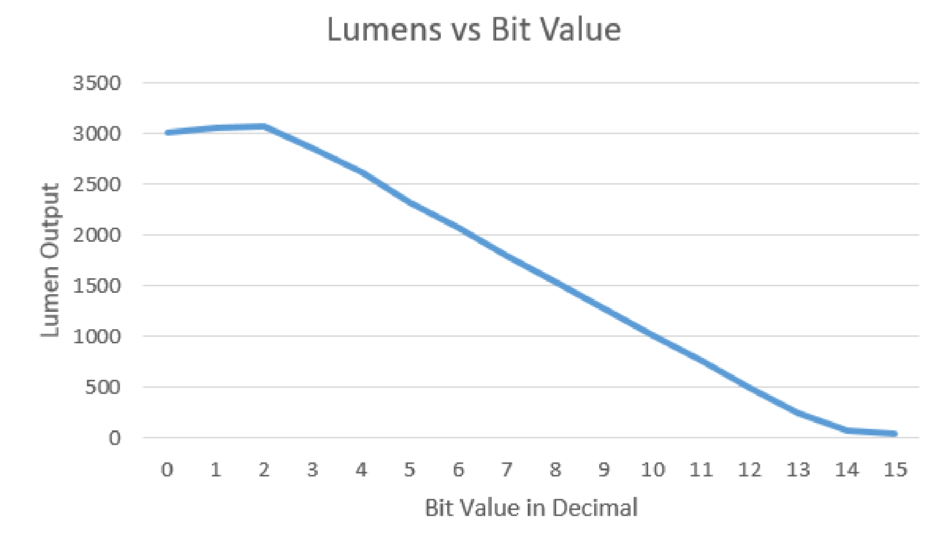

Figure 14: Lumens vs Input Value

From the results, we can see that we can only generate 14 unique levels instead of the 15 that we specified in the design document. Also the lumen output is 20 % higher than what was anticipated. This is due to the variable resistances of the MOSFET transistor which averages out to around 2Ω not the 4Ω. This results in a higher power usage, but at the specified 2500 lumens we are able to meet all requirements.

4 Cost

4.1 Parts

Table 5: Costs for LED Circuits

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
LTC6992C-1	Lineartech	3.83	1.83	45.75
T2N7002AK,LM	Toshiba	0.15	0.07	8.40
MLCAWT-A1-0000-000XE3CT	Cree	0.32	0.21	25.2
BC2665CT-ND	Vishay	0.18	0.12	3.00
ERJ-3EKF1001V	Panasonic	0.10	0.01	1.20
RC0402FR-07806RL	Yageo	0.10	0.01	1.20
RC0805FR-07806RL	Yageo	0.10	0.01	1.20
RC0603FR-0720KL	Yageo	0.10	0.01	1.20
RC0402JR-0710KL	Yageo	0.10	0.01	1.20
Total				82.95

Table 6: Costs for Power Circuitry

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
KJX-PM-4S	Kycon	2.49	2.49	2.49
MDS-090AAS15 BA	Delta Electronics	47.04	47.04	47.04
232KXBK-ND	Yageo	0.15	0.10	0.50
CF14JT6K80	Stackpole	0.15	0.10	0.20
SR225E104MAR	AVX	0.16	0.16	0.96
RDE5C2A101JOS1H03A	Murata	0.10	0.10	0.20
FG28X7R1E684KRT06	TDK	0.10	0.10	0.20
T495D686K020AATE070	Kemet	1.63	1.63	9.78
PLV1H330MC1LTD	Nichcon	1.86	1.86	7.44
7443551331	Wurth	3.27	3.27	6.54
IRF7468TRPBF	Infineon	0.94	0.94	1.88
15SQ045TR	SMC Diodes	0.59	0.59	1.18
LTC1624IS8PBF	Linear Technology	8.92	8.92	8.92
HHR-450AB21L2X4	Panasonic	67.44	67.44	134.88
ERJ-6BWFR051V	Panasonic	0.58	0.58	1.16

