Adjustable Focus, Intensity, and Gradient Light for Commercial Photography

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1 Introduction

1.1 Objective

Lighting is a crucial part of photography, and is one that despite the advances in technology has barely expanded past the dumb bulb phase of development. Photographers have to use custom-made filters for individual photoshoots, and change out the filters depending on the effect desired. Rick Kessinger studio would like a photography light that can be adjustable based on specific photoshoot requirements.

Our proposed solution is to create a programmable light array which can control three criteria, Intensity, how bright the overall light is, Focus, the location of the brightest spot of the light, and Gradient, the gradient of light from bright to dark. Each of these criteria will be controlled by an external knob which regulates the light settings independent of each other. These control inputs will then be routed to an array of LED lights which will adjust their values depending on user input. The entire design will be portable and include a battery system that is internally chargeable.

1.2 Background

Because of the niche use of a controllable LED bar light, a retail product does not exist. Despite that, this product would allow unprecedented freedom for a photographer. According to commercial photographer, a controllable light would allow “painting with light.” Unfortunately because the lack of an existing solution, Mr. Kessinger is forced to create a makeshift gradient out of diffusion paper and then tape it onto an LED light bar. This solution is clumsy and very restrictive as it forces the user to make a new filter every time a different gradient is needed. Additionally, because the LED bar is not purpose built for a photographer, it has the disadvantage of being powered by a wall plugin. This is difficult for a photographer as at times, the only light on in the photography studio is the LED light bar.

With our solution, the photographer will be mobile and in full control of the lighting for a photoshoot. This control would allow for fast adjustment and turnaround between different angles or different photoshoot and the ability to fully create the artist’s vision.

1.3 High-Level Requirements

- The brightness of all the LEDs must range from 0 lumen output to 220 lumens per LED and 0 to 3500 lumens for the entire light bar

- Must be able to adjust the gradient of light from bright to dark from -73 lumens per inch to -5 lumens per inch across an interval of 3 inches to 48 inches respectively.
- Must have cordless operation
- Operate for 20 minutes on battery alone

2. Design

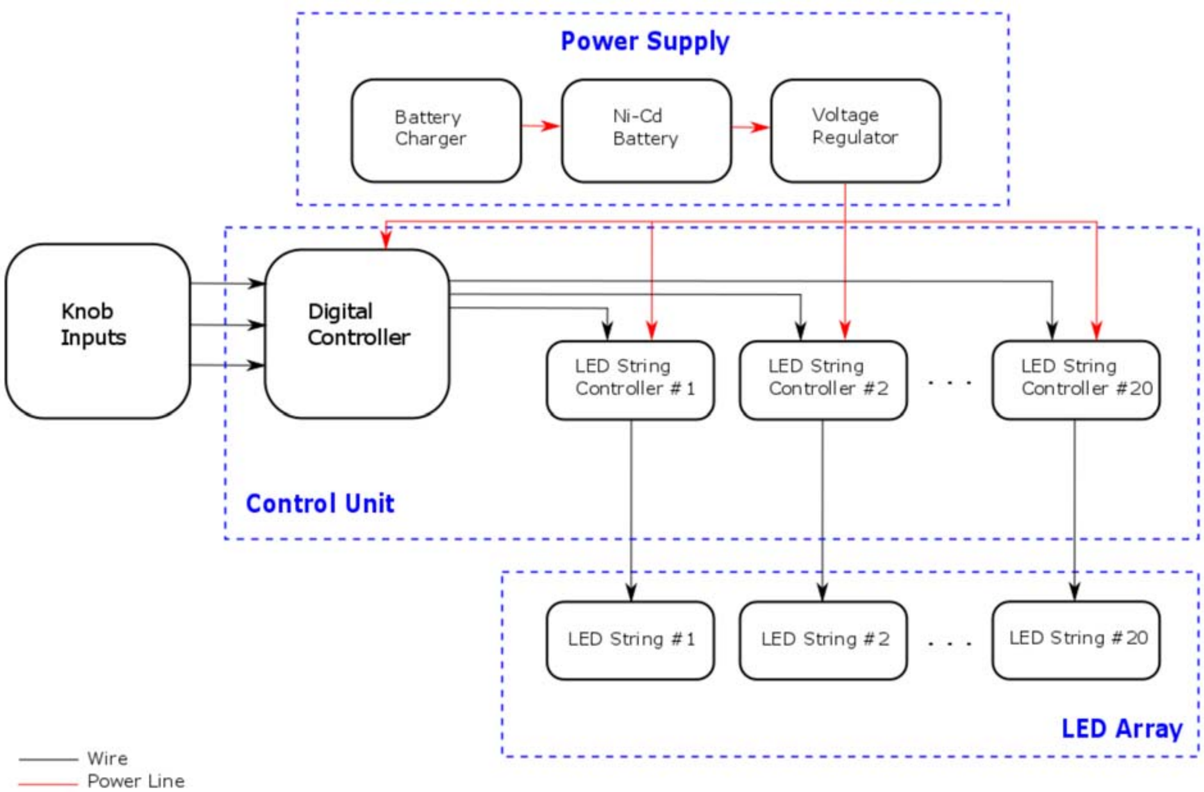


Figure 1: System Block Diagram

2.1 User Inputs

The user input will consist of three digital encoders and a two position switch. The first knob will control the focus of the light which is where the center of the light gradient is. The second will control the gradient of the light which describes how wide or thin the gradient is across the bar. The third knob controls the intensity of the light which describes the maximum brightness across the light bar. The two position switch will control the color temperature of the light. Each position on the switch will correspond to either warm or cool color temperature. For the focus and intensity encoder, we will use the four most significant bits and for the gradient encoder we will use the five most significant bits.

Requirement: Each input knob will constantly send a digital signal to our controller describing its current setting.

2.2 Power Supply

The power supply circuitry for the lightbar was designed to supply a maximum of 100W to the LED strings using either a wall outlet or nickel metal hydride batteries. The calculation for total power is:

16 strings of 2 3.2V Cree LED's powered at a maximum 93.75% duty cycle:
    (32 LED's * 3.1V * 0.9375 duty cycle) = 92.256 W
20 logic IC's at 3.3V:
    (20 * 5V * ~50mA) = ~5 W
16 PWM circuits for LED control:
    (16 * 0.6 W maximum rating) = 9.6 W
2 NiMH batteries at 9.6V charging at a rate of 2.25A
    (9.6V * 2.25A) = 21.6W

In order to reduce the complexity of the power circuitry, the batteries will not charge unless all of the LED's are off.

Peak power required when the LEDs are on:
    92.256 + 3.3 + 9.6 = 105.156 W

Peak power required when the batteries are charging:

    5W + 21.6W = 26.6W

2.2.1 AC/DC Adapter

Inputs: Standard US Wall outlet at 120VAC 60Hz

Outputs: AC/DC Adapter at 26VDC ± 8V at 2.5A

Description:

This module will use a 5:1 transformer to step down the input voltage from 120VAC to 24VAC. A full wave bridge rectifier will be rectify this to 25VDC with a peak-to-peak ripple of ± 7V. This module will also implement a fuse for short circuit protection.

A line frequency, 120VAC/24VAC transformer with two output coils will be used to step down the single 120VAC wall outlet voltage down to 24VAC. Two separate output coils will be used in order to power two separate DC/DC Input-to-Battery Converter stages. In order to keep voltage ripple on the output of this stage within acceptable limits, a large amount of capacitance will be needed. In order to keep the output voltage peak to peak ripple on both outputs within 16v, the required capacitance per output is:

$$V_{ripple} = \frac{I_{Load}}{2f\ C}$$

$$C = \frac{I_{Load}}{2f\ V_{ripple}} = \frac{2.5A}{2\,(60Hz)\,(16V)} = 1.3mF$$

where I_{Load} is the load current, V_{ripple} is the ripple voltage, f is the line frequency, and C is the output capacitance. The output capacitance was chosen to be 1.5mF as the closest round number to this value.

<include schematics>

2.2.2 DC/DC Input-to-Battery Charger Converters

Inputs: AC/DC Adapter at 26VDC ± 8V at 2.5A

Outputs: 14.5V ± 1V at 4.5A

Description:

To power each DS2715 battery charger IC, a voltage supply between 4.5 and 16.5V was needed. Two buck step-down converters will be implemented, one per battery charger, that will step-down the AC/DC adapter output to a level of 14.5V ± 1V. The LTC1624 controller IC was chosen for this task. Note that this controller has a switching frequency of 200kHz.

