Current-Controlled LED Driver with Adjustable Brightness and Safety Cutoff

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***Abstract*—This paper explores the design and implementation of a current-controlled light-emitting diode (LED) driver with adjustable brightness and safety cutoff using analog electronics. Since LEDs are current-controlled devices, this LED driver maintains a set current through the LED by raising or lowering an input DC voltage using a buck-boost converter. Brightness can be set automatically from an external control voltage, or manually using a potentiometer. A safety thermistor on the LED shuts off the output should the LED overheat. This switching topology is widely used in high-power LED lighting solutions for high energy efficiency and longevity, and is implemented in the circuit described in this paper.**

***Keywords* — LED, current supply, feedback control, switching mode power supply, buck-boost, energy efficiency, illumination**

I. Introduction

Lighting for rooms and buildings accounts for a significant portion of energy use – the US Energy Information Administration estimates that 216 billion kilowatt-hours (kWh) of energy, or 5% of total US energy usage, was used for residential and commercial lighting in 2019 [1]. LED lighting is gaining widespread adoption as a more efficient, longer-lasting alternative to traditional incandescent and fluorescent bulbs – for the same light output, commercially available LED bulbs only consume 8 watts of electricity, while incandescent bulbs consume 60 watts [2] and fluorescent bulbs consume 13 watts [3].

LEDs are more energy efficient than incandescent bulbs, but they require a more complex driver that outputs a constant current across the LED, with brightness proportional to current. This current limiting LED driver can be as simple as a current-limiting resistor in series with the LED, although significant power is dissipated by the resistor itself instead of the load. More commonly, a switching DC-DC power supply with feedback control over the current is used, providing higher efficiency but requiring more design considerations. This switching topology is used in most LED lighting solutions.

This LED driver will implement the switching controller and a temperature cutoff to safely drive LEDs from a DC input, using discrete components. It can drive LEDs up to 5 Amps, with higher or lower forward voltages than the input voltage.

This paper discusses the design and implementation of this LED driver. First, an overall system block diagram is presented, then each block's design will be explained. In the end, the simulation process and design of a printed circuit board (PCB) will be discussed. This circuit should be capable of safely driving high-power LEDs.

II. Design Overview

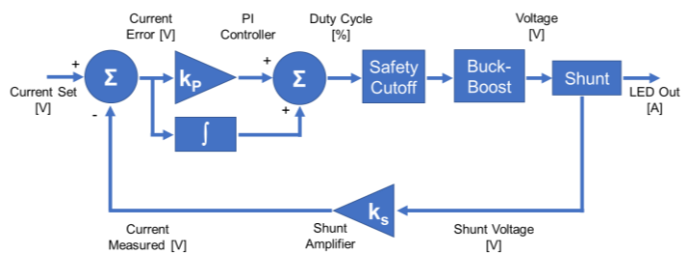

Fig. 1. Overall block diagram of the LED driver

Figure 1 shows the system block diagram.

Central to this driver is a buck-boost converter, a DC-DC switching converter that raises or lowers the output voltage from the input voltage. The buck-boost converter output connects to the LED through a shunt resistor, a small-valued resistor used for measuring LED current. The measured LED current is subtracted from the setpoint current, and the resulting current error is then fed into a PI feedback controller that sets the buck-boost output voltage accordingly. For safety, a temperature cutoff uses an LED-mounted thermistor to disable the buck-boost should the LED overheat.

The power supply for the circuit is a regulated +/- 15 V.