Continued on next page

Table 6 – continued from previous page

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
CRA2512-FZ-R100ELF	Stackpole	0.60	0.60	1.20
CMF5016R900FHEB	Vishay	0.61	0.61	1.22
MFR-25FBF52-1K	Yageo	0.61	0.61	1.22
CF14JT10K0	Stackpole	0.10	0.10	0.20
HVR250006983FR500	Vishay	0.10	0.10	0.20
MFP-25BRD52-100K	Yageo	0.10	0.10	0.20
NXFT15XH103FA2B025	Murata	3.51	3.51	3.51
C907U102MYVDBA7317	Kemet	0.28	0.28	0.56
C3216X5R1E476M160AC	TDK	1.26	1.26	10.08
VJ0603V104ZXXCW1BC	Vishay	0.10	0.10	0.80
7443551331	Wurth	3.27	3.27	6.54
SI2333CDS-T1-GE3	Vishay	0.43	0.43	1.56
2N7002-7-F	Diodes Inc	0.15	0.15	0.60
FK3506010L	Panasonic	0.43	0.43	0.43
BAX16TR	ON Semi	0.19	0.19	0.76
SM74611KTTR	Texas Instruments	3.68	3.68	7.36
15SQ045TR	SMC Diodes	0.59	0.59	1.77
BAX16TR	ON Semi	0.19	0.19	0.19
DS2715	Maxim	8.33	8.33	8.33
12FR015E	Ohmite	0.63	0.63	1.26
S20KQCT-ND	Stackpole Electronics	0.63	0.63	1.26
232KQCT-ND	Yageo	0.10	0.10	0.50
CF14JT6K80	Stackpole Electronics	0.10	0.10	0.20
SR225E104MAR	AVX	0.16	0.16	0.32
RDE5C2A101J0S1H03A	Murata	0.10	0.10	0.20
AR215C102K4R	AVX	0.10	0.10	0.20
AR215C102K4R	AVX	0.10	0.10	0.20
FG28X7R1E684KRt06	TDK	0.10	0.10	0.20
T495D686K020ATE070	TDK	1.63	1.63	9.78
PLV1H330MCL1TD	Nichcon	1.86	1.86	7.44
7443551331	Wurth	3.27	3.27	6.54
IRF7468TRPBF	Infineon	0.94	0.94	1.86
15SQ045TR	SMC Diodes	0.59	0.59	0.59
LTC1624IS8PBF	Infineon	8.92	8.92	8.92
LT4356IMS-1TRPBF	Linear Tech	8.92	8.92	8.92
Total				318.49

Table 7: Digital Controller Costs

Part	**Manufacturer**	**Retail Cost ($)**	**Bulk Purchase Cost ($)**	**Actual Cost ($)**
Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
5M160ZT100C5N	Altera	3.7	3.7	3.7
5M240ZT100C5N	Altera	4.9	4.9	4.9
GRM155C80J106ME11D	Murata Electronics	0.02541	0.02541	0.15246
RC1206FR-071KL	Yageo	0.032	0.032	0.064
RC1206FR-0710KL	Yageo	0.032	0.032	0.064
LT1963AES8-1.8#PBF	Linear Technology	4.52	4.52	4.52
Total				13.40

Table 8: User Inputs Costs

Part	**Manufacturer**	**Retail Cost ($)**	**Bulk Purchase Cost ($)**	**Actual Cost ($)**
EAW0J-B24-AE0128L	Bourns Inc.	8.29	8.29	24.87
OEJL-50-4-5	Kilo International	6.01	6.01	18.03
1091-1026-ND	Bulgin	3.91	3.91	3.91
2750654	RadioShack	5.84	5.84	5.84
4609X-101-472LF	Bourns Inc.	0.51	0.51	1.53
Total				54.18