A schematic of the converter is shown in Figure (???) below:

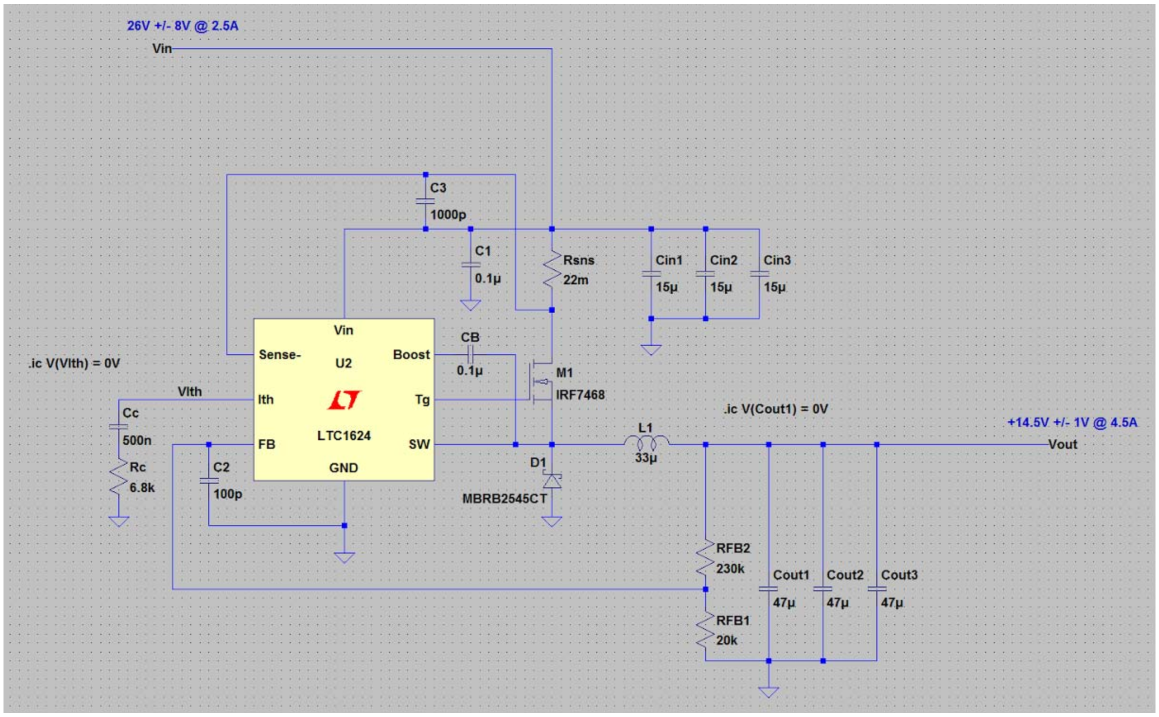


Figure (???) Input to Charger Converter Schematic

The feedback resistors RFB1 and RFB2 to the converter will set the output voltage of the converter. The output voltage is given by:

$$V_{out} = 1.19V\ (1 + \frac{R_{FB1}}{R_{FB2}})$$

where V_{out} is the output voltage, RFB1 is the lower feedback resistor, ad RFB2 is the upper feedback resistor. For an output voltage of 14.5V, R_{FB1} was chosen to be 20kΩ, resulting in a R_{FB2} value of 230kΩ.

To keep peak to peak ripple on the inductor roughly 40% of the output a minimum inductance of:

$$L_{min} = \frac{V_{out}(V_{in} - V_{out})}{\Delta i_L f_s V_{in}} = \frac{14V\ ((25{+}8)V - 14V)}{0.4\ (4.5A)\ (200kHz)\ (26{+}8)V} = 22.88\mu H$$

is required. Where L_{min} is the minimum inductance value, V_{out} is the output voltage, V_{in} is the input voltage, Δi_L is the peak-to-peak ripple current, and f_s is the switching frequency. A 33µH inductor was chosen in order to keep the inductance above the minimum value even with a ±20% tolerance.

The sense resistor to the LTC1624 is used to sense the current through the MOSFET in order to control the converter's output. According to the LTC1624 datasheet:

$$R_{SNS} = \frac{100mV}{I_{max}} = \frac{100mV}{4.5} = 22.22m\Omega$$

where R_{SNS} is the sense resistor resistance and I_{max} is the maximum output current. A 22mΩ ± 1% 1W sense resistor was chosen to set the current sense value. Total power dissipation in the resistor will be at most:

$$P_{SNS} = I_{SNS}^2 R_{SNS} = (4.5)^2\ (22m\Omega) = 0.446W$$

In order to keep the output ripple within ±1V, an output capacitance of

$$C_{min} = \frac{\Delta i_L}{8 f_s V_{in}} = \frac{0.4\ (4.5A)}{8\ (200kHz)(26{+}8)V} = 2.25\mu F$$

was required. Where V_{in} is the input voltage, Δi_L is the peak-to-peak ripple current, and f_s is the switching frequency. However, the main driver of the output capacitance choice in this design was not the steady state ripple. For a large load step, the output voltage can overshoot the set value. The absolute maximum input voltage to the battery chargers is 16.5V. An absolute maximum output voltage during an overshoot was chosen to be 16V for a load step from zero to full load in order to ensure some margin for error. The minimum capacitance required for this is:

$$C_{min,\ OS} = \frac{(\Delta i_L)^2 L}{2 V_{out} \Delta V_{pp}} = \frac{(4.5)^2 30\mu H}{2\ (14V)\ (0.5V)} = 43.39\mu F$$

Additionally, the ESR of the output capacitors must be less than $2R_{SNS}$ for stability of the control loop. In order to satisfy all three requirements and have some margin for error, two 47μF capacitors in parallel were chosen for the output. Each capacitor has a 50mΩ of ESR, for a total of 25mΩ ESR when the two capacitors are in parallel.

The diode must be able to withstand a reverse voltage of at most 34V, a peak current of 6.3A, and an average current of:

$$I_{D,\ average} = I_{out} (1 - \frac{V_{out}}{V_{in}}) = 4.5A\ (1 - 0.42) = 2.65A$$

Where I_{out} is the output current, $I_{D,\ average}$ is the average diode current, V_{out} is the output voltage, and V_{in} is the input voltage.The SR1045-TP shottkey diode was chosen for this task for it's low forward drop. Maximum current for this diode is rated at 10A.

The Infineon N-channel MOSFET part number: IRF7468TRPBF was chosen for this converter because of its low drain-to-source on resistance at 16mΩ and low reverse transfer capacitance at 38pF . This will help to minimize losses in the MOSFET. Using the formula given on the LTC1624 datasheet, losses for the MOSFET were estimated. The calculation is:

$$P_{M1} = \frac{V_{out}}{V_{in}} (I_{max})^2 R_{DS,\,On} + 2.5\,(V_{in})^{1.85} I_{max} C_{rss} f_s$$
$$= \frac{14V}{(26+8)V} (4.5A)^2 (0.016) + 2.5\ (24+8V)^{1.85}\ (4.5A)\,(38pF)\,(200kHz) = 0.232W$$

where P_{M1} is the average power consumed by the MOSFET, V_{out} is the output voltage, V_{in} is the input voltage, I_{max} is the output current, $R_{DS,\,On}$ is the MOSFET on state drain-to-source resistance, C_{rss} is the MOSFET reverse transfer capacitance, and f_s is the switching frequency.

A simulation of the output voltage and current under full load is shown in Figure (???) below:

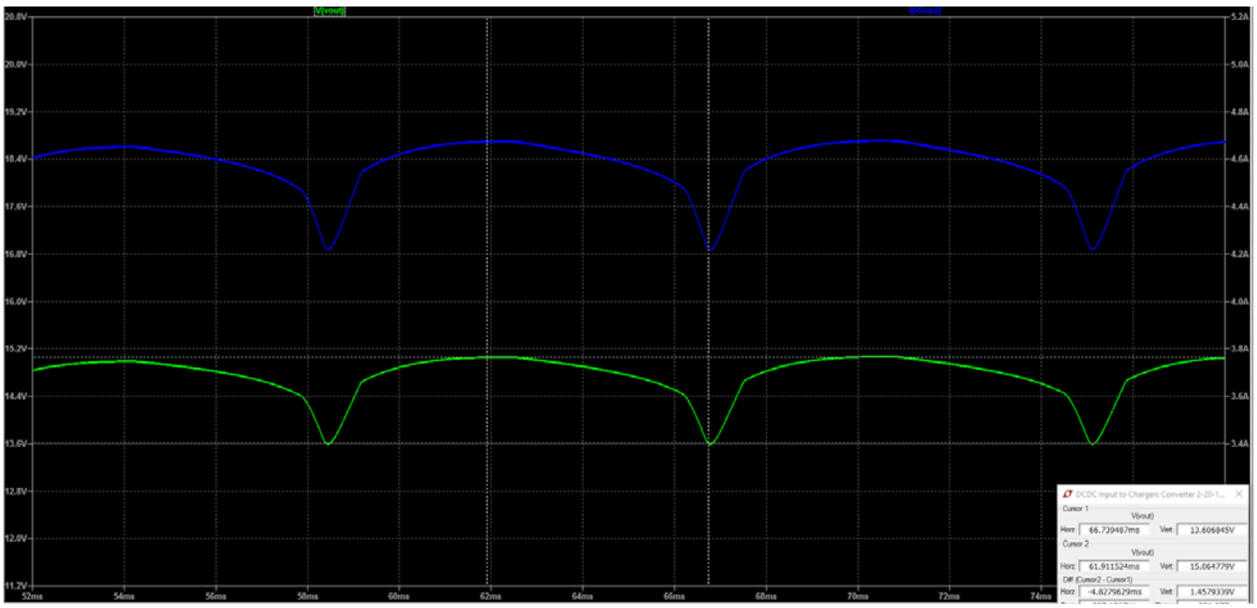


Figure (???) Voltage versus Current of Input to Charger Converter at Full Load

The peak-to-peak voltage ripple is 1.45V under full load conditions, which is within the ±2V peak-to-peak range required by this converter. This should be sufficient to meet the design requirements.