A. Buck-Boost Controller

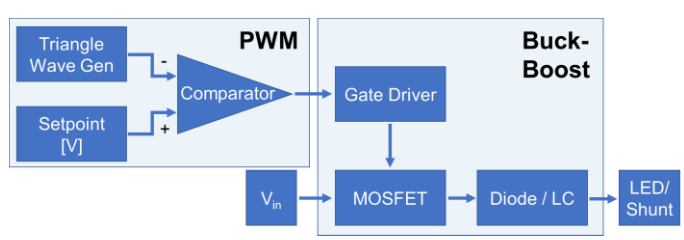

Fig. 2. Buck-boost circuit block diagram

The buck-boost controller raises/lowers a DC input voltage at the output by oscillating power between an inductor and capacitor using a rapidly switching MOSFET. The MOSFET switches at a fixed frequency, but its duty cycle is varied to change the output voltage with the below equation, where D is duty cycle between 0 and 1.

$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D} \tag{1}$$

The buck-boost transfer function is nonlinear, especially approaching the 0% and 100% duty cycle extremes. If driven near the upper extreme, the output voltage could grow exponentially, a non-desirable situation. Duty cycle has been capped between 20-80% to ensure relatively linear operation.

Since this is an inverting topology, the LED cathode (-) will connect to the output, with the anode (+) connected through a current-sensing shunt resistor to ground.

The converter consists of a PWM generator that controls the buck-boost power electronics, shown in Figure 2.

1) *PWM Generator*

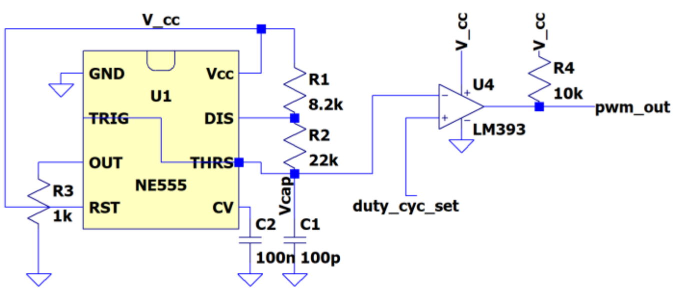

Fig. 3. PWM generator schematic diagram

This block generates a PWM signal first using a 555 triangle wave generator, outputting at a fixed 100 kHz between 5-10 V when V_{CC} = 15 V. The triangle wave's voltage is compared against a setpoint voltage, also between 5-10 V, and the resulting waveform is an adjustable PWM waveform, with higher setpoint voltages leading to higher PWM duty cycles.

The switching frequency, 100 kHz, was chosen to minimize the size of the buck-boost inductor and capacitor, where larger component values are required at lower frequencies, while being implementable on through-hole PCBs. The LM393 comparator was used for its high slew rate.

Alternatively, a sawtooth wave generator could be used instead of this triangle wave generator, producing the same effect. The circuit would involve a JFET current source that charges a capacitor, which then discharges once a threshold voltage is reached. The triangle wave generator was chosen as it has been implemented in previous switching converters before.

2) *Power Electronics*

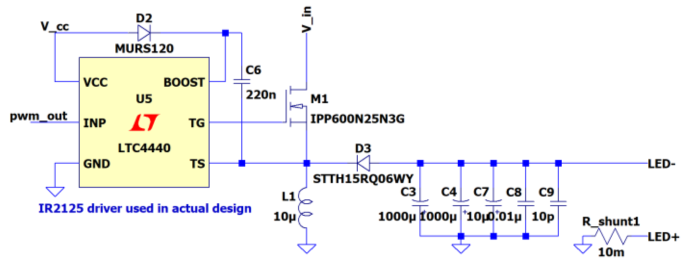

Fig. 4. PWM generator schematic diagram

A buck-boost converter works by rapidly transferring energy between an inductor's current and a capacitor's voltage. This process is driven by a diode and PWM-driven NMOS switch.

The high-side NMOS switch is driven by the IR2125 gate driver IC, since the NMOS source floats above ground. The IPP600N25N30G NMOS and STTH15RQ06WY diode were chosen for their sufficiently high current and voltage ratings.

