

University of Victoria
Faculty of Engineering
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Efficient Variable-Brightness LED Flashlight

Personal Project
Victoria, British Columbia

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January 4, 2006

in partial fulfillment of the requirements of the
B.Eng. Degree

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January 4, 2006

Dear Mr. Bazylak,

Please accept the accompanying confidential ENGR 446 report entitled "Efficient Variable-Brightness LED Flashlight."

This report is the result of a personal project completed at home in Victoria, BC, while I was also working for How2Sare Technologies Inc. During my fourth work term as a 4A electrical engineering and computer science student at the University of Victoria, I designed and built 3 generations of prototype LED flashlights. This report will detail the design, construction, and testing of these flashlights and cover some future improvements.

While working on this project, I learned about switching power supply design, debugging circuits with a multimeter and a digital oscilloscope and programming and using PIC microcontrollers. I feel that this knowledge will be helpful in future work terms, and in my career.

I would like to thank the Autonomous Under Water Vehicle Team for lending me their PIC programmer.

Sincerely,

Dylan Hoen

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Summary

It was the goal of this project to make a small, efficient, durable, rechargeable LED flashlight that could last a whole camping trip without needing to recharge or replace the batteries. One of the ways that flashlights are inefficient is that different situations require different amounts of light, and most flashlights only have one brightness level. If the flashlight had a wide range of brightness levels, and the minimum brightness needed was used in each situation, the battery life of the flashlight could be extended significantly. This report will detail the design, construction and testing of 3 generations of prototype variable-brightness LED flashlights.

Glossary

A	Amperage	(a measure of electric current)
AA	A standard battery size and shape	
DIP	Dual Inline Package	(a socket form factor)
k	Kilo Ohm	(a measure of electric resistance)
LED	Light Emitting Diode	(an electronic device)
mA	Miliamp	(a measure of electric current)
mAh	Milliamp-Hour	(a measure of charge)
MCD	Milicandela Equivalent	(a measure of light intensity)
methaline-chloride	A chemical that dissolves Plexiglas and vulcanizes it together.	
mm	Milimeter	(a measure of distance)
NIMH	Nickel Metal Hydride	(a type of battery chemistry)
PIC microcontroller	A brand of microcontroller produced by Microchip.	
uF	Microfarad	(a measure of capacitance)
uH	Microhenry	(a measure of inductance)
uS	Microsecond	(a measure of time)
V	Voltage	(a measure of electric potential)

1.0 Introduction

It was the goal of this project to make a small, efficient, durable, rechargeable LED flashlight that could last a whole camping trip without needing to recharge or replace the batteries. One of the ways that flashlights are inefficient is that different situations require different amounts of light and most flashlights only have one brightness level. If the flashlight had a wide range of brightness levels, and the minimum brightness needed was be used in each situation, the battery life could be extended significantly.

In the last few years, white LEDs have become more efficient than the most efficient low voltage incandescent flashlight bulbs. A single LED can be efficient over a wide range of power levels, while each filament in an incandescent light has an efficiency curve that drops off as the power changes. Sodium, Metal halide, and fluorescent lights can still be more efficient than LEDs, but the efficient ones that were available were too big to be used in a flashlight with a focused beam. LEDs were the best choice to maximize efficiency for a small flashlight.

2.0 The first prototype

Victoria was not a good place to buy high efficiency white LEDs. Between Queale Electronics, Pacific Coast Electronics, and Radio Shack, the best LEDs that could be found were about 2,500 MCD (millicandela equivalent) at 20 mA (milliamps). MCD is a measure of the light intensity at the center of the beam produced by the LED. LEDs are advertised with the light intensity at the center of the beam and the angle of half intensity. It is difficult to find information about the total number of lumens emitted by LEDs and no equipment was available to measure the output of the LEDs, so no luminous efficiency calculations could be done here. The web page of a company named, "SuperBrightLEDs.com" was discovered with a wide selection of LEDs including some white LEDs that could do 10,000 MCD at 20 milliamps, but their prices were too high (Better than the prices in Victoria though). Finally, on Ebay, a factory in China was found that had ten 6,000 MCD LEDs for about \$0.50 each (Due to a hard drive crash, the emails with the exact pricing and specifications of these LEDs were lost and the Ebay auction details got deleted 2 months after the auction ended, so these prices and specifications are just estimates from memory). It was decided that these LEDs should be purchased for the first prototype.