2.2.3 DC/DC Battery-to-LED Converters

Inputs: 14V ± 1V at 4.5A from the DC/DC Input to Battery converters or 9.6V ± 1.6V from a battery pack

Outputs: 7V ± 0.5V at 9A

Description:

To power the PWM circuits and logic at a stable 7V as the battery voltage varies, a converter that could step a range of 8V to 11.2V down to 7V was needed. This converter will also need to accept 14V ± 1V from the Input-to battery charger converters. To accomplish this, buck converters will be needed. The LTC1624 was chosen again for this purpose. Many of the parts used in the DC/DC Input-to-Battery Charger module were reused in the Battery-to-LED Converter in order to streamline the process of buying components.

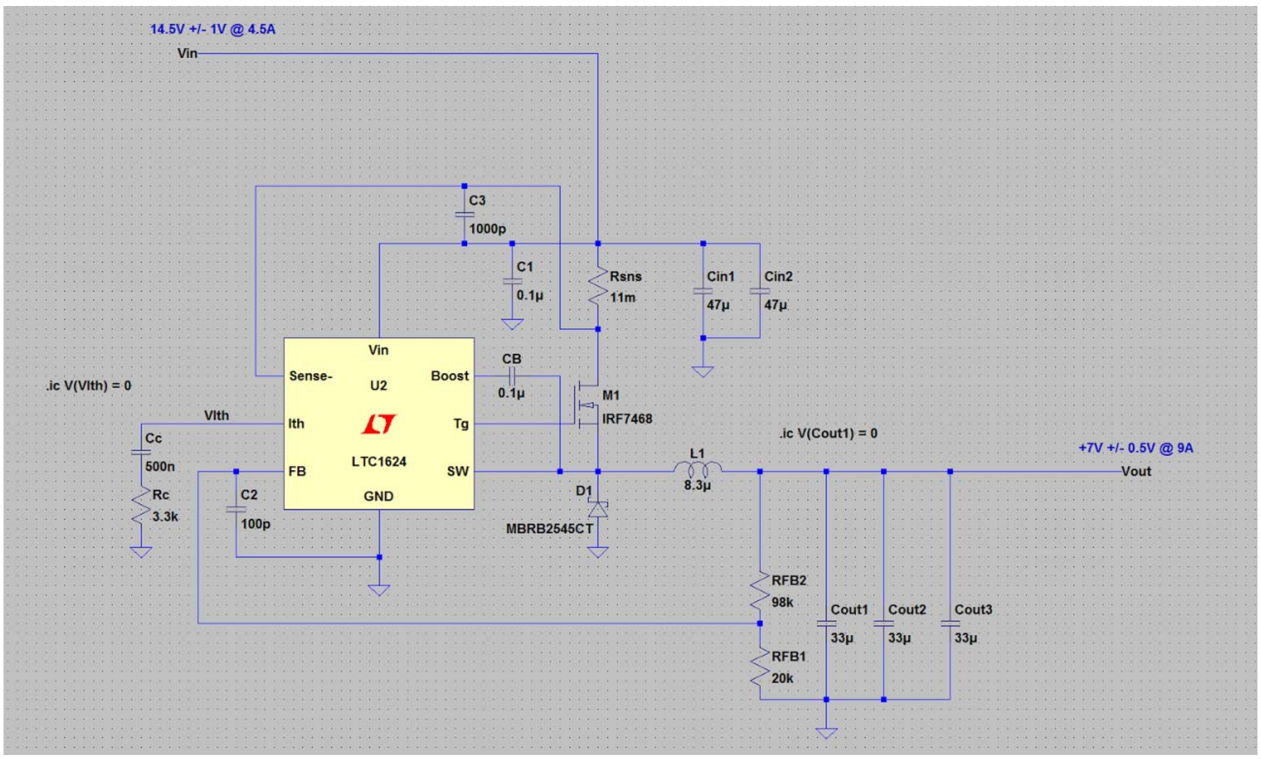


Figure (???): DC/DC Battery-to-LED Converter Schematic

The feedback resistors RFB1 and RFB2 to the converter will set the output voltage of the converter. The output voltage is given by:

$$V_{out} = 1.19V\ (1 + \frac{R_{FB1}}{R_{FB2}})$$

where V_{out} is the output voltage, RFB1 is the lower feedback resistor, ad RFB2 is the upper feedback resistor. For an output voltage of 7V, R_{FB1} was chosen to be 20kΩ, resulting in a R_{FB2} value of 98kΩ.

To keep peak to peak ripple on the inductor roughly 40% of the output a minimum inductance of:

$$L_{min} = \frac{V_{out}(V_{in} - V_{out})}{\Delta i_L f_s V_{in}} = \frac{7V\ (14V - 7V)}{0.4\ (8.0A)\ (200kHz)\ (14V)} = 5.47\mu H$$

is required. Where L_{min} is the minimum inductance value, V_{out} is the output voltage, V_{in} is the input voltage, Δi_L is the peak-to-peak ripple current, and f_s is the switching frequency. A 8.3μH inductor was chosen as a close value above 5.47μH. The maximum current rating of the inductor is 11A.

The sense resistor to the LTC1624 is used to sense the current through the MOSFET in order to control the converter's output. According to the LTC1624 datasheet:

$$R_{SNS} = \frac{100mV}{I_{max}} = \frac{100mV}{9.0A} = 11.11m\Omega$$

where R_{SNS} is the sense resistor resistance and I_{max} is the maximum output current. A 11mΩ ± 1% 2W sense resistor was chosen to set the current sense value. Total power dissipation in the resistor will be at most:

$$P_{SNS} = I^2_{SNS} R_{SNS} = (9.0)^2\ (11m\Omega) = 0.891W$$

In order to keep the output ripple within ±0.5V, an output capacitance of

$$C_{min} = \frac{\Delta i_L}{8 f_s \Delta V_{out}} = \frac{0.4\ (9.0A)}{8\ (200kHz)(0.5V)} = 4.5\mu F$$

was required. Where ΔV_{out} is the output voltage ripple, Δi_L is the peak-to-peak ripple current, and f_s is the switching frequency. However, the main driver of the output capacitance choice in this design was not the steady state ripple. For a large load step, the output voltage can overshoot the set value. A very large capacitance will be required between the converter and the PWM circuits because the PWM circuits are constantly switching. Relating maximum overshoot to the the minimum capacitance required to ensure that the overshoot is no greater than the allowed converter ripple:

$$C_{min,\,OS} = \frac{(\Delta i_L)^2 L}{2\ V_{out} \Delta V_{pp}} = \frac{(9.0A)^2 8.3\mu H}{2\ (7V)\ (0.5V)} = 96.04\mu F$$

Additionally, the ESR of the output capacitors must be less than $2R_{SNS}$ for stability of the control loop. In order to satisfy these requirements and have some margin for error, three 33μF capacitors in parallel were chosen for the output for a total capacitance of 99μF. Each capacitor has 25mΩ of ESR, for a total of 8.33mΩ ESR when the three capacitors are in parallel.

The diode must be able to withstand a reverse voltage of at most 14V, a peak current of 9A, and an average current of:

$$I_{D,\,average} = I_{out}\,(1 - \frac{V_{out}}{V_{in}}) \;=\; 9.0A\,(1 - 0.5) \;=\; 4.5A$$

Where I_{out} is the output current, $I_{D,\,average}$ is the average diode current, V_{out} is the output voltage, and V_{in} is the input voltage. The SM74611KTTR made by Texas Instruments was chosen for this task. The maximum current rating for this diode is 15A. The average forward voltage is 26mV, which will keep losses to a minimum.