Generally, higher switching frequencies allow the use of smaller-valued inductors. The time duration that the inductor conducts current in each cycle is shorter at higher frequencies. Also, the inductor should be sized appropriately so it is always conducting current in operation, whether from V_{in} or to the load, also known as continuous conduction mode (CCM) [4]. Smaller values are also physically smaller, using less PCB area. The inductor in this design is 10 µH, chosen to operate in CCM.

Large capacitors help minimize output current ripple, caused by oscillations in the output voltage at steady state. Each switching cycle of the NMOS causes output voltage to increase and decrease, translating to current ripple across the load. However, large capacitors also slow the response of the circuit to changes in setpoint, take up more PCB area, and cost more. This design uses 2000 µF of capacitors, with a range of smaller capacitors placed in parallel to absorb high-speed transient events.

B. *LED Load*

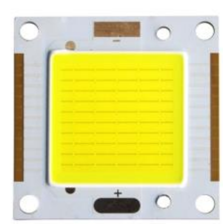

Fig. 5. Sample chip-on-board power LED, 50 watt, 40mm x 40mm [5]

Power LEDs are often chip-on-board (CoB) modules, which contain multiple LEDs connected in series, immersed in phosphor on a PCB. CoB modules come in a range of wattages and size, and must be properly cooled with a heatsink or liquid cooling solution to avoid overheating.

The LEDs used for testing are a 36 V, 30 W CoB module and a 12 V, ~75 W LED strip used for interior lighting.

C. Current-Sense Shunt Resistor

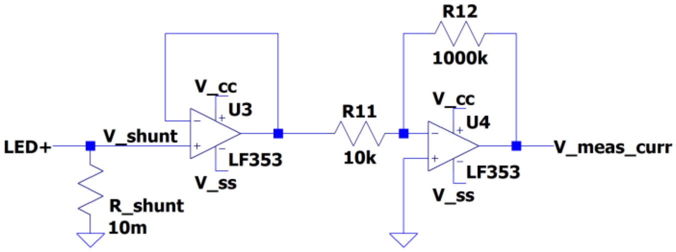

Fig. 6. Current-sense shunt resistor and amplifier, schematic diagram

Current is measured using a shunt resistor, a small-valued (10 mΩ) resistor placed in series between the LED cathode and ground. The same LED current also flows through the resistor, and Ohm's Law dictates that voltage across a resistor V_R is proportional to the current flow.

$$V_R = I \cdot R \tag{2}$$

The current-sensing circuit amplifies V_R such that 1 V at the output corresponds to 1 Amp through the LED. First, an op-amp buffer samples V_R due to its high input impedance, with 1 Amp current corresponding to -10 mV V_R. Next, an inverting op-amp amplifies the signal 100x, producing the desired output.

Alternatively, current measurement can be done noninvasively using a Hall effect current sensor, which senses magnetic fields from current through a concentric wire. This can further increase efficiency by eliminating power dissipation from the shunt resistor, but would add complexity and cost to the circuit. Thus, this approach was not used.

D. Error Subtractor

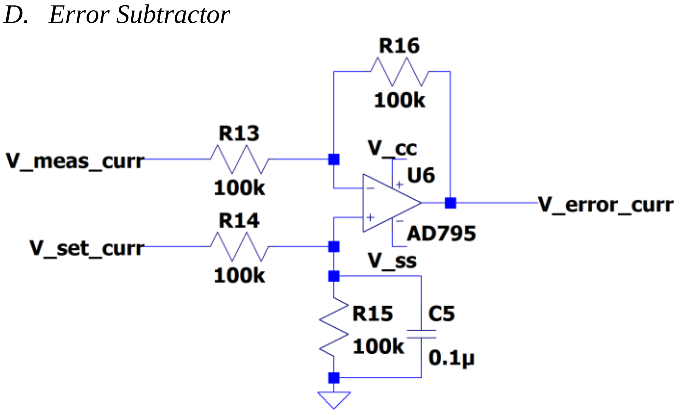

Fig. 7. Error subtractor schematic diagram

The error subtractor compares the measured shunt current against the setpoint using an op-amp subtractor. The setpoint and shunt measurement units are both 1 V = 1 Amp. The resulting current error is passed into the PI-controller, which then controls the buck-boost converter.