Table 9: Miscellaneous Costs

Part	**Manufacturer**	**Retail Cost ($)**	**Bulk Purchase Cost ($)**	**Actual Cost ($)**
9902	Keystone Electronics	0.111	0.111	5.328
2203	Keystone Electronics	0.453	0.453	10.872
640454-4	TE Connectivity AMP Connectors	0.1228	0.1228	2.7016
3-640441-4	TE Connectivity AMP Connectors	0.19	0.19	4.18
302-S101	On Shore Technology Inc.	0.28	0.28	0.56
P0302	Terasic Inc.	50.00	50.00	50
MDS-090AAS15 BA	Delta Electronics	47.04	47.04	47.04
Total				120.68

4.2 Labor

Table 10: Labor Cost

Name	Hourly Rate	Hours Invested	Total Cost (Hours*Hourly Rate*2.5)
Nick	$40.00	250	$25,000.00
Andrew	$40.00	250	$25,000.00
Eric	$40.00	250	$25,000.00
Total		750	$75,000.00

Note that the work was done on a volunteer basis, driving the project labor cost down to **$0**

This brings the total cost of the project down to the materials cost of **$589.70**. Otherwise, the cost to create this project including labor for three engineers would have been **$75,589.70**.

5 Conclusion

5.1 Accomplishments

At the end of this project, we had completed the entire light bar system capable of controlling the focus, intensity, and gradient of a 2500 lumen output light bar. We were also able to design the power circuitry necessary to supply the light bar using battery power for 30 minutes without power from the AC/DC adapter. Unfortunately, due to a miscommunication with the machine shop, we were not able to obtain a usable housing. Instead, we created a prototype using plywood as a proof of concept.

5.2 Uncertainties

While the battery alone was able to power the light bar for 30 minutes under test conditions, there is uncertainty as to the performance of the battery in a non-ideal case. Internal resistance can vary with battery temperature and the battery leakage over long periods of time could both reduce the effective usable time of the light bar. Additionally, the user inputs were soldered to a perfboard. In future designs, a PCB would be much more reliable.

5.3 Ethical considerations

The Purpose of this project is to design a LED light bar for light painting. As a portable battery powered device, we must consider code 1 of the IEEE code of ethics. Section 1 states that we must consider the decisions that we make which will impact the health, safety, and welfare of the public [4]. We must consider the possible health and safety of the consumers when using the light such as potential weight issues with a portable device. Thus, we have considered issues that relate to potential electrocution with high power electronics, and possible rupture and destruction of the battery. To compensate for these issues, we have designed and built battery protection circuits. In addition, in order to make a viable commercial product, we would need a container built to IP53 specifications.

Because of the nature of our project and working with a photography studio, we must interact with and communicate with Section 5 states that we must improve the understanding of technology, appropriate application, and potential consequences [4]. So we worked with Rick Kessinger Studios to make sure our technology development applied in such a manner that would be beneficial for photographers. We educated photographers at Rick Kessinger Studios of the limits of our design in terms of the lighting effects of PWM and the potential dangers of battery usage and high power design. Additionally, we have given Rick Kessinger resources and pointers for future technology projects involving photography.

5.4 Future work

Future design work of the LED bar requires a more complete final physical design. The inexpensive diffusion nylon used should be replaced with quarter-inch plexiglass to diffuse better. An aluminum light fixture according to our design document rather than the proof of concept plywood that we used could be used. In addition, the light output of the bar should be brought up for better photography use. Lithium-ion batteries should be used to bring up the current and power limit of the battery circuit, or any other higher capacity battery with safety measures implemented. Once the battery's capacity is increased, brighter LEDs with scaled load resistors can be used.