As with the Input-to-Battery Converters, the Infineon N-channel MOSFET part number: IRF7468TRPBF was chosen for this converter because of its low drain-to-source on resistance at 16mΩ and low reverse transfer capacitance at 38pF . This will help to minimize losses in the MOSFET. Using the formula given on the LTC1624 datasheet, losses for the MOSFET were estimated. The calculation is:

$$P_{M1} \;=\; \frac{V_{out}}{V_{in}}\,(I_{max})^2\,R_{DS,\,On} \;+\; 2.5\,(V_{in})^{1.85}\,I_{max}\,C_{rss}\,f_s$$
$$=\; \frac{7V}{14V}\,(9.0A)^2\,(0.016) \;+\; 2.5\;(14V)^{1.85}\;(9.0A)\,(38pF)\,(200kHz) \;= 0.671W$$

where P_{M1} is the average power consumed by the MOSFET, V_{out} is the output voltage, V_{in} is the input voltage, I_{max} is the output current, $R_{DS,\,On}$ is the MOSFET on state drain-to-source resistance, C_{rss} is the MOSFET reverse transfer capacitance, and f_s is the switching frequency.

A simulation of the converter at full load is included in Figure (???) below:

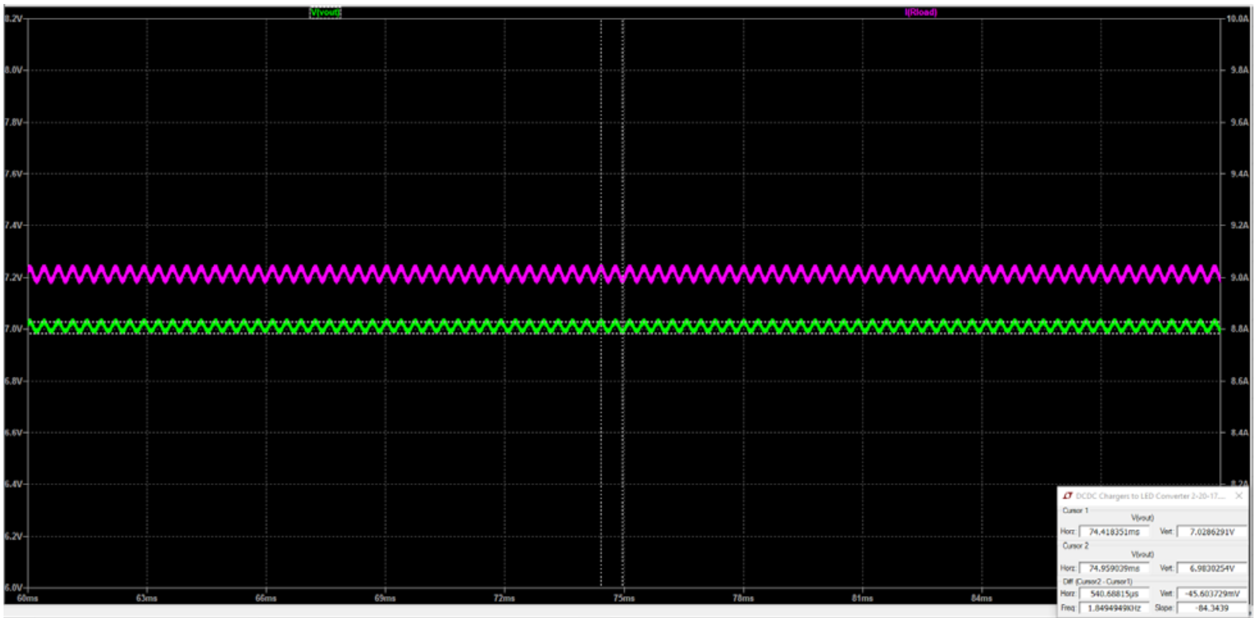


Figure (???): Charger-to-LED Converters Full Load Output Ripple

The voltage ripple in simulation at full load is 45mW peak-to-peak. This is more than sufficient for the design to function.

2.2.4 Nickel Metal Hydride Battery Chargers

Inputs: 14V ± 0.5V from the Battery-to_LED Converters

Outputs: 2.25A fast charge current to charge the batteries. Up to 7A from the batteries to the load or up to 4A from the Input-to-Battery Charger Converters to the load.

Description:

The Maxim DS2715 battery charger IC's will be standalone chargers for the two NiMH batteries. The batteries will be fast charged at 0.5C (2.25A) for no more than 200 minutes. Charging will be terminated by dT/dt using a 10k NTC thermistor mounted to the battery pack to sense temperature. After the batteries reach full charge, a maintenance charge of no more than 0.033C (148mA) will be used to offset any battery leakage.

A schematic of the charger is shown in Figure (???) below:

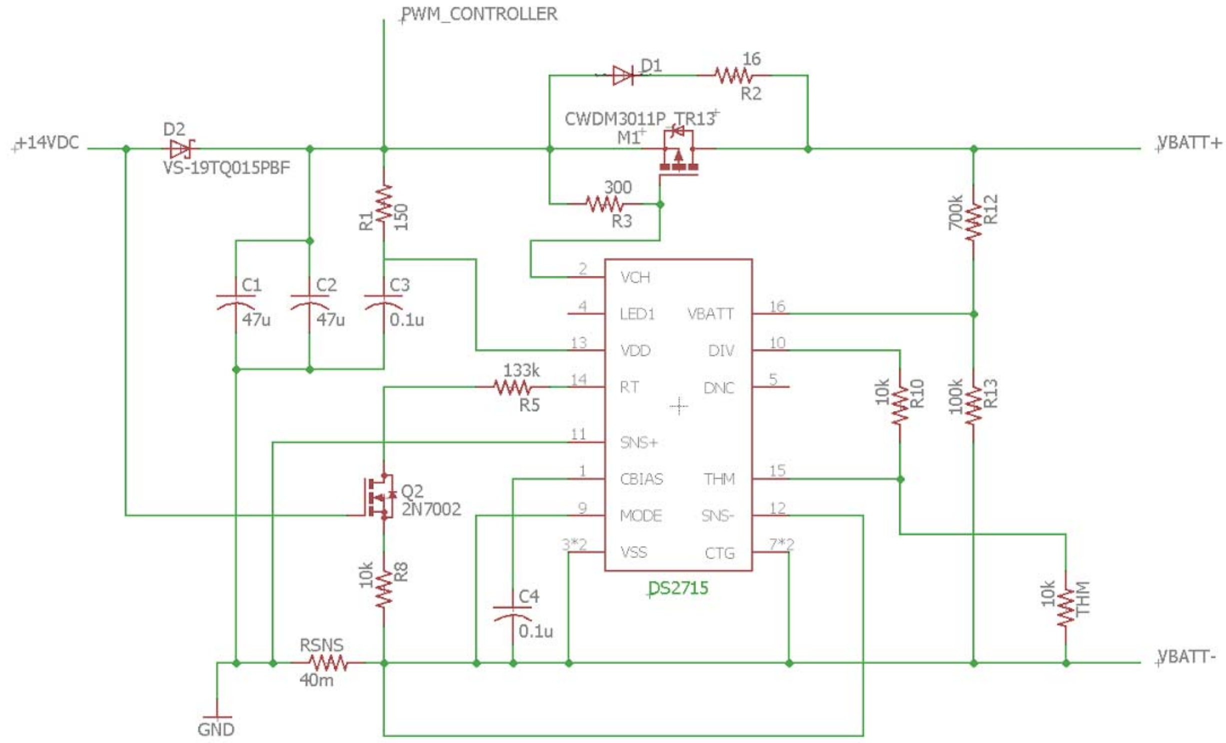
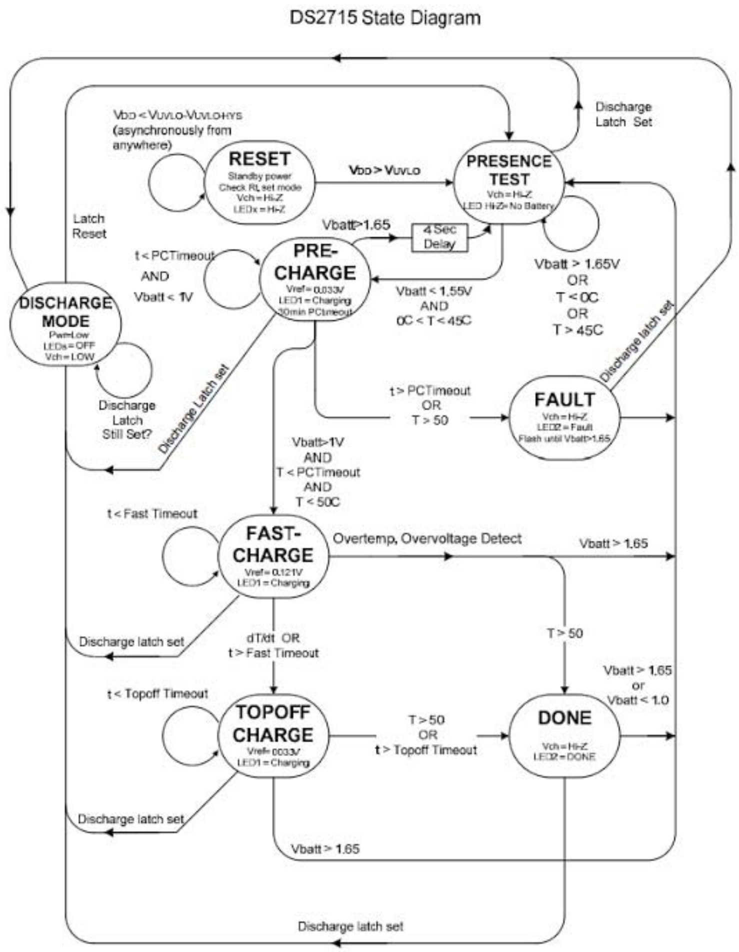