Figure 1: The first prototype. The bottom left shows the first switch switched on and the bottom right shows both the first and second switches switched on:



The first prototype (Figure 1) was constructed out of parts that were left over from other projects. It used 4 rechargeable 1600 mAh (milliamp-hours) NIMH (Nickel Metal Hydride) AA sized batteries, which were placed in a 4 AA battery holder, which connected them in a series. Over 80% of the battery's discharge cycle, the voltage across each battery varies between 1.3V and 1.2V, averaging 1.25V. With 4 AA batteries in a series, the voltage totals 4 batteries * 1.25V / battery = 5V. The 4AA holder had been damaged in a short circuit from a previous project, which melted the plastic and wrecked the 9V battery connector on top. Wires were soldered to the broken connector and electrical tape was used to hold it together. Three switches of a 5 switch DIP (Dual in-line package) package were used to switch 3 different circuits on and off.

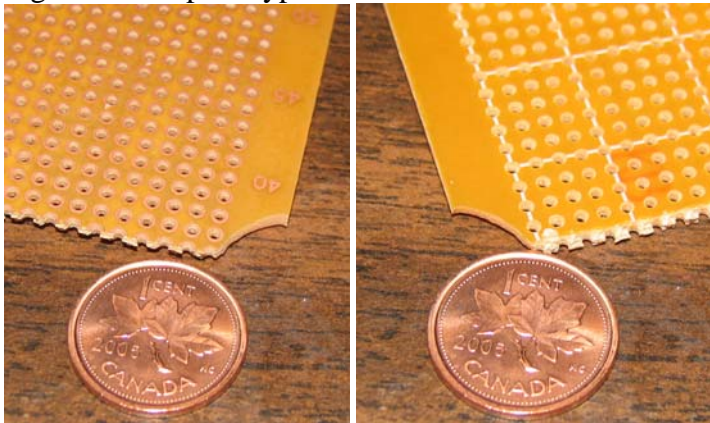
The first switch switched on a single white LED connected to a single 100 ohm resistor. LEDs have a fairly constant voltage across them over a wide range of currents. These 5 mm white LEDs usually have somewhere between 3.2V and 3.6V across their terminals when at their rated current of 20 milliamps. Taking an average of 3.4V, the current across this LED was $(5V - 3.4V) / 100 \text{ ohms} = 16\text{ma}$, which is just under the LED's rated current of 20ma. At this current, the battery would last $1600\text{mAh} / 16\text{mA} = 100 \text{ hours} = 4 \text{ days}$. At this power level, the flashlight was bright enough to walk around in a dark room or read a map, but it was not useful at lighting up things that were more than 10 feet away.

The second switch powered 4 more LEDs through a 10-ohm resistor. The amount of current used by this circuit was $(5V - 3.4V) / 10 \text{ ohms} = 160\text{mA}$. Each LED carried $\frac{1}{4}$ of the current, which was $160\text{mA} / 4 = 40 \text{ mA}$. There used to be a 5'th LED for 32mA each, but it broke, either due to burning out, or getting crushed in a backpack full of heavy objects. These 5mm LEDs are rated at 20 mA. Doubling the rated current usually doesn't burn out the LEDs (Especially out doors in the Canadian climate). It makes the LEDs brighter, but less efficient. Having the LEDs a little bit less efficient is not a problem because there is already the alternative choice of using the single LED mode when efficiency is needed. Usually when the second switch is turned on, the first switch is also turned on for a total of $160\text{mA} + 16\text{mA} = 176 \text{ mA}$. At that current the batteries would last $1600\text{mAh} / 176 \text{ mA} = 9 \text{ hours}$. At that power level, much more detail can be seen, including objects that are 20 feet away.

The third switch powers a red and blue LED blinker circuit that appears to blink at a similar frequency to the lights on top of a police car. Its purpose is to get someone's attention from a long distance away. It was estimated that the batteries could keep this circuit blinking for about 3 days.

All of the components were soldered into a prototype board with copper pads one side with holes drilled into them with a spacing of 1/10 of an inch (same spacing as a bread board) (see figure 2), and the wiring was drawn in solder on the copper pad side of the board.