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Appendix A Requirements and Verifications

Table 11: Digital Controller Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Zero Gradient • Output digital signals that describe a gradient ranging of zero, where one LED string is on and the next is off. • 5 Points	1. Verification (a) Connect CPLD and supplementary chips to a benchtop DC power supply set to 1.8V (b) Supply the CPLD inputs with digital input signals to describe a gradient of 0, intensity of 15, and focus of 7 (c) Use multimeter to read outputs of digital controller. Ensure intensity at focus is 15 and intensity at the neighboring strings is 0	Y
2. Maximum Gradient • Output digital signals to describe a gradient of 31, where one LED is on at full intensity at one end of the light and each LED string down the light is one intensity level lower than the last. • 5 Points	2. Verification (a) Connect CPLD and supplementary chips to a bench-top DC power supply set to 1.8V Supply the CPLD inputs with digital signals to describe a gradient of 31, intensity of 15, and focus of 0 (b) Use multimeter to read outputs of digital controller. Ensure the intensity at the focus is 15 and the intensity goes down one step per string	Y

Continued on next page

Table 11 – continued from previous page

Requirement	Verification	Verification status (Y or N)
3. Gradient Location • Any of the 15 LED strings will be able to be the center of the gradient. • 5 Points	3. Verification (a) Connect CPLD and supplementary chips to a bench-top DC power supply set to 1.8V. (b) Supply the CPLD inputs with digital signals to describe an intensity to be 15 and a gradient of 0 (c) Sweep focus input from 0 to 15. At each step using a multimeter to measure the corresponding output to ensure it is at level 15	Y

Table 12: LED String Controller Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. PWM Duty Cycle • Must be able to PWM from 0 to 93.75% duty cycle • 4 Points	1. Verification (a) Attach 2Ω resistor to drain of control transistor (b) Probe with Oscilloscope to determine duty cycle. (c) Step through control voltages to R-2R ladder at 1.8V (d) Ensure that the duty cycle falls within 6.25% of expected cycle	Y
2. Power Consumption • Must consume less than 10% of the power of LED strip • 4 Points	2. Verification (a) Attach 1.8V sources to the R-2R ladder (b) Measure current through last 2R in R-2R ladder (c) Extrapolate current across 2R to Norton Equivalent to find power sink	Y

Continued on next page

Table 12 – continued from previous page

Requirement	Verification	Verification status (Y or N)
3. Minimum Frequency • Must have a frequency above 1kHz to avoid camera flicker • 2 Points	3. Verification (a) Attach 1.8V source for worst case scenario on R-2R ladder(4b0001). (b) Attach 2Ω resistor to transistor drain. (c) Probe with oscilloscope the control transistor (d) Ensure frequency is above 1kHz.	Y

Table 13: LED Array Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Luminous Output • Each LED circuit must output 26 lumen for total of 2500 lumens across bar • 3 Points	1. Verification (a) Attach Power supply with duty cycle of 93.75% to transistor in LED array (b) Attach LED to 4.0V benchtop DC supply (c) Examine with light meter the overall brightness of one LED circuit (d) Make sure each LED circuit outputs 26 lumens (e) Repeat for all 16 circuits	Y

Continued on next page

Table 13 – continued from previous page

Requirement	Verification	Verification status (Y or N)
2. Power Consumption • Power consumption of LEDs must not be greater than 40W • 2 Points	2. Verification (a) Attach transistor to power supply square wave of 4.0V. (b) Attach LED to a bench-top 4.0V source (c) Probe with Multimeter the voltage across dump resistor (d) Probe with Multimeter the voltage across LEDs (e) Extrapolate current across resistor and ergo the LEDs (f) Calculate total power per LED sub-circuit and ensure that it is less than 40W	Y

Table 14: Battery Charger Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Battery Charge State • Within 4 hours, the charger must fully recharge the batteries from a completely discharged state to a capacity necessary for 30 minutes of light bar operation. • 4 Points	1. Verification (a) Take a fully discharged battery pack, as indicated by a battery voltage of less than 1.0V per cell, and attach it to the charging circuit. (b) Monitor the battery temperature in 15 minute intervals using a hand held IR sensor to ensure that it remains below 50C (c) Terminate the charging process after 4 hours. (d) Using a DMM, measure the battery voltage. Ensure that this voltage is at least 9.6V	Y