Figure (???): The NiMH Battery Charging Circuit

The DS2715 regulates the charging of up to 10 NiMH cells in series configuration. The DS2715 acts as a linear regulator, controlling current through the pass transistor M1. After the IC confirms that there is a cell present, it enters precharge mode. This mode slowly charges depleted cells at ¼ the rate of fast charge until they are above the 1.0V per cell required for safe fast charging. Once the cells have been precharged, the IC proceeds to the fast charge phase. Fast charging is terminated using the dT/dt method. When the cell pack's thermal rate of change exceeds $0.5°C$ per minute, fast charging terminates. To prevent damage to the battery caused by overcharge, fast charging also terminates if the battery pack temperature exceeds $50°C$ at any time or if the charging time exceeds the duration set using the charging timer resistor, R_5. Once the battery is deemed to be fully charged, the DS2715 enters topoff mode. A small maintenance current is used to offset the charge lost to any leakage of the battery. The DS2715 remains in this state until it detects that the battery has begun to discharge or that a fault has occurred.

A state diagram of the DS2715 charging cycle as given by the IC datasheet is shown in Figure (???) below:



Figure(???): DS2715 charge cycle

R1 and C3 form a low-pass filter with the crossover frequency set at:

$$f_c = \frac{1}{2\pi R_1 C_3} = \frac{1}{2\pi(150\Omega)(0.1\mu F)} = 10kHz$$

to filter out high frequency noise. THM1 is a 10k NTC thermistor used to sense the temperature of the battery pack. The resistors R12 and R13 are used to ensure that the cell voltage is presented to the V_{batt} pin. Because each battery pack is 8 cells;

$$R_{12} = (8-1)R_{13}$$

choosing R_{13} as 100kΩ, then R_{12} must be 700kΩ.

D2 was chosen to prevent current flowing backward into the Battery-to-LED Converters. THe diode must be able to pass at least 4.5A of current and withstand 13.2V of reverse voltage.

The Texas Instruments SM74611KTTR diode was chosen for it's small 26mV forward voltage. Total power dissipation at 4.5A will be 0.117W, which is acceptable.

The maintenance charge current into the battery is set by the resistor R_2, a current of:

$$R_2 = \frac{(V_{in} - V_{f,D1}) - (\#cells * V_{cell, full\ charge})}{I_{maint}}$$

$$R_2 = \frac{(14.5V - 0.65V) - (8 * 1.45V)}{148mA}$$

$$R_2 = 15\Omega$$

The CWDM3011P TR13 transistor was chosen as the pass element in the battery charging circuit. The CWDM3011P TR13 has an $R_{DS,On}$ of 20mΩ. The battery packs will be charged at a current of 2.25A. This corresponds to a power dissipation of 100mW, which is acceptable. The gate source voltage of the CWDM3011P TR13 is at most 3.5V. The DS2715 operates most efficiently when 10mA is sunk into the V_{CH} during charging. R_3 was chosen such that this is the case:

$$R_3 = \frac{3.5V}{10mA} = 350\Omega$$

The DS2715 measures the charging current through the battery back using a sense resistor in series with the battery pack. The sense resistor was determined by:

$$R_{SNS} = \frac{V_{FC}}{I_{FC}} = \frac{121mV}{2.25mA} = 53m\Omega$$

Where R_{SNS} is the value of the sense resistor, V_{FC} is the regulation target voltage set by the DS2715 IC, and I_{FC} is the desired charging current. Power lost in in the resistor at full current will be 268mW.

The resistor R_T sets the fast charge timeout period. According to the HHR-450AB21L2X4 datasheet, the batteries should be fully charged within at most 200 minutes of charging. The formula for R_T is:

$$R_5(0.0015) = t_{max}$$

$$R_5(0.0015) = 200$$

$$R_5 = 133k\Omega$$

where R_T is the timing resistor value and t_{max} is the maximum allowed charging time in minutes.

2.2.5 Nickel Metal Hydride Batteries

Inputs: 2.25A charging from the battery charger

Outputs: 9.6V ± 1.6V depending on the level of charge at up to 8.5A to the PWM controller

Description:

In order to function throughout the entirety of a photoshoot, the batteries must be able to sustain the lightbar for at least 30 minutes. If the batteries are depleted before this time, they run the risk of dying out during a photoshoot.

By far, the components that draw the most power are the LEDs, which can draw up to 1A per string when the lightbar is fully illuminated. In order to fully illuminate the lightbar while still keeping the weight taken up by the batteries manageable and to avoid the safety concerns associated with lithium ion batteries, two nickel metal hydride battery packs were chosen to power the lightbar. The Panasonic HHR-450AB21L2X4 nickel metal hydride battery pack operates at 9.6V nominal with a capacity of 4.5mAh for a total of:

$$9.6V * 4.5Ah = 43.2Wh$$

of stored energy per pack. Each pack is made up of 8 1.2V nominal cells. Two of them will be able to supply the lightbar for the required 30 minutes at full intensity for:

$$\frac{2*43.2Wh}{100W} * \frac{60\ minutes}{1h} = 51.84\ minutes$$

As stated in section 2.2.3, the batteries will be charged using fast-charging at 0.5C terminated using the dT/dt method or until 200 minutes have elapsed. This will be followed by a much smaller trickle charge to offset energy lost to battery leakage. See section 2.2.3 for more information on battery charging.

Each battery pack weighs 449g, for a total of:

$$2 * 0.499kg * 2.2\ lb/kg = 2.2lbs$$

Each pack is 72.8mm x 18.2mm x 134.0mm (Length x Width x Height)

2.2.6 Nickel Metal Hydride Battery Protection

Inputs: 9.6V ± 1.6V from the batteries or 14V ± 0.5V from the DC/DC Input-to-Battery Converters

Outputs: No less than 8.0V at no more than 4.5A to the Battery-to-LED Converters

Description:

In order to protect the batteries from undercharge or overcurrent, the LTC-4356 surge stopper will be used to provide undervoltage lockout at 8.0V and overcurrent protection at 9.5A. Below 8.0V, continued discharge of the batteries could damage the cells. At more than 9.6A, the logic and LED circuits could be damaged.

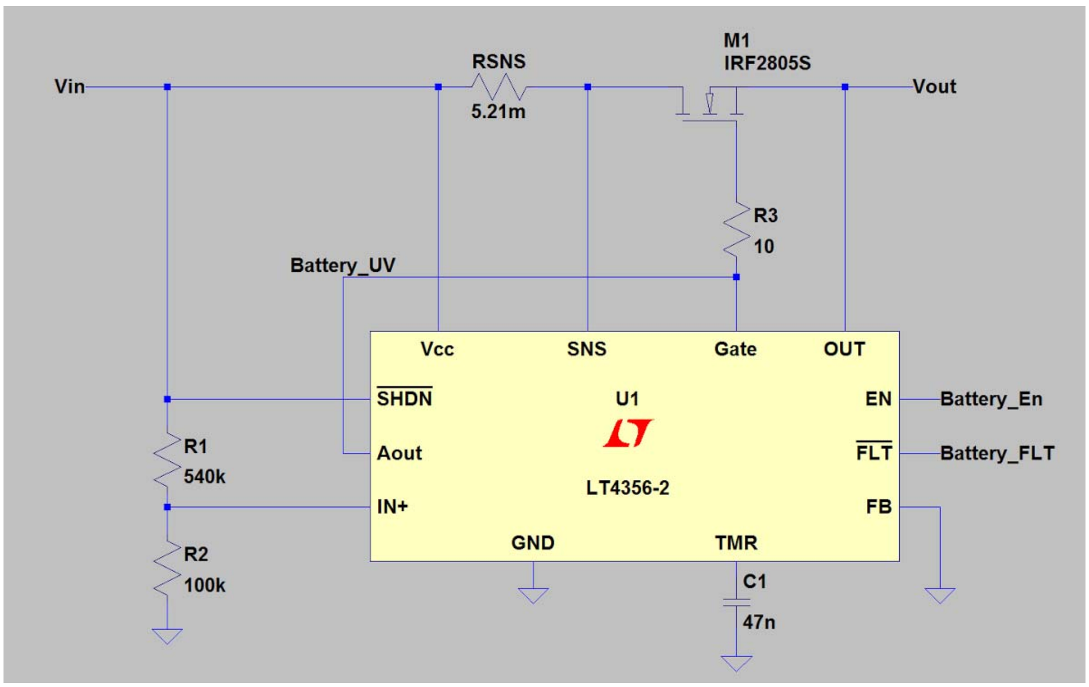


Figure (???) Battery UVLO and OC Protection Schematic

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

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

for the lower limit of 8.0V required by the battery packs, R2 was chosen to be 100kΩ and R1 was chosen to be 540kΩ. For any voltage on the V_{CC} 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 the R_{SNS} sense resistor. 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. Every 42.5ms, the timer capacitor C1 Is set such that the surge stopper will retry turning on the MOSFET.