Figure 2: The prototype board:

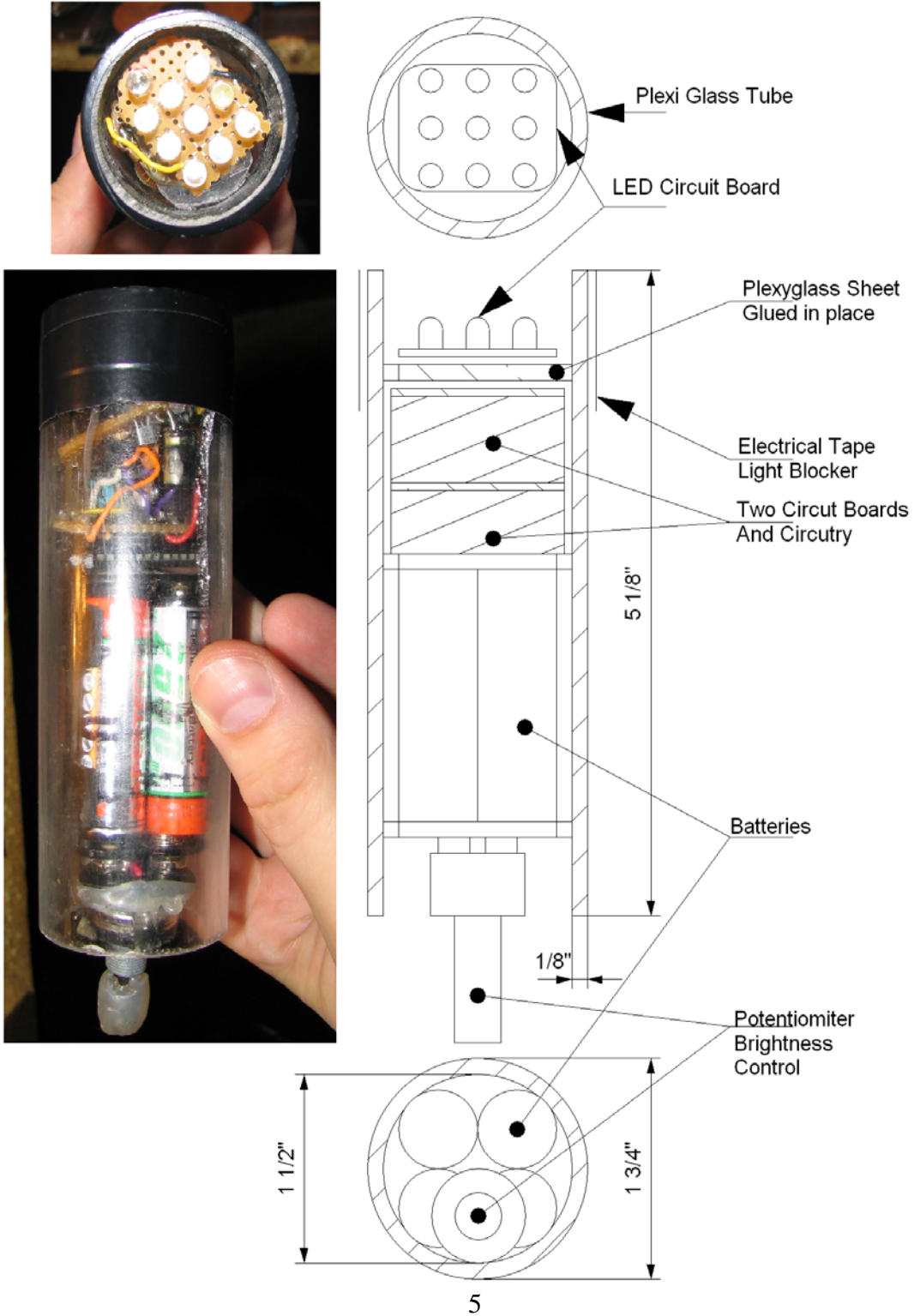


The board was glued to the end of the battery holder that didn't have the 9V battery connectors, and electrical tape was wrapped around it to block light from shining back into the eyes of the person using the flashlight.

This was a fairly nice flashlight to use. It was 90% battery and 10% circuitry and structure by volume, it lasted a long time, and fit in a jeans pocket, but it still had a few problems. There were only 2 brightness settings, its maximum brightness wasn't particularly bright, the switches could accidentally be turned on when the light was packed in a backpack with other objects, the capacitors for the LED blinker circuit could easily be broken off, the electrical tape that blocked the light from hitting the users eyes collapsed the first time the flash light was put into a pocket, and the glue holding the circuit board to the battery holder gave out. A new proto type had to be designed.