Table 15: NiMH Battery Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. light bar Battery Life • Sustains operation of the LEDs for at least 30 minutes. • 3 Points	1. Verification (a) Charge the battery up to full charge using the battery charger circuit. (b) Connect the battery to a 2.4Ω resistor. Start a stopwatch. Stop when the battery voltage falls below 1.0V per cell. Ensure that the stopwatch time is greater than 30 minutes.	Y

Table 16: DC/DC Buck Converters Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Output Ripple • The converter output remains within 4.0V 0.1V for output currents in the range of 0.4A to 5.0A • 3 Points	1. Verification (a) Attach a 10Ω resistor to the output of the converter. (b) Attach oscilloscope probes to the output of the converter. (c) Supply the converter with 14.875V. (d) Ensure that the output voltage stays within 4.0V ± 0.1V (e) Repeat for a range of resistances down to 0.8Ω	Y

Table 17: Battery Protection Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Under-voltage Lockout • Under-voltage lockout engages for an input of lower than 8.2V. The lockout condition remains until the voltage increases above 8.2V • 2 Points	1. Verification (a) Attach a 10kΩ resistor to the output of the LTC4356. (b) Attach an oscilloscope probe to the LTC4356 output and input. (c) Supply the LTC4356 with 14V (d) Slowly decrease the input voltage to a level below 8.2V. Check that the output voltage falls to zero. (e) Increase the supply voltage back to 14V. (f) Verify that the output is 14V	Y
2. Over-current Protection • Over-current protection engages for any current more than 5.5A. • 1 Point	2. Verification (a) Attach a load box to the output of the LTC4356. (b) Attach an oscilloscope probe to the LTC4356 output and input. Attach a current probe to the device output (c) Supply the LTC4356 with 14V (d) Slowly decrease the resistance of the potentiometer until the output current rises above 5.5A. Check that the output voltage falls to zero. (e) Decrease the output current to 2.5A (f) Verify that the output is 14V	Y

Table 18: Linear Regulator Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Output Voltage Stability • Regulator output remains within 1.8V ± 0.1V at maximum output current of 0.5A • 2 Points	1. Verification (a) Attach a 3.6Ω resistor to the output of the regulator. (b) Attach oscilloscope probes to the output of the regulator. (c) Supply the regulator with 4.0V. (d) Ensure that the output voltage stays within 1.8V ± 0.1V	Y

Table 19: User Inputs Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Contacting Encoder • Encoder Provides 8-bits of output to represent 128 distinct positions • 4 Points	1. Verification (a) Setup Encoder and associated resistor network with the 8 outputs wired as inputs to a CPLD (b) Program CPLD with lookup table program to decode encoder outputs (c) Wire 7 LEDs as outputs from the CPLD (d) Rotate encoder knob (e) Visually confirm LEDs operate as 7 bit up-counter	Y

Continued on next page

Table 19 – continued from previous page

Requirement	Verification	Verification status (Y or N)
2. Three Position Switch • Three position switch must be able to route a voltage to either one of the two outputs or neither of them • 1 Point	2. Verification (a) Wire center terminal of switch to the output of a 1.8V bench supply (b) Measure voltage of two outside terminals when switch is in each of the three positions (c) Ensure that when the switch is in the middle, neither terminal is biased (d) Ensure that when the switch is in the left position, the right terminal is biased to 1.8V and the left terminal is unbiased (e) Ensure that when the switch is in the right position, the left terminal is biased to 1.8V and the right terminal is unbiased	Y