$$I_{limit} = \frac{50mV}{R_{SNS}}$$

R_{SNS} was chosen to be 11mΩ in order to limit current to 4.5A. The $R_{DS,On}$ of the MOSFET M1 is 4.7mΩ. At maximum load, this corresponds to a power dissipation of:

$$P_{M1} = I^2 R_{DS,On} = (4.5A)^2 (4.7 * 10^{-3} \Omega) \; = \; 0.095W$$

which is well below the maximum power rating of the MOSFET. At maximum load, the maximum sense resistor dissipation is:

$$P_{Rsns} = I^2 R_{SNS} = (4.5A)^2 (11 * 10^{-3} \Omega) \; = \; 0.223W$$

so a ½ watt resistor will be chosen to ensure that the sense resistor does not exceed its dissipation limit.

A simulation of a short circuit on Vout is included in Figure (???) below:

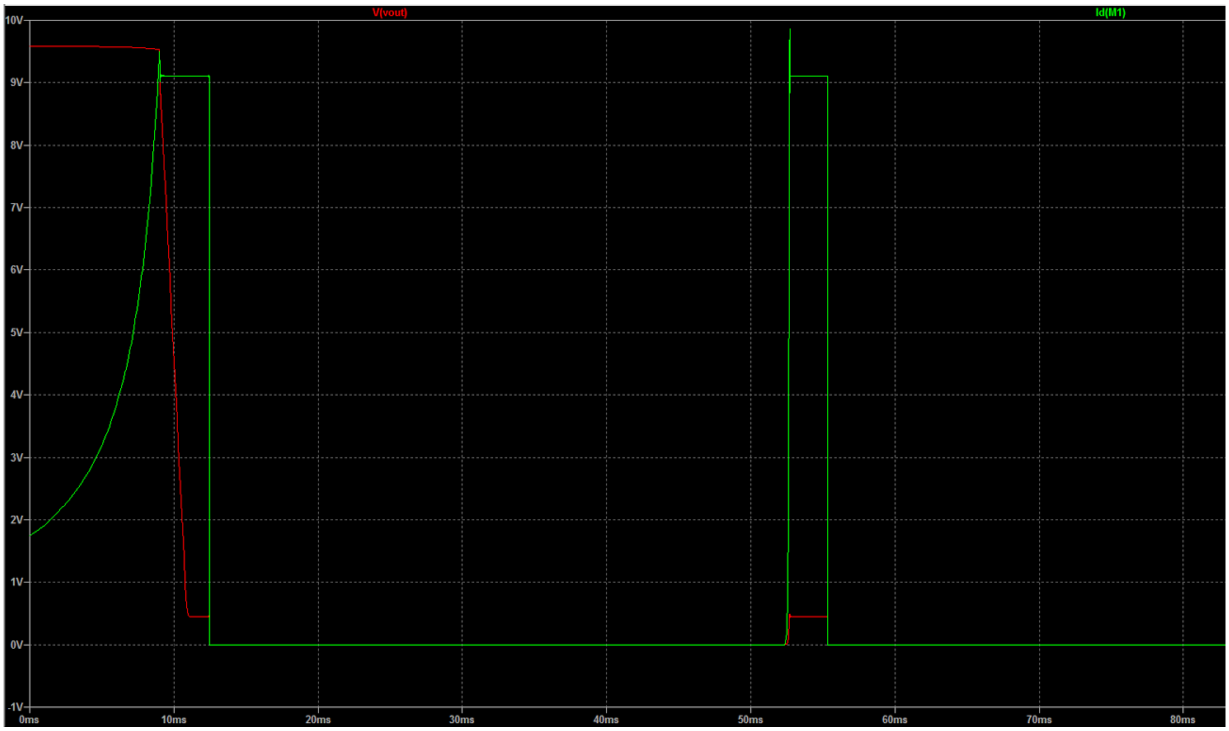
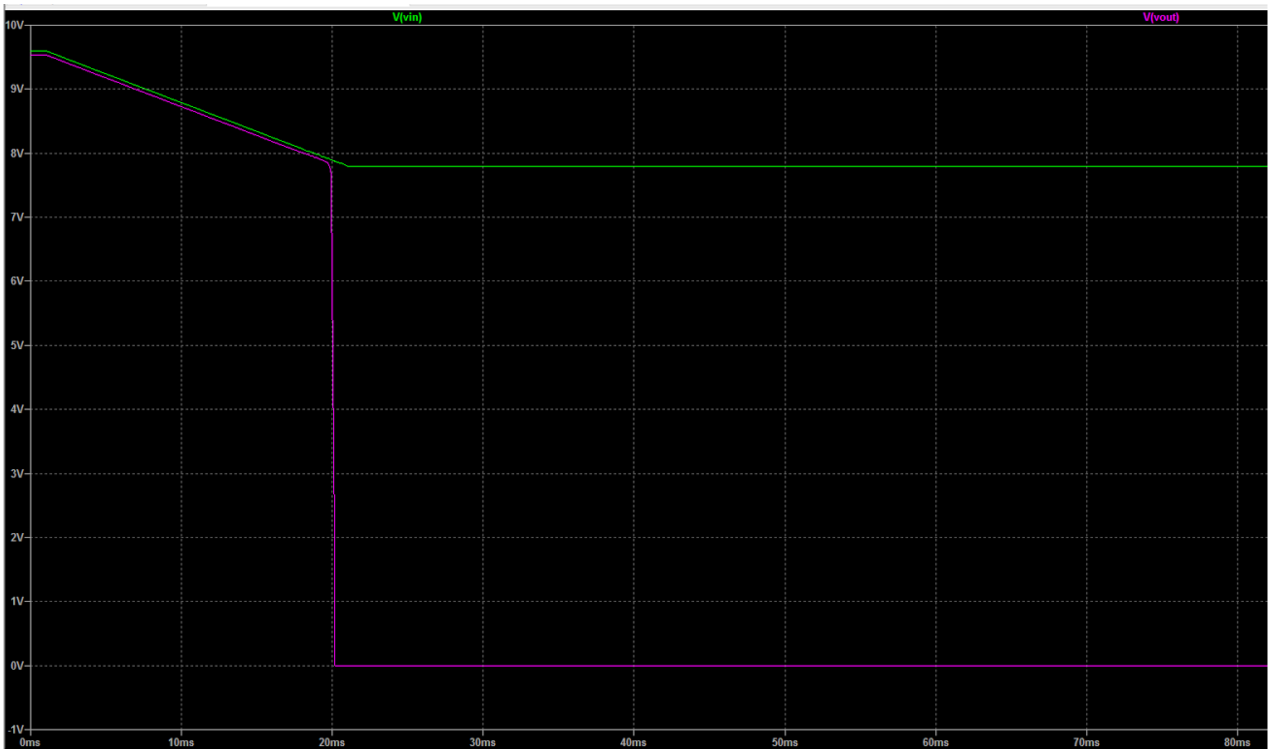


Figure (???) Surge Stopper Short Circuit Current Test

The surge stopper was started with a slowly increasing load current. As Figure (???) shows, the current is stopped after it reaches 4.5A and the output voltage drops quickly. The surge stopper then retries turning on the pass transistor again 42.5ms later, detect that the short is still present, and shuts off the MOSFET again.

A simulation of a voltage below 8.0V on Vin is included in Figure (???) below:



As shown in the figure, when V_{in} drops below 8.0V, the pass transistor is turned off and the output voltage drops to 0V. Given this data, the battery protection should operate as intended.

2.2.7 Logic-Level Linear Regulator

Inputs: 7.0V ± 0.5V from the Battery-to-LED Converter at 1.5A

Outputs: 0.5A at 3.3V to supply the Digital Logic

Description:

Some form of conversion will be necessary to create the 5V needed by the digital logic. In order to accomplish this, a linear regulator was chosen. Because the logic consumes relatively little power, this was considered acceptable.