3.0 The second prototype

Figure 3: The second prototype:



The goal of the second prototype was to increase maximum brightness, make the range of brightness's continuous between off and full power, increase durability, and do a better job of blocking the light from the sides of the LEDs from blinding the user.

A clear Plexiglas tube was chosen as the outer case for its strength, familiarity with working with the material, and because it is clear and shows off the cool circuitry inside. The smallest tube diameter that could fit the 4 AA battery holder was chosen, and the battery holder fit perfectly with less than 1mm clearance. The tube was purchased at industrial plastics and paint for about \$16 for a 3 foot length. Electrical tape was wrapped around the end with the LEDs in it to block the light leaking from the side from blinding the person using the flashlight.

Putting more current through the LEDs made them less efficient, so to make the LED flashlight brighter and efficient, more LEDs had to be added. On ebay, nine 16,000 MCD 5mm white LEDs were purchased from China for about \$0.50 each (The technology available had improved since the last prototype).

This time, it was decided to have full analog control over the LED's brightness, rather than switch different numbers of them on and off at different times. The previous design had a 3.4V out of 5V drop across the LEDs. That means that $5V - 3.4V = 1.6V$ was wasted across the current limiting resistor and only $3.4V/5V = 68\%$ of the battery's energy was being used up in the LEDs. Any current limiting circuit with all of the LEDs in parallel would be limited to the same efficiency. Another problem was that the LEDs in parallel wouldn't share the current equally, making them less efficient, and possibly burning damaging some of them. The solution was to put them all in series and use a switching power supply to produce the necessary voltage and current to power them all.

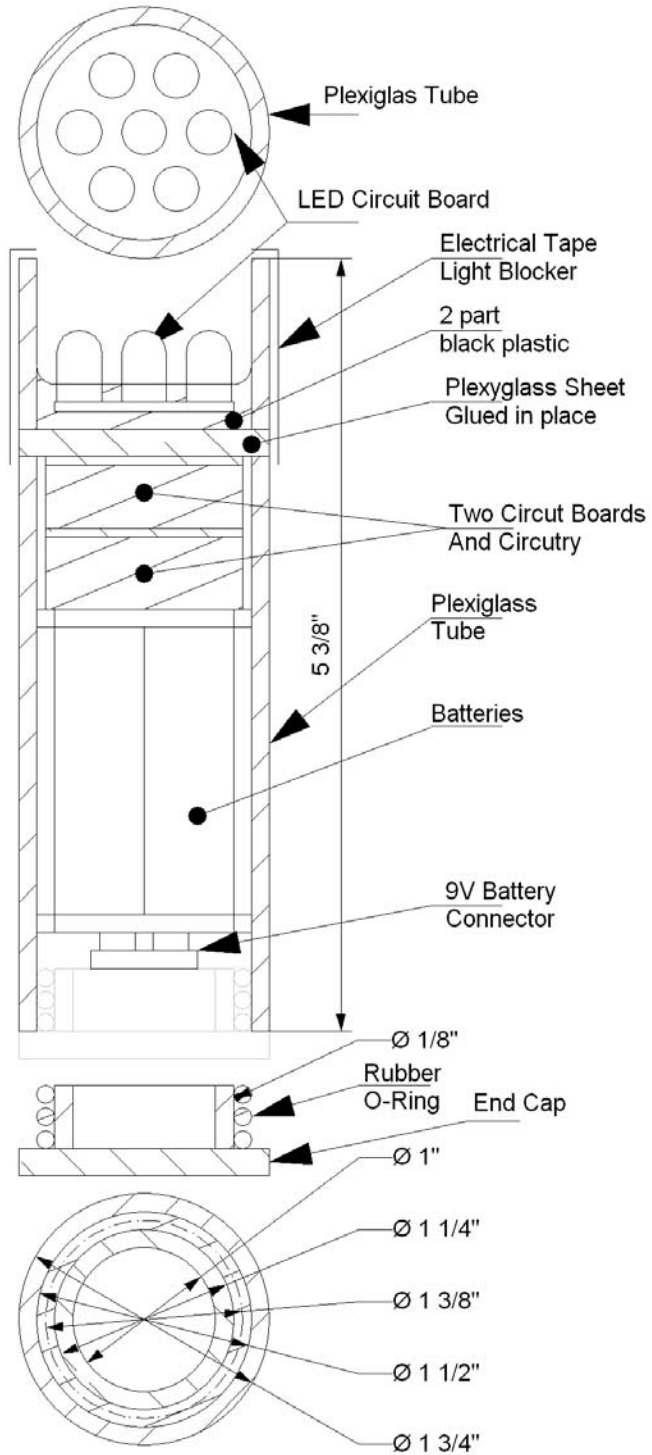
The beginnings of a current feedback switching power supply was designed and it was realized that the number of components needed wouldn't fit on a round circuit board with the same diameter as the tube. It was decided that all of the *decision-making* circuitry would be replaced by software inside of a PIC microcontroller.