The 0.1 µF bypass capacitor C5 is a low-pass filter for steps and transients in the error, helping prevent large current overshoot in the output. Large steps in the error without the low-pass filter could cause large, potentially dangerous current spikes. The capacitor smooths out these large transients.

Reducing high-speed transients proves useful when the system is first turned on, where the buck-boost is not yet outputting but the setpoint is commanding a current, instantaneously yielding a large error. The buck-boost then commands the largest output voltage possible, overshooting the setpoint until the system settles in steady state. However, limiting this overshoot can protect the LEDs or load.

E. PI controller

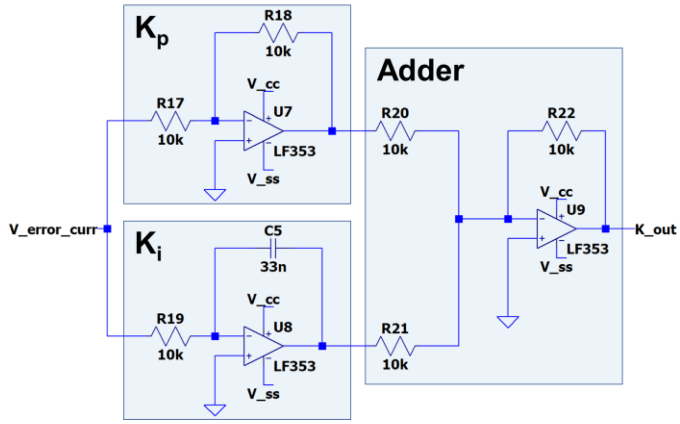

Fig. 8. PI controller schematic diagram

The PI controller sets the buck-boost converter's duty cycle based on the measured current error. The two parts, a proportion (P) and integral (I) controller, react differently to the error signal and are summed together in the controller's output.

The P controller outputs in linear proportion to the input error with a fixed gain – the larger the difference between measured and set current, the larger the output voltage. This relationship is shown in Equation 3. The fixed gain effectively sets how fast the system will respond to error, and is set as a unity gain per Equation 4.

$$V_p = -K_p \cdot V_{err} \tag{3}$$

$$K_p = \frac{R_{18}}{R_{17}} \tag{4}$$

The I controller accumulates and outputs error over time as an integral function. Integrating error helps correct steady-state error inside the system – if the system steadily outputs less current than requested, the I controller will fix this steady-state error over time.

Equations 5 and 6 show the mathematical model of an integral controller.

$$V_p = -K_i \int_0^t V_{err}(t)\, dt \tag{5}$$

$$K_p = \frac{1}{R_{19} \cdot C_5} \tag{6}$$

Finally, the proportional and integral controller outputs are added together in the inverting op-amp adder, with a unity gain. The adder's P and I gains can be independently adjusted to weight the controllers differently, by changing the values of R20 and R21.

The net output voltage sits at 0 V for 50% duty cycle, with negative voltages corresponding to smaller duty cycles and positive voltages corresponding to larger duty cycles.

Control loop tuning has major impacts on system performance and can prevent or minimize overshoot, steady-state error, and other parameters. For example, the P controller must be tuned so it doesn't overcompensate for error, causing overshoot (K_p too high). Also, it cannot react too slowly to error with an overdamped response (K_p too low). The I controller term must be sufficiently large to fix steady-state error, but cannot be so large that it resists overall changes.

Picking P and I gains involved simulating the overall circuit with different component values, and optimizing for reduced steady-state error, minimum overshoot, and fast step response.