The LT1085 was chosen as a reliable low dropout fixed regulator for this purpose. A schematic is shown in Figure (???) below:

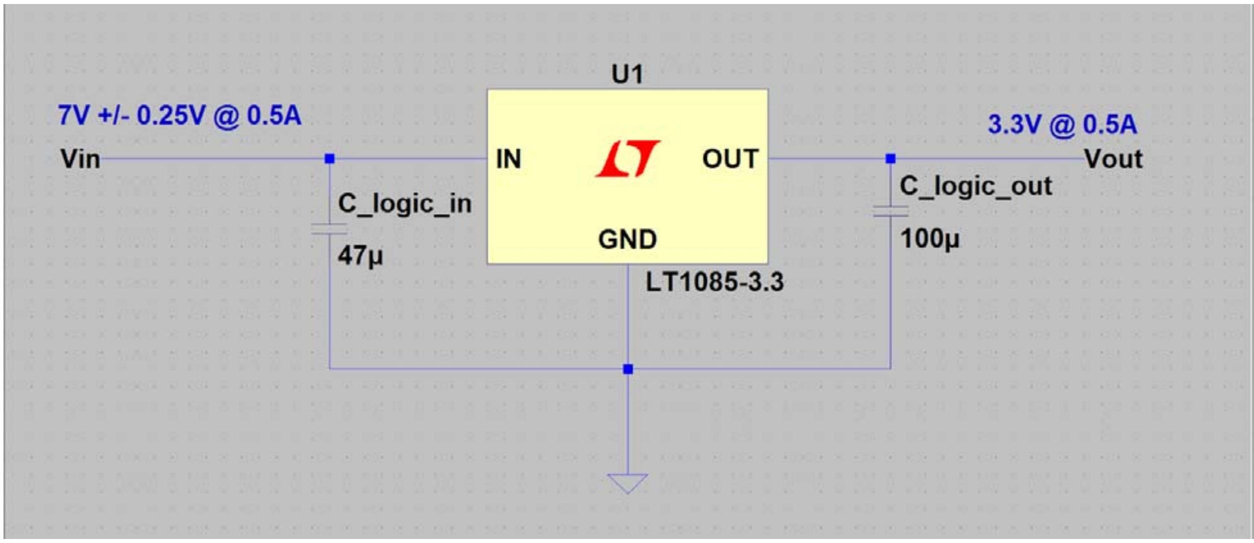


Figure (???) Logic-Level Linear Regulator Schematic

The worst-case dissipation of the regulator will be:

$$P_{Loss} = (V_{Out} - V_{in})(I_{Out,max}) = (7V - 3.3V)(0.5A) = 1.85W$$

which will cause a temperature rise of:

$$T_J = P(\theta_{JA}) + T_A = 1.85W * 30°C/W + 40°C = 95.5°C$$

The absolute maximum junction temperature rating for this component is 125 $°C$, so this is acceptable.

2.3 LED Array

The LED Array will consist of 32 LEDs in 16 strings of 2. Each LED string of 2 will be controlled externally by the LED string controller and will have 16 different brightness levels which help dictate the gradient level. The strings of 2 are to manage the cost and ease of soldering as individual LEDs are too small to comfortably solder and star arrays larger than 2 will have too much of a voltage drop that can be supplied by our battery.

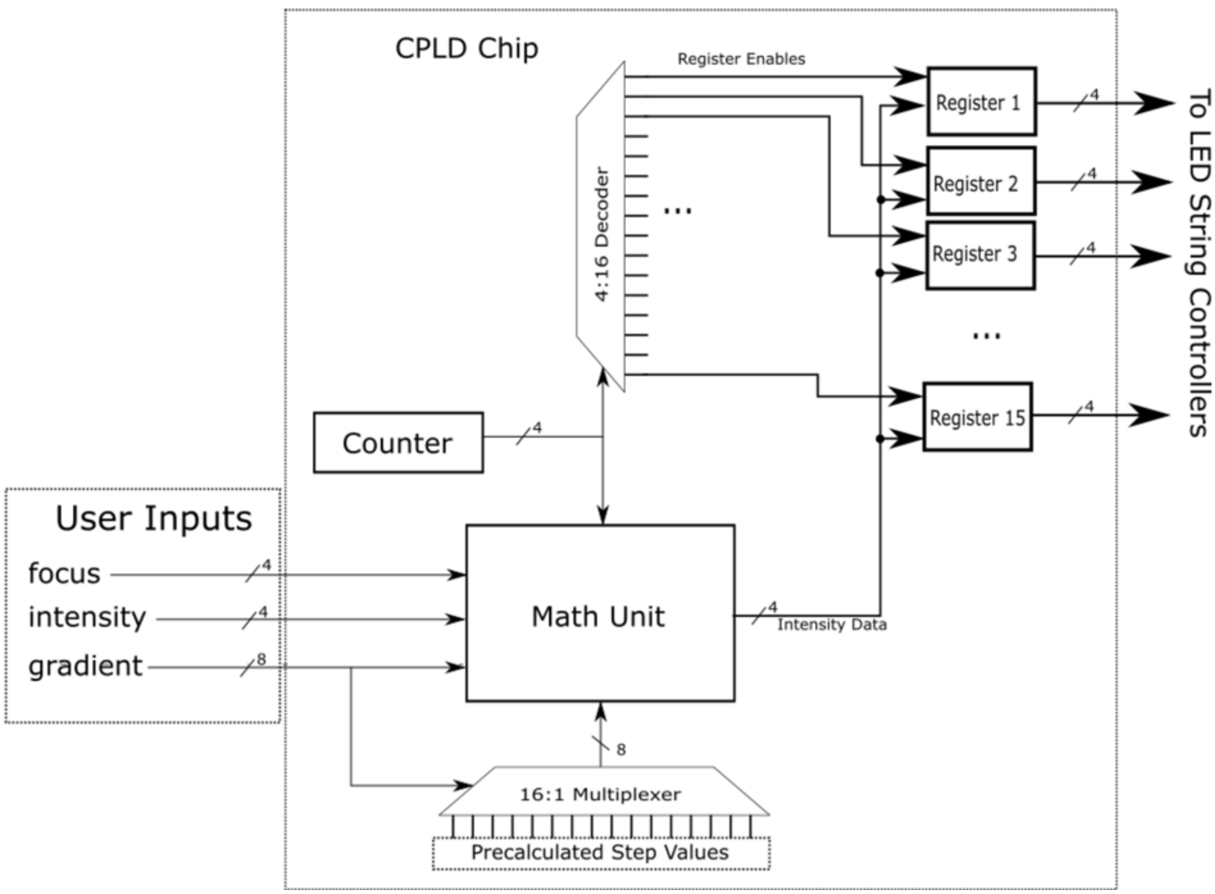
Requirement 1: Each LED must at maximum be outputting 110 Lumens for a total of 3500 Lumens across the entire bar

Requirement 2: The entire LED array (32 LEDs) cannot consume more than 100 watts at max power

2.4 Control Circuitry

The control circuitry will dictate the brightness level of each individual LED which overall will form the gradient, focus, and intensity of the light bar. This will control the brightness of the LEDs to 16 different levels which will produce a nice gradient from 0% to 94% across the bar.

2.4.1 Digital Controller



The Digital Controller will take the previously discussed 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’b0000) to 93.75% (4’b1111). The controller will be made entirely from digital logic rather than an MCU to create a simple, low power design. The most efficient way to create the digital logic is to use a CPLD which allows all of the circuitry to be on one chip rather than the 60 chips we would need to implement it with other integrated circuits.

On the CPLD, 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.

Requirement 1: Operate at 3.3V and consume less than 10% of the LED Circuitry

Requirement 2: Create a gradient ranging from zero, where one LED string is on and the next is off, to 15 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.

Requirement 3: Any of the 15 LED strings will be able to be the center of the gradient

Requirement 4: The light will be able to output warm, neutral, or cool light as dictated by the user input.

2.4.2 LED String Controller

The LED String Controller will have a PWM(Pulse-Width-Modulation) control circuit that will take the 4-Bit control signal from the master digital controller and alter the duty cycle of the internal clock generated circuit based on this 4-bit control signal.

Requirement 1: Must control the LED Intensity to 16 levels. Each Intensity setting must be distinguishable from each other (±6.25% Intensity or less).

Requirement 2: Must at most output 110 lumens with control input 4'b1111.

Requirement 3: Must consume less than 10% power of the LED strip.

Requirement 4: Must not flicker to the human eye or camera, so must have a pulse frequency of above 1 kHz.

2.5 Housing

The housing block will consist of a black external casing with a detachable battery slot. In addition to smooth the LED output, diffusion glass will be installed.