The flashlight was tested and measured to use 250 mA at its brightest setting and 5.5 mA at its dimmest setting, at which point more power is going to the microcontroller than the LEDs. At this point in time, 2500 mAh AA batteries had become available, so on the brightest setting the flashlight would last $2500 \text{ mAh} / 250 \text{ mA} = 10$ hours, and on the dimmest setting, the flashlight would last $2500 \text{ mAh} / 5.5 \text{ mA} = 455$ hours = 19 days.

This flashlight was nice to use with its full analog brightness control and maximum brightness being several times brighter than the previous prototype, but it still had a few problems. The Plexiglas acted a bit like optical fiber and transmitted some of the light back into the user's eyes. This wasn't blinding, but it reduced the signal to noise ratio of vision in the dark. The potentiometer stuck out of the back of the tube and was glued to the 9V battery connector that connected to the AA holder. This potentiometer often got bumped and wiggled around and has caused the 3 solid core wires attached to it to snap and need resoldering several times now. This can be partially fixed by replacing the solid core wire with multycore wire. Another problem was that the microcontroller was always using power, even when the flashlight was turned down so far that it was basically turned off. The wires that hold the potentiometer also hold the batteries in place, and the batteries hold the potentiometer right side up. If the battery connector is disconnected from the batteries to keep them from draining, everything wiggles even more, causing the wires to break faster, and there is the possibility that the battery connector can land crooked on the battery holder and cause a short circuit, which has happened once. Another problem is that the circuitry was open and exposed to rain and sand getting in. Yet another prototype needed to be designed.

4.0 The third prototype

Figure 6: The third prototype:



The goal of this prototype was to make everything solid and weatherproof, use zero power when the flashlight is turned off, completely block out the light from shining back into the user's eyes, and make the switching power supply slightly more efficient.

This time, seven 60,000 MCD LEDs were purchased from Ebay for about \$1 each. These LEDs were bigger than the 5mm ones that had been used before, but were still rated at 20mA. They had a larger lens that could focus the light into a sharper beam, which caused the huge increase in MCD. These seven LEDs were arranged in a honeycomb shape that just barely fit inside of the Plexiglas tube.