F. *Safety Cutoff - Duty Cycle*

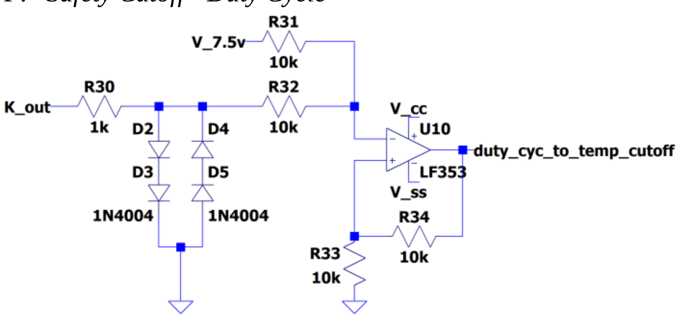

Fig. 9. Duty cycle cutoff and adder, schematic diagram

This circuit limits the PI controller's output duty cycle to limit the buck-boost converter to a relatively linear operating region. Otherwise, in extreme nonlinear regions, the output voltage can exponentially grow, a dangerous situation that's hard to control.

The PI controller's output is confined between -1.4 and +1.4 V, corresponding to roughly 20% – 80% duty cycle, using two opposing pairs of diodes. A diode's forward voltage is normally 0.7 V, so connecting two diodes in series yields an overall forward voltage of 1.4 V. Below 1.4 V, the diodes do not conduct and voltage remains unchanged, but the diodes conduct above 1.4 V and cap the voltage. The second, opposite pair of diodes limits negative voltages to -1.4 V. Resistor R30 limits current through the diodes.

An op-amp adder centers the limited duty cycle output around 7.5 V, the center of the PWM generator's triangle wave. The signal is added to a fixed 7.5 V reference voltage from a linear regulator, and the output can drive the buck-boost circuit.

Duty cycle limiting is only recommended for converters with nonlinear transfer functions, like buck-boost and boost converters. For step-down buck converters with linear transfer functions, the limiter is not necessary.

G. *Safety Cutoff – Temperature*

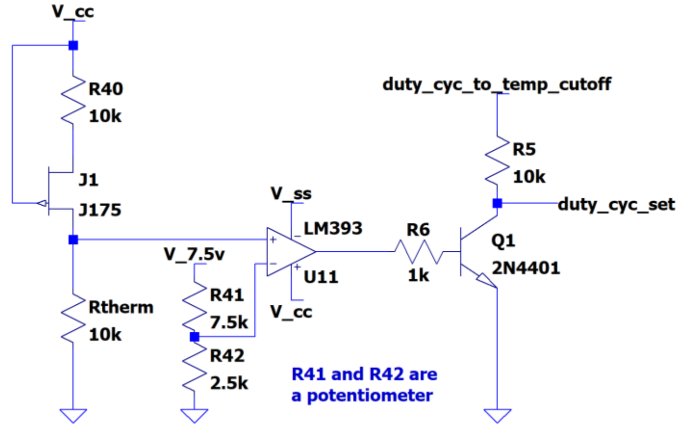

Fig. 10. Temperature cutoff schematic diagram

Power LEDs are very heat-sensitive and can easily fail from overheating if not properly heatsinked or cooled. This design uses a thermistor mounted on the LED heatsink to sense temperature.

The thermistor is a positive-temperature coefficient (PTC) resistor, meaning its resistance rises proportionally with temperature. This particular thermistor is 10 kΩ at 25°C.

The thermistor is connected in series to a JFET constant current source, with the thermistor voltage increasing with thermistor resistance as temperature rises. Once the thermistor voltage exceeds an adjustable cutoff voltage, a comparator switches on an NPN transistor, tying the duty cycle output to ground. In normal operation, the NPN transistor would be open, and the duty cycle output would continue to the buck-boost converter.

This temperature cutoff can be bypassed using a PCB jumper, as temperature in LED strips and other LEDs is hard to measure.

