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LED LIGHT DESIGN

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Abstract

Three prototype light fixtures that used Light Emitting Diodes (LED) for machine tools were developed. These light fixtures were designed with a significant focus on improving current light fixtures in the areas of efficiency, light head shape, fixture to machine tool, light quality, and heat dissipation. The prototypes were tested by trial at the Rapid Engineering Manufacturing factory in Wuxi, China, and suggestions for future improvements to each design were developed.

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East 1 Manufacturing Facility

For all of their useful input on our designs.

Introduction

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Goal Statement

The goal of this project is to design and create LED factory task lights with emphasis on the following five features: efficient circuit, appropriate light head shape, functional structural frame, adequate heat dissipation, and excellent light quality.

Background

LED's

Light Emitting Diodes, more commonly known as LED's, were invented in the second half of the twentieth century. The earliest LED's were only able to emit light in the infrared range, and thus their applications were limited. Since then, LED technology has developed into the visible spectrum, and LED's are finding all kinds of applications, from flashlights to jumbotrons.

LED Benefits

The advantages that LED's hold over existing lights are both economic and environmental.

Economically, LED's consume much less power than both incandescent and fluorescent lights. In terms of efficiency, LED's can produce about 90 lumens per watt of power consumed, and this number is steadily increasing. A standard incandescent light generally produces a maximum of 20 lumens per watt, and a standard fluorescent light only produces up to 40 lumens per watt. In addition, the lifespan of an LED is far longer than that of other lights. Most manufacturers rate the life of their LED's at approximately 100,000 hours, where incandescents are generally rated for a 1,000 hour life, and fluorescent lights are at 20,000 hours. This increase in lamp life decreases lamp replacement costs.

LED's hold a strong environmental advantage over modern fluorescent lights because production and disposal are environmentally friendly. Fluorescent lights must contain a certain amount of mercury in order to work. Mercury is toxic, so fluorescent lights require special handling for disposal, which adds to their overall cost.

LED Technology

LED's are semiconductor chips. They emit light at a very specific frequency when electrons jump between separate p-type and n-type semiconductors. The point of contact between these chips is called the p-n junction. Both the specific frequency of light emitted and the electric potential needed cause the jump depend on atoms of exotic elements being substituted for a small percentage of the silicon atoms. The process of exposing pure silicon to atmospheres containing high concentrations of these elements is called "doping", and the material's charge and conductivity are very dependant on the elements that they've been doped with.

In order to understand how the electrons jump from one side to the other, one must first understand how materials conduct electricity. Electrons in the atoms of most materials are gathered in two different "bands": the valence band, and the conduction band. The conduction band corresponds to the outermost electron shell and, in accordance with its name, is where transfer of electrons between atoms takes place. The valence band, on the other hand, refers to the outermost shell of electrons that is filled to capacity with electrons. The difference in distinct energy levels between these two shells is known as the band gap. Metals have no distinct band gap, therefore electrons are free to move to the conduction band at no energy cost, and therefore metals conduct electricity well. Nonmetals have a large band gap, so valence electrons can't get to the conduction band easily, and thus nonmetals do not conduct well. Semiconductors, as their name implies, have a medium band gap, and so their electrons can jump to the conduction band with only a little energy input. Doped semiconductors, in addition to having different numbers of electrons, have different band gaps than their non-doped counterparts.

P-type semiconductors have been doped so that they are lacking in electrons (p means positive here). As a result, their valence bands are not quite full, and their conduction bands are empty. Each location in the p-type material that is missing an electron is known as a hole. N-type semiconductors, on the other hand, have been doped to have an excess of electrons, so their valence bands are full, and there are some extra electrons in their conduction bands.

Both p- and n-type semiconductors are normally electrically stable, however when an electric potential is applied across the two, electrons travel easily between them, jumping from the crowded n-type conduction band to the empty p-type valence band. For the individual electrons, this jump, in addition to switching atoms, means a change in energy level. As we know from basic physics, when an electron falls from a higher atomic energy level to a lower energy level, the excess energy leaves the electron in the form of a photon and thus light is emitted.

The exact color of the light emitted depends directly on the amount of energy lost in the jump from the n-type to the p-type, and thus the band gaps associated with the two. As a result of that, the choice of doping materials for both the n and p sides of the LED controls the color output of the LED. Since the band gap associated with a given doping material is very consistent for all samples of a doped semiconductor, LED's of a given type emit only very specific frequencies of light, which generally come across as the primary colors of light (red, green, and blue). In order to create white LED's, manufacturers dope the LED materials with several different materials to create a mixed light output that comes across as white.

The supply voltage that is required to get the electrons over the band gap is also directly proportional to the size of the band gap, so differently colored LED's require slightly different input voltages to emit light. Supplying too great of a voltage will cause electrons to move through the material too quickly, and the LED will burn itself out. Without enough voltage, the electrons will not make the jump, and nothing will happen. It should also be noted that if the supply voltage is attached backwards, and enough voltage is supplied to make the electrons flow backwards, then the doping of the n-type and p-type semiconductors will break down and the LED will become unusable.