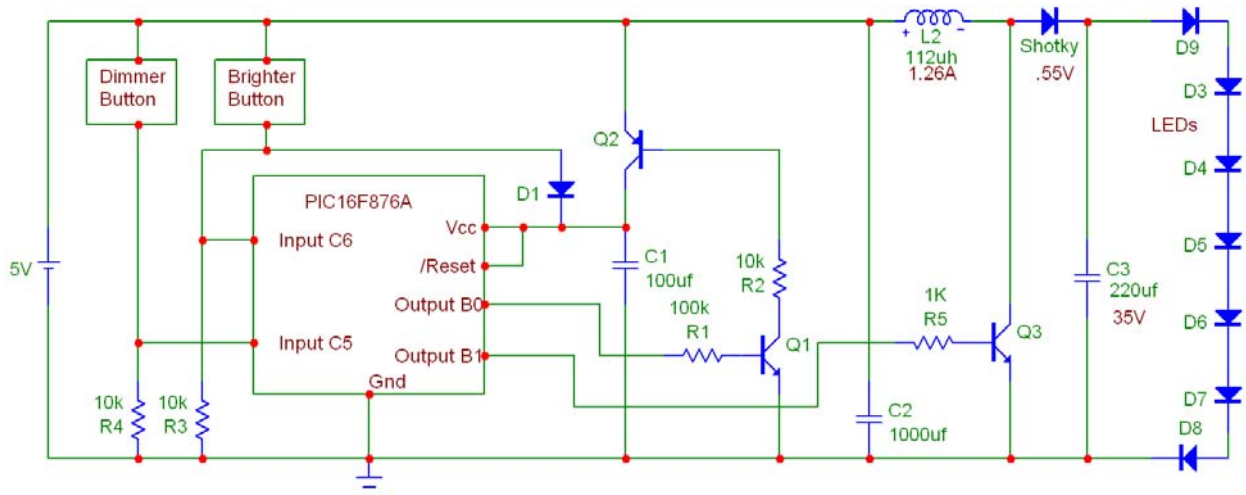
The case was designed to be waterproof. The tube was cut into 2 pieces and a flat, round piece of Plexiglas was vulcanized to the end of the shorter Plexiglas tube using methaline-chloride. Holes were drilled into the flat piece to run the LED wires through. The wires were soldered to the LED circuit board and run through the holes drilled in the flat Plexiglas sheet. A mixture of 2 part plastic and black pigment was poured into this Plexiglas cup and the LED circuit board was pressed into this plastic and when the liquid plastic had hardened, this part was sealed water proof. The rest of the circuitry and batteries was put into the larger Plexiglas tube and the larger Plexiglas tube was vulcanized to the other end of the flat piece of Plexiglas. Two holes were drilled into the Plexiglas tube and a button was inserted into each hole and glued in place. A piece of clear tape was placed over the buttons to seal the holes. An end cap was made by vulcanizing a piece of Plexiglas tube with a smaller diameter than the flashlight tube to another flat piece of Plexiglas. Three O-rings were placed around this thinner Plexiglas tube. The tube and O-rings were dipped into methaline-chloride and as the Plexiglas dissolved, it took the shape of the O-rings, which locked the O-rings in place. The O-rings were removed and cleaned and coated in silicon O-ring grease and then reinserted back onto the skinny Plexiglas end cap when it was dry. When this end cap was inserted into the other end of the flashlight, it sealed the electronics inside watertight. The end cap also fit very snugly and compressed the batteries and circuitry together so that nothing could jiggle around when the flashlight was shaken. It felt very solid.

The flashlight was turned on and put in a sink filled with water. It sank to the bottom, about 2 inches under the surface. After about 5 minutes, it appeared that no water had leaked into the circuitry chamber of the flashlight.

Electrical tape was wrapped around the LED end of the flashlight from hanging over the edge a bit, all the way down to just past the joint where the flat piece of Plexiglas separated the two tubes. Between the electrical tape, and the black liquid plastic seal, no light from the LEDs could shine backwards towards the user's eyes.

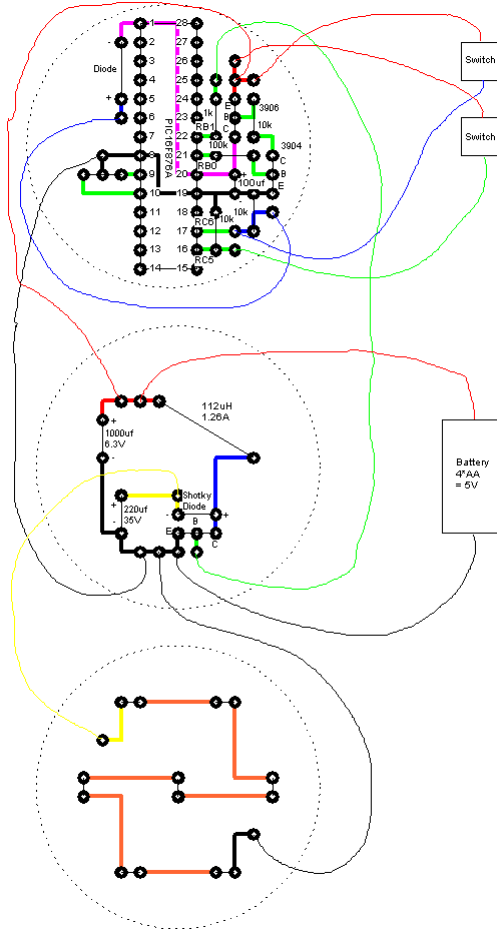
Instead of a potentiometer giving analog control over brightness, there are 2 buttons. One button doubles the brightness each time it is pressed, and the other button halves the brightness each time it is pressed (see red buttons on the left middle of figure 6). These buttons also double as the on and off buttons. When the flashlight is off, it uses only a few microamps. Refer to the schematic in Figure 7 below. The battery is on the left hand side. The wire along the bottom is ground, and most of the wire along the top is +5V. The 2 buttons are normally open circuits. The microcontroller is not powered at this point in time, so transistor Q1 is turned off, so transistor Q2 is turned off, so there is no power going through Q2, so the microcontroller is not powered. Transistor Q3 is also turned off because the microcontroller is not powered. At 5 V, only a few microamps can pass through the Shotky diode and 7 LEDs in a series and through the capacitors. NIMH batteries naturally discharge them selves at approximately 50% per month (wild guess from vague memory). At 2500 mAh, that is $2500 \text{ mAh} / (30 \text{ days} * 24 \text{ hours} / \text{day}) = 3.5 \text{ mA}$, which is much much greater than a few micro amps, so for all practical purposes, when the flashlight is off, it uses no power at all. When the brighter (on) button is pressed, current goes through D1 and into Vcc of the microcontroller, which turns it on. The program waits one second to verify that the button was pressed on purpose and not bumped accidentally, and then sets output B0 to high, which turns on Q1, which turns on Q2, which connects Vcc to +5V, which powers the microcontroller. When the brighter (on) button is released, the microcontroller stays powered through Q2. When the dimmer button is pressed enough times, the microcontroller sets output B0 to low, which turns off Q1, which turns off Q2, which cuts power to the microcontroller. Capacitor C1 helps to stabilize the voltage powering the microcontroller.