H. *Input Current Gain Multiplier*

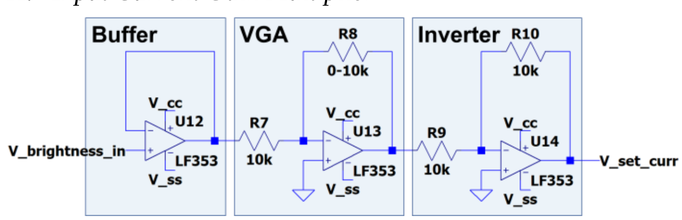

Fig. 11. Input current gain multiplier schematic

The brightness is set using an input voltage between 0 – 5 V, which is multiplied by a gain to correspond to a current setting. Different LEDs have different current ratings, so this gain must be adjusted by LED.

As shown in Figure 11, an op-amp buffer first samples the voltage with high input impedance. The sampled voltage is then multiplied by an inverting variable gain amplifier (VGA) with gain set by potentiometer R8, allowing for gains less than 1. Then, another unity-gain inverting op-amp rectifies the voltage output, which is then passed to the error subtractor.

III. Simulation Results

This circuit was tested in Analog Devices' LTSpice circuit simulator to verify this circuit's operation and tune component values. First, the overall circuit was drawn in LTSpice, block by block. Individual blocks were tuned and tested in simulation, (e.g. the triangle wave generator was tuned for 100 kHz), then connected for overall system tests.

The first test verified that the system would reach a steady-state current output. This initial system would overshoot on turn-on, then undershoot, then reach steady-state operation relatively slowly. Figure 12 shows an early system test not incorporating an I controller; the red line is I_{out} vs. time, green is voltage output, and blue is commanded duty cycle.

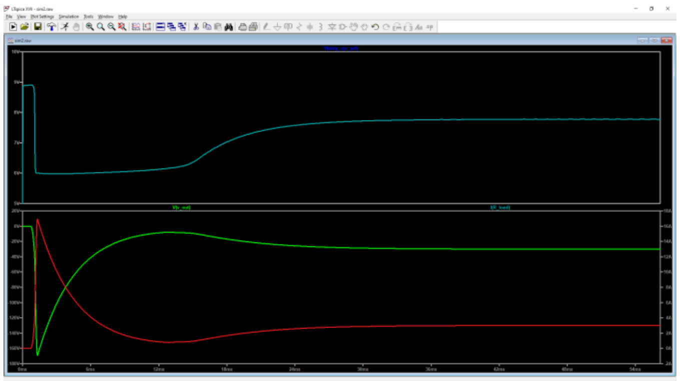

Fig. 12. First working simulation test.
Buck-boost L = 50 µH, C = 330 µF. K_p = 1, R_i = 1 MΩ, C_i = 470 µF

Then, the PI controller values were tuned. Faster convergence at the setpoint was achieved by increasing K_p, without the system becoming unstable. Steady-state accuracy was improved by increasing K_i, but not too much to cause integral wind-up. The output capacitance was also increased to minimize voltage ripple at high output power.

The next test verified that the system would react to changes in the setpoint. The system was switched on with an initial setpoint that was suddenly increased in a step function, the most extreme scenario. This helped optimize for minimal overshoot and convergence time at the new setpoint. The red line is output current, green is voltage, and blue is commanded duty cycle.

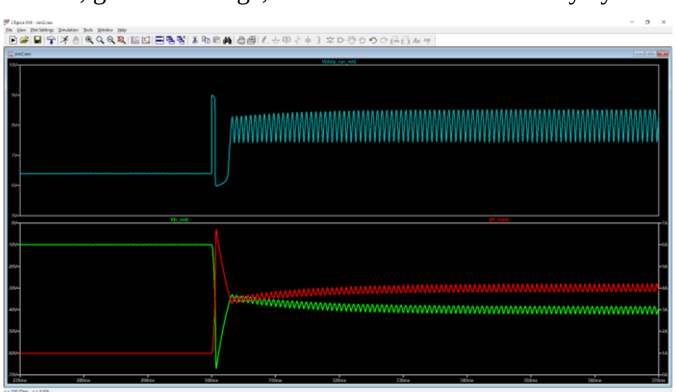

Fig. 13. Step response from 1A to 4A
Buck-boost L = 50µH, C = 330µF. K_p = 3.3, R_i = 10 kΩ, C_i = 330nF