Existing LED Applications

Lighting as a field began to develop in the early twentieth century with the advent of the electric light bulb. Finally, there was a source of lighting with a relatively constant light output. Light is measured in several different ways. The most basic unit is intensity, measured in candela or millicandela. Intensity is generally only measured for a single light source, so any fixtures that incorporate more than a single light source (i.e. most LED systems) are measured differently. Luminosity is a measure of the total light reflected per unit area off of a surface that has been placed at a specified distance. Luminosity is a useful measure because it can be measured on a per-fixture basis rather than on a per-light source basis.

Most existing LED applications can be categorized into two basic categories: small-scale and large. Small-scale applications, such as flashlights, reading lights, and indicator lights usually only make use of very few LED's and are intended for very specific purposes. They are also generally powered by batteries. Large-scale applications involving multiple thousands of LED's include LED jumbotrons in sports arenas and architectural lighting showcases, like the Fremont Street experience in Las Vegas. Neither of these categories provides light on the scale that we will be designing for; however both of them contribute something to our knowledge of the problem.

Most of the early uses for LED's were in small-scale applications, they were especially useful as indicator lights because the are small, work for hundreds of thousands of hours with very little decrease in light output, consume little power, and give off very little heat when compared to incandescent bulbs. More recently, LED's have found their way into small portable task lights, especially flashlights. Their low power consumption makes them ideal for this because they make better use of their batteries. To relate this to the goals of our project, these small-scale applications exploit the simplicity of LED's. Our goal is to make our fixtures as simple to power and rearrange as possible.

Large-scale applications of LED's showcase both their versatility and their durability. One of the best examples of large-scale applications is the Fremont Street Experience in Las Vegas. The Experience uses 1.4 million individual LED's to illuminate the underside of a large pavilion in Las Vegas. The LED's are controlled by a set of computers and are used for shows underneath the pavilion. The Experience has been running with LED's and without any major interruptions since 2004, even with external components exposed to the weather.

While both of these applications give off light, neither of them is concerned with illumination. Smaller products are focused on lighting individual tasks, while larger products don't really provide illumination as much as they provide a lighted screen on which to display images. The smaller products emphasize power advantages of LED's and larger products emphasize the durability and versatility advantages of LED's. With our fixtures, we want to emphasize both of these characteristics.

Rapid Engineering Manufacturing

Rapid Engineering Manufacturing (REM) is a small contract manufacturer based in Wuxi, China. They mostly do short runs of custom fasteners, ball valves, or really anything, but they are also looking to expand their business into other fields. They have a relatively new facility and are looking at the long-term costs of maintaining it. One way that they want to cut down on operating costs is to install highly efficient LED lighting systems throughout the factory. Since they have a new factory, installing a new system should be relatively easy to do. Also, if these LED lights work out, they could consider creating a whole product line of low-cost LED task lighting.

REM has already begun the changeover to LED illumination with their overhead lights. We will be furthering the changeover by developing fixtures to be used as task lighting on specific machine tools. Currently, most of the task lighting that they have is incandescent; the bulbs frequently burn out and don't always get replaced. With our LED fixtures, we would like to see that change. Specifically, replacement costs and maintenance time will be reduced or eliminated.

REM's business is specialty nuts, pins, and rivets, and the machine tools that we will be designing our fixtures for will be working metal. As a result, the fixtures that we design will have to be able to withstand flying metal chips and other dangers that are associated with the shop environment.

Methodology

Introduction

Our methodology, at a first glance is very simple. First we planned our time and researched the current task lighting. Then, we created several computer aided design (CAD) models and prototyped. Finally, we ran some test on the prototypes and installed them in the REM facility so that we could get direct feedback from the workers.

Overall Project Planning

During our first week in Wuxi, our REM sponsor, Al Barry, gave us a few lectures on project planning. The sumary of those lectures can be found in Appendix XX; suffice it to say that we followed those guidelines as we laid out a plan for our project.

We divided our project into three major phases: planning, fabrication, testing. In the planning phase, we researched and experimented with various pieces of our

Planning Phase

In the planning phase, we separated our work into five directions. The first was to find an appropriate shape for the light head, the second was to figure out if heat dissipation is a problem for LED light fixtures, the third was to design a simple AC circuit, the fourth to design a structural frame to hold the light head, and finally, the fifth was to determine the light quality that we desired from our lights.

Shape of Housing Design

Compared with common lights, LED's possess several unique characteristics, such as narrower light angles, lower heat emission, cooler light colors, and so forth. Because of these new characteristics, the task light housings that are currently in use simply aren't appropriate for LED lights, so for this project we have designed a new shape fit for LED lights. In our design process, we divided the schedule into three phases: brainstorming, creating a decision matrix and choosing three shapes for future development.