Figure 7: The schematic of the third prototype (Ceramic resonator clock not shown):



The switching power supply is similar to the one from the second prototype, but this time there is no LED resistor to tell the microcontroller how much current is going through the LEDs. Removing this resistor makes the flashlight more efficient as there is no more energy being wasted through it. The switching power supply was built in a breadboard and tested with a 50% duty cycle square wave. The frequency of this square wave was adjusted until there was about 30mA going through the LEDs, which is 150% of their rated current. This on period was measured to be 20 uS and was hard coded into the microcontroller's program. The 50% duty cycle with the 20 uS on period became the brightest setting of the flashlight. Each time the dimmer button gets pressed, the duty cycle gets cut in half by increasing the amount of off time and keeping the on time exactly the same. Nine levels of brightness were programmed in, with the dimmest setting being 20 uS on and 10220 uS off. At that point the microcontroller used several times more power than the LEDs did and there was no point making a dimmer setting.

Figure 8: The circuit board layout of the third prototype:



The circuit board layout of the flashlight was divided into 3 boards (See Figure 8). The board at the bottom of the image is the LED board. The middle board contains the high current and high voltage components of the switching power supply. The top board contains the microcontroller and button circuitry.

The flashlight's power consumption was tested. At the flashlight's dimmest setting, it was measured to use 7.1 mA and at its brightest setting, it was measured to use 240 mA, and the few settings below the highest one each used approximately half the current of the one before. At the brightest setting, the flashlight would last $2500 \text{ mAh} / 240 \text{ mA} = 10.4$ hours. At the dimmest setting, the flashlight would last $2500 \text{ mAh} / 7.1 \text{ mA} = 352$ hours = 14.7 days. The dimmest setting was tested out in the woods at night, and was determined to be adequate for remaining on a trail at regular walking speed without worrying about crashing into things.

This flashlight was almost perfect, except for a couple problems. Once the batteries have been drained to 20% of their full charge, the voltage starts to drop faster. The microcontroller was designed to be used between 4.5V and 5.5V. The microcontroller is powered through Q2, which uses up some of the battery's voltage. Also, the 9V battery connector was designed to work with 9V batteries, which can't handle very much current, so the wire used is very thin and its resistance uses up some of the battery's voltage too. Under full power, when the battery has less than 20% charge left, the voltage will drop too low to power the microcontroller, and the flashlight will suddenly turn off. It can be turned back on again and will work at a dimmer setting for a while. This problem can be reduced by replacing the 9V battery connector wire with wire rated for higher current, and fixed by replacing the 5V 20Mhz microcontroller with a 3V 10 mhz version.

The second problem is a mysterious one that has repeated 3 times after a few weeks of flashlight use. The flashlight will spontaneously start flashing after hours of being on steady. The flashing will get slower and slower and brighter and brighter until finally it fries one of the LEDs and the LED compartment needs to be sawed off and rebuilt. At first it was thought that the LEDs were defective. To test the LEDs to see if they were defective and easily burned out, 10 of them were run at 40 milliamps each by powering them with a 12V power supply and a current limiting resistor. After a week, all of the LEDs were still working, so the LEDs were probably not defective. It is unknown why the LEDs stop conducting steadily, and start flashing, but when it does start, while the LEDs are off, the capacitor charges up, and when they suddenly start conducting, a huge avalanche of current gets dumped through the LEDs. This huge avalanche is what ends up frying them. To reduce this avalanche, the capacitor could be reduced in size, and a resistor could be added in series with the LEDs. This resistor would reduce the efficiency of the flashlight, but save it from destroying its self.