2.6 Risk Analysis

The largest risk to the completion of our project is in the LED string controllers. In order for our product to be functional, our light must put out a smooth, constant gradient. This means that lighting within a strip needs to be relatively consistent and intensity control across the gradient must be precise. Controlling brightness precisely entails controlling the current through each branch precisely.

If we don't have enough precision we will end up with a choppy unappealing gradient or a light with brightness hotspots. The biggest challenge to making a tightly controlled current is doing so without excessive power consumption or cost. With an unlimited budget and power supply we could easily create a controller that delivers multiple precise brightness levels. Our challenge is designing a low power, low cost circuit that can still deliver the necessary precision.

The string controller must be able to output 16 different levels of current so that the brightness of the LED strip cannot overlap with an adjacent LED strip. This implies that the precision of the controller must be at least 6.25% accurate otherwise the LED brightness levels will be indistinguishable from one another.

3. Requirements and Verifications

Block	**Requirement**	**Verification**
Digital Controller	Digital Controller operates at 3.3V	Test CPLD and supplementary chips on a power supply set to 3.3V to ensure proper operation. Additionally test circuitry at ∓10% to account for supply fluctuations.
	Create a gradient ranging from zero, where one LED string is on and the next is off, to 15 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.	Use multimeter to read outputs of digital controller when the gradient input is set to zero and intensity is 15. Ensure intensity at focus is 15 and intensity at the neighboring strings is 0. Repeat for Gradient equals 31, focus equals 0, and intensity equals 15. Ensure the intensity goes down one step per string.
	Any of the 15 LED strings will be able to be the center of the gradient	Set input intensity to be 15 and sweep focus from 0 to 15 at each step using a multimeter to measure the corresponding output to ensure it is at level 15.

	The light will be able to output warm, neutral, or cool light as dictated by the user input.	Run an LED string controller at full intensity without the led attached. Check the decoder outputs to ensure that the correct string is receiving all current while the other two are receiving none. Check for all possible switch positions.
LED String Controller	1. Must be able to PWM from 0 to 93.75% duty cycle 2. Must output 110 lumens at 93.75% duty cycle 3. Must consume less than 10% of the power of LED strip 4. Must be above 1kHz to avoid camera flicker	1. Verification for requirement 1: 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 3.3V d. Ensure that the duty cycle falls within 6.25% of expected cycle 2. Verification for requirement 2: a. Attach LEDs to transistor source b. Attach 2Ω resistor to transistor drain c. Supply LEDs with 7.0V source d. Observe brightness with light-meter 3. Verification for requirement 3: a. Attach 3.3V 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 4. Verification for requirement 4: a. Attach 3.3V source for worst case scenario on R-2R ladder(4'b0001) b. Attach 2Ω resistor to transistor drain c. Probe with oscilloscope the control transistor

		d. Ensure frequency is above 1khz
LED Array	1. Each LED circuit must output 220 lumens for total of 3500 lumens across bar 2. Power consumption of LEDs must not be greater than 100W	1. Verification for Requirement 1: a. Attach PWM side of LED-PWM subcircuit to control signal of 3.3V with input 4’b1111. b. Attach LED side of LED-PWM subcircuit to 7.0V source c. Examine with light meter the overall brightness of one LED circuit d. Makes sure each LED circuit outputs 220 lumens e. Repeat for all 16 circuits 2. Verification for Requirement 2: a. Attach PWM side of LED-PWM subcircuit to control signal of 3.3V with input 4’b1111. b. Attach LED side of subcircuit to 7.0V source to 7.0V source c. Probe with Multimeter the voltage across resistor d. Probe with Multimeter the voltage across LEDs e. Extrapolate current across resistor and ergo the LEDs f. Calculate total power per LED-PWM subcircuit
AC/DC Adapter	1. The AC/DC Adapter must provide a voltage of 26V ± 8V over the expected range of operation	
DC/DC Input-to-Charger	1. The converter output remains within 14.5V ±	1. Verification for requirement 1: a. Attach a 3.22Ω resistor

Converters	1.0V at maximum output current.	to the output of the converter. b. Attach oscilloscope probes to the output of the converter. c. Supply the converter with 26V. d. Ensure that the output voltage stays within 14.5V ± 1.0V
Battery Chargers	1. Within 4 hours, the charger must fully recharge the batteries from a completely discharged state to a capacity necessary for 30 minutes of lightbar operation.	2. Verification for requirement 1: a. Take a fully discharged battery pack (as indicated by the battery voltage) and attach it to the charging circuit. b. Monitor the battery temperature in 15 minute intervals using a handheld IR sensor to ensure that it stay below 50°C c. Terminate the charging process after 4 hours. d. Using a DMM, measure the battery voltage. From this voltage and the battery charge curve, determine the capacity of the battery.
Batteries	1. Sustains operation of the LEDs for at least 30 minutes.	1. Verification for requirement 1 a. Charge the batteries up to full charge using the battery charger circuits. b. Connect each battery (including protection circuitry) to a string of 8 LEDs all set to PWM at 93%. Time the the battery discharge with a stopwatch. Stop when the undervoltage lockout engages.

Battery OC and UVLO Protection	1. Undervoltage lockout engages for an input of lower than 8.0V. The lockout condition remains until the shutdown pin on the LTC4356 is pulled low briefly. 2. Overcurrent protection engages for any current more than 9.6A. The protect condition remains until the shutdown pin on the LTC4356 is pulled low briefly.	1. Verification for requirement 1 a. Attach a 10kΩ resistor to the output of the LTC4356. b. Attach an oscilloscope probe to the LTC4356 output and input. c. Attach a SPST switch to the shutdown pin of the LTC4356. d. Supply the LTC4356 with 14V e. Slowly decrease the input voltage to a level below 8.0V. Check that the output voltage falls to zero. f. Increase the supply voltage back to 14V. g. Pull the shutdown pin low briefly, then high again. h. Verify that the output is 14V 2. Verification for requirement 1 a. Attach a 10kΩ potentiometer 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. Attach a SPST switch to the shutdown pin of the LTC4356. d. Supply the LTC4356 with 14V e. Slowly decrease the resistance of the potentiometer until the output current rises above 9.6A. Check that the output voltage falls to zero. f. Decrease the output current to 4.5A

		g. Pull the shutdown pin low briefly, then high again. h. Verify that the output is 14V
DC/DC Battery-to-LED Converters	1. The converter output remains within 7V ± 0.5V across the expected range of operation	3. Verification for requirement 1: a. Attach a 0.78Ω resistor to the output of the converter. b. Attach oscilloscope probes to the output of the converter. c. Supply the converter with 14.5V. d. Ensure that the output voltage stays within 7V ± 0.5V
Logic Linear Regulator	1. Regulator output remains within 3.3V ± 0.66V across the range of output currents 0.0A to 0.5A	

4. Tolerance Analysis

5. Cost Analysis

6. Schedule

7. Safety and Ethics

There are several safety concerns with regards to a portable lighting fixture. nickel-cadmium batteries can fail catastrophically in three ways, either temperature failure, undercharge failure, or overcharge failure[1]. To compensate for temperature failure, the battery will have a thermistor which will monitor the temperature of the batteries. The DS2715 will monitor the battery temperature using the thermistor and disconnect the battery from the circuit if the battery temperature is above 50°C. Furthermore, a voltage and current regulating circuit will control the charging output to prevent overcharge which can lead to a thermal reaction. An undercharge protection circuit will also be implemented to prevent undercharge and the destruction of the battery beyond 1.0V per cell. Additionally, a the following safety plan will be followed at all times while working with batteries in the lab:

- To prevent runaway current, batteries will be stored in a secure location with the terminals covered by insulating material to ensure that no short circuit can occur.
- If the battery swells, bulges outward, becomes noticeably hot, or makes a noise of any kind, the battery will be disconnected immediately and placed in a battery bag as far away from anything potentially flammable as possible. A TA will then be notified to dispose of the battery as soon as possible.
- A MSDS for the battery will be in the lab at all times when the battery is connected to an electrical circuit.
- Batteries connected to any electrical circuit will not be left unattended for any amount of time.
- Measure temperature using an IR sensor. Do not touch the batteries if they are above 30°C

In addition, as an electronic device that could operating in limited outside conditions, the outside casing must be built to IP 53 specifications to prevent accidental shorting of the internal circuit. Additionally, while LED lights do not produce a significant amount of heat, the fixture must be kept at under 40°C.

In terms of ethics considerations, we must follow the IEEE code of ethics specifically codes 1 and 5. Code 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. In addition, we must consider issues that relate to potential electrocution with high power electronics, and possible rupture and destruction of the battery.

Code 5 states that we must improve the understanding of technology, appropriate application, and potential consequences[4]. So we must work with Rick Kessinger Studios to make sure our technology development applied in such a manner that would be beneficial for photographers. In addition, we must educate 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.

Citations and References

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