These values were further fine-tuned. The inductor was decreased to 10 µH to ensure CCM operation, and the capacitor was increased to a large 2000 µF to reasonably minimize ripple current. However, the problem of overshoot start-up remained. Inserting bypass capacitor C5 in the error subtractor helped fix this overshoot by smoothing sharp edges in the duty cycle, with simulated overshoot decreased from ~100 Amps to a more manageable ~20 Amps over 1 ms.

This final circuit was simulated again with simulated real components, but the LTSpice simulation does not seem plausible. The simulation shows nanosecond-length 10 Amp spikes, which would not be possible in real life.

Fig. 14. Step response test with real-simulated components, from 2 A to 5 A
Buck-boost L = 10 µH, C = 2000 µF. K_p = 1, R_i = 10 kΩ, C_i = 330 nF

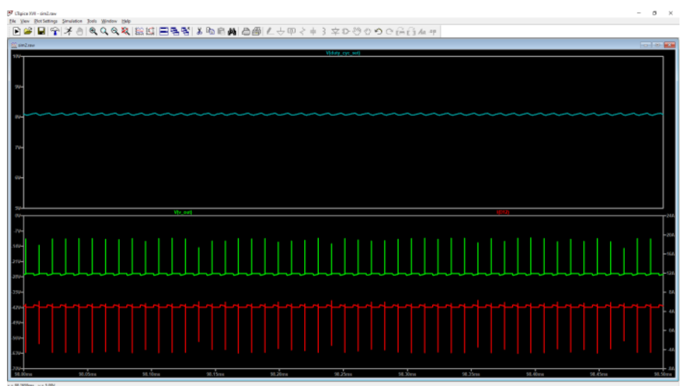

Fig. 15. Unrealistic current spikes at 5 A steady-state for above simulation, 50 ns / div. Each 10 A current pulse lasts less than 1 ns.

With the circuit simulated and tested, a PCB layout was designed for testing in real life. Additional fine-tuning will be required on the PCB, as simulated components do not perfectly match real-world components.

IV. Implementation

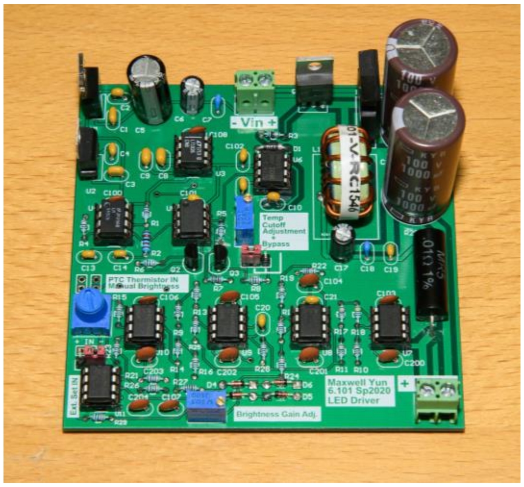

Fig. 16. Fully assembled PCB

Transferring the system from simulation to reality requires picking optimal components from real life, designing a PCB in Altium, ordering components and fabricating PCBs, then assembling and testing the overall PCBs.

The general-purpose LF353 JFET dual op-amp is used for its sufficiently high input impedance and gain-bandwidth product. Its 8-pin DIP package combines two op-amps, more space efficient than single-op-amp chips.

The LM393 dual comparator is used because the 100 kHz switching frequency is too fast for the LF353 op-amp, but no problem for the comparator. The dual-comparator 8-pin DIP package also helps minimize PCB size.