5.0 Conclusions

Three generations of prototype LED flashlights were built, with each generation better than the previous one. The third generation was almost perfect, except for 2 problems. The problem where it turns off when the battery still has 20% of its charge left can be fixed with thicker battery connector wire and choosing a microcontroller rated for lower voltage. The mysterious strobe light of death problem could probably be fixed by putting a resistor in series with the LEDs. Testing of the flashlights at different brightness levels showed that the flashlight could even be useful at a brightness level that could be maintained for 2 weeks without recharging the batteries. Varying the brightness of the flashlight as different light levels are needed in different situations can greatly extend the battery life of the flashlight, while maintaining the same usefulness as a normal flashlight with a fixed brightness.

6.0 Recommendations

The wires of the 9V battery connector should be replaced with wire rated for higher current. The microcontroller should be replaced with one that can handle lower voltage. The capacitor in parallel with the LEDs should be reduced in capacity. A resistor should be put in series with the LEDs to protect them.

References

General References:

"WORK TERM REPORT GUIDELINES" UVic engineering coop web page
<<http://www.coop.engr.uvic.ca/engrweb/WTR.HTML>> April 1, 2004 revision

```
#include <pic.h>           // defines pins and bits for PIC16F876
#include "common.h"        // commonly used constants and macros
#include "delay.h"         // DelayUs(), DelayMs(), DelaySec()

void main()
{
    BYTE buttoncount = 1;
    BYTE maxbutton;
    WORD buttontime = 0;
    BYTE depressed = 0;
    WORD delay;
    WORD map[11];
    WORD unit;

    TRISB0 = OUTPUT;
    TRISB1 = OUTPUT;
    TRISB2 = OUTPUT;
    TRISB3 = OUTPUT;
    TRISB4 = INPUT;
    TRISB5 = INPUT;
    TRISB6 = OUTPUT;
    TRISB7 = OUTPUT;

    RB0 = 0;
    RB1 = 0;
    RB2 = 0;
    RB3 = 0;
    RB4 = 0;
    RB5 = 0;
    RB6 = 0;
    RB7 = 0;

    unit = 20;

    maxbutton = 9;

    map[9] = 1*unit;
    map[8] = 3*unit;
    map[7] = 7*unit;
    map[6] = 15*unit;
    map[5] = 31*unit;
    map[4] = 63*unit;
    map[3] = 127*unit;
    map[2] = 255*unit;
    map[1] = 511*unit;
    map[0] = 511*unit;

    buttoncount = 1;

    delay = map[buttoncount];

    DelayMs(250);

    depressed = 1;

    RB6 = 1;

    while(TRUE)
    {
        RB7 = 1;
        DelayBigUs(unit);
        RB7 = 0;
        DelayBigUs(delay);
    }
}
```



```
#include <pic.h>           // defines pins and bits for PIC16F876
#include "common.h"        // commonly used constants and macros
#include "delay.h"         // DelayUs(), DelayMs(), DelaySec()

void main()
{
    BYTE buttoncount = 1;
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    WORD buttontime = 0;
    BYTE depressed = 0;
    WORD delay;
    WORD map[11];
    WORD unit;

    TRISB0 = OUTPUT;
    TRISB1 = OUTPUT;

    TRISC6 = INPUT;
    TRISC5 = INPUT;

    RB0 = 0;
    RB1 = 0;

    unit = 20;

    maxbutton = 9;

    map[9] = 1*unit;
    map[8] = 3*unit;
    map[7] = 7*unit;
    map[6] = 15*unit;
    map[5] = 31*unit;
    map[4] = 63*unit;
    map[3] = 127*unit;
    map[2] = 255*unit;
    map[1] = 511*unit;
    map[0] = 511*unit;

    buttoncount = 1;

    delay = map[buttoncount];

    DelayMs(250);

    depressed = 1;

    RB0 = 1;

    while(TRUE)
    {
        RB1 = 1;
        DelayBigUs(unit);
        RB1 = 0;
        DelayBigUs(delay);

        buttontime += delay + unit;

        if (RC6 || RC5 || depressed)
        {
            if (buttontime >= 50000)
            {
```