Appendix B Battery Charging Waveforms

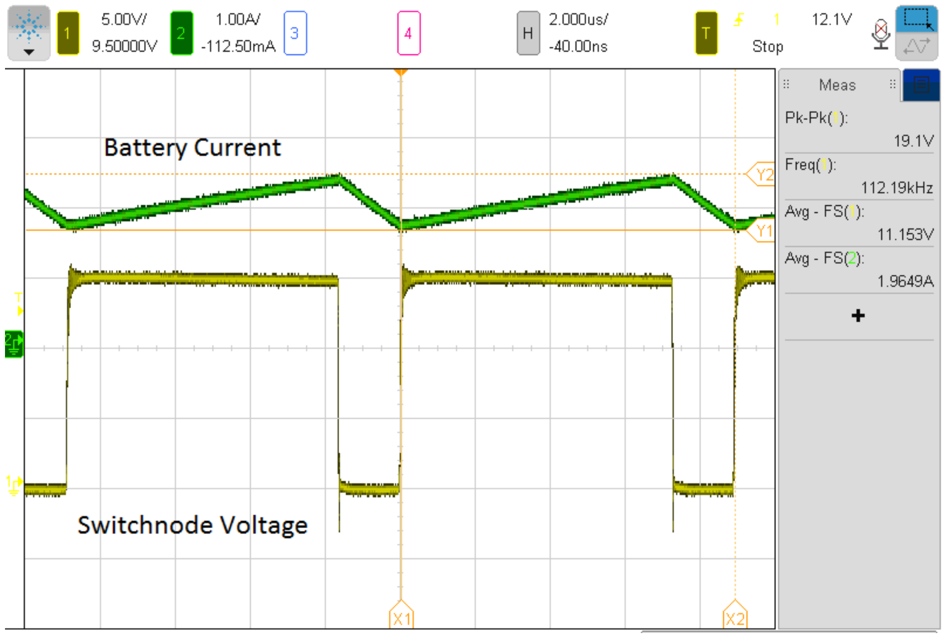

Figure 15: Battery Current and Switchnode Voltage During Fast Charge

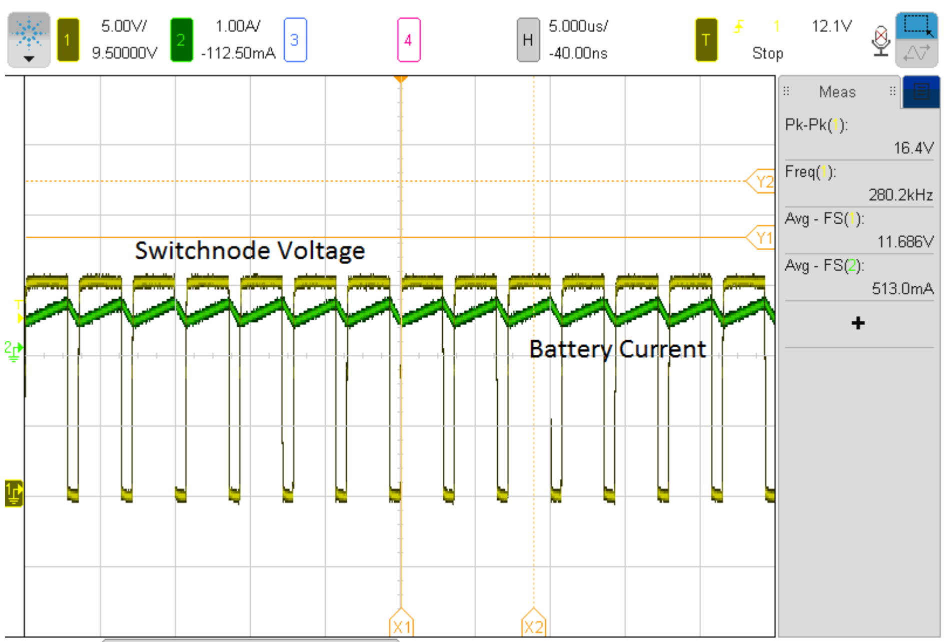

Figure 16: Battery Current and Switchnode Voltage During Topoff