Vcc is a +15 V source supplied by a 7815 linear regulator stepping down the input voltage. Vss is -15 V, supplied from an LT1026 charge-pump voltage inverter sufficient for the low power demand on that rail. The linear-regulated 7.5 V rail uses a 78S75 linear regulator supplied from the +15 V rail.

The switching MOSFET is an Infineon IPP600N25N3G rated for 250 V, 25 Amps, sufficient for handling the buck-boost circuit's voltage spikes. The diode is an STMicro STTH15RQ06WY, rated for 600 V and 15 Amps. The inductor is rated for 12.5 Amps, with a low ESR of 7 mΩ. These components are chosen because their voltage and current ratings are large enough for this buck-boost converter, but the overall component footprint is small enough to fit on a PCB.

Bypass capacitors of 100 nF are inserted adjacent to the voltage rails of each IC, in close physical proximity, to remove noise from the IC voltage supply.

Resistors are conventional 1% ¼-watt resistors except for the shunt resistor, which is a 1% 5-watt wirewound resistor. Capacitors are typically ceramic, except for the electrolytic filtration capacitors and main buck-boost capacitors (1000 µF).

The PCB was built in Altium by copying the schematic from LTSpice, specifying real components and copying their pinouts/footprints from datasheets, then arranging and connecting components on a PCB in an orderly fashion. The PCB was fabricated by PCBWay, with overall size 10cm x 10cm.

Consecutive functional blocks are placed adjacent to one another to minimize wiring length. The power MOSFET, diode, and inductor are isolated in a corner from the logic electronics due to their significant switching noise. To handle high current, their traces are 75 mil wide on both PCB sides vs. the usual single-sided 10 mil traces. The groundplane has additional clearance around those traces to avoid the switching frequencies capacitively coupling into ground.

Brightness is either set with a potentiometer on the board or by external voltage input, selectable by jumper. This input is multiplied to produce the current setpoint by an adjustable gain set by a potentiometer. The temperature cutoff voltage is adjustable by potentiometer and can be bypassed by jumper.

V. Challenges

Picking component values for the buck-boost converter was difficult due to the tradeoffs required. A smaller inductor means the converter would operate in CCM, but at the same time is less stable than a larger inductor. Also, the capacitor ended up being as large as can physically fit on the PCB, but it was initially difficult to pick a value to simulate with.

Also, tuning the PI controller was challenging, as changing one variable would require changing the other in tandem. With no prior experience in control systems tuning before, it was difficult at first to know which variables to change for the desired outcome.

Finally, implementation was also challenging and required the hardware debugging typical of hardware projects. For example, the PCB schematic uses a pull-down resistor on the LM393 comparator output, which requires a pull-up resistor. This issue required troubleshooting and last-minute wire fixes soldered on the PCB itself.

The overall PCB did not work because the IR2125 gate driver did not work as a gate driver, exhibiting unpredictable behavior across multiple chips despite being implemented correctly. Since the IR2125 is too unreliable to use, a replacement gate driver must be found, and the PCB layout updated for the new gate driver. However, individual logic blocks were tested separately and worked as expected.

VI. CONCLUSION

This paper explores the design and implementation of a current-controlled LED driver using a DC-DC buck-boost circuit. This circuit is widely used in LED lighting due to its efficiency and adjustable brightness, with monolithic, single-chip controllers widely used in industry. I have demonstrated the implementation of this basic circuit using discrete analog components, in software simulation and in hardware. In the future, I'd like to build an auto-brightness module that sets the LED brightness proportional to outdoor brightness, to potentially help the human circadian rhythm.

VII. ACKNOWLEDGEMENTS

I would like to thank Gim Hom and the 6.101 teaching staff for teaching the course and rapidly adapting to the circumstances of this semester. I'd also like to thank my family for providing an electronics workbench with the old test equipment I used to implement this circuit.

VIII. REFERENCES

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