Brainstorming

Brainstorming is a group activity used to identify many ideas as potential solutions to one problem. We first wrote down as many different housing shapes as we could think of. The point of this was simply to gather ideas. We then analyzed their strong and weak points in order to find the best shapes.

The following chart (Figure 1) is the result of our brainstorming. There are five directions, including rectangular shapes, circular shapes, trapezoidal shapes, compound shapes, triangular shapes and rectangular shapes. Furthermore, each direction is followed by between 2 and 7 similar shapes, resulting in a total of 18 potential shapes for our design.

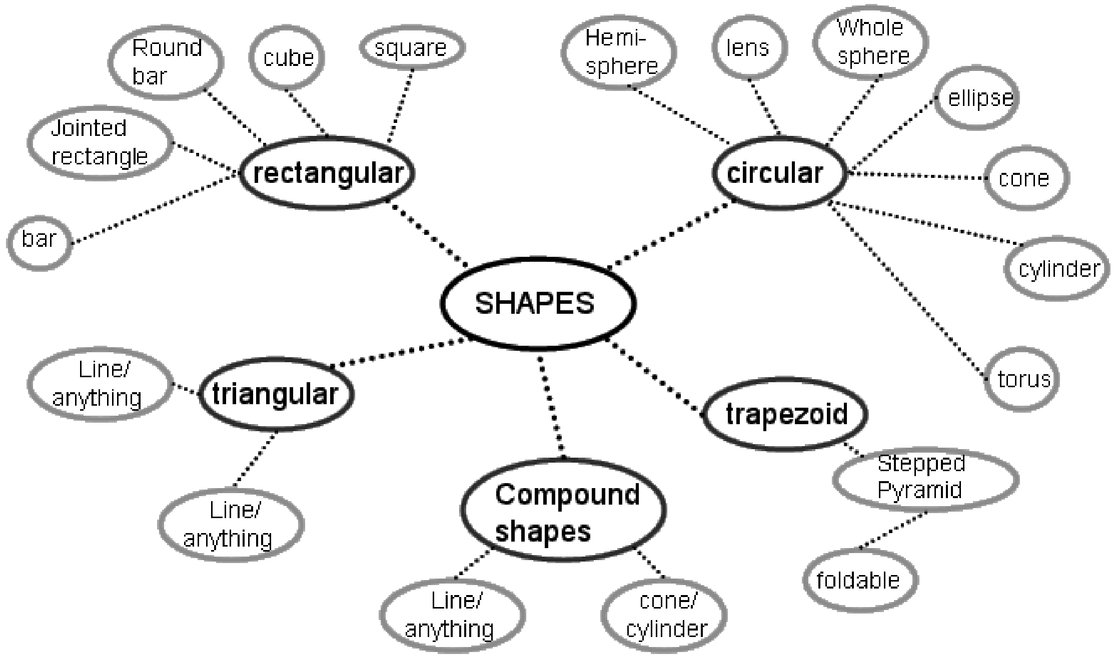


Figure 1: Brainstorming Results

Creating a Decision Matrix

After shapes brainstorming, we created a decision matrix to choose the stronger solutions. Decision matrices are commonly used in engineering to make design decisions or rank options. In this case, we used it to rank options coming from shapes brainstorming.

The following table (Table 1) is our final decision matrix. In this table, there are nine main key factors, including feasibility, innovation, appearance, focusability, heat dissipation, light area, printing PCB and collapsible function. Additionally, each factor has a coefficient that varies from 1 to 2.5. Each project member filled out a similar matrix, and the scores shown below are the average of those five tables (which can be found in

Appendix I: Shape Matrices).

Shapes Matrix											
	Feasibility	Innovation	Appear-ance	Focus function	Adjust-ability	Heat dissipation	Light area	Printing PCB	Collapsible function	Tatal	Order
Coefficient	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
2 hinged rectangle	3.375	3.5	3.125	2.5	4.25	3.75	4.125	5	4.25	59.6875	1
Jointed bar	3	4.25	2.625	2.25	4.5	4	4.25	4.5	3.75	59.25	2
Ziggurat	3.25	4.5	4.5	2.5	2	3.625	3.75	4	3.25	55.4375	3
Stepped cone	3.25	4	4.5	2.5	2	3.125	3.75	3.5	3.25	52.4375	4
Torus	3.75	4.5	3.625	2.75	2	4.25	3.75	3.5	0.25	51.125	5
Round bar	3.75	3	3.75	3.75	2.5	3.5	3.5	3.75	0.5	49.5	6
Cage	2.5	4	3.25	3.5	1.5	4.5	3.875	2.375	2.25	48.75	7
Right tetrahedrom	2.875	3.375	3.5	2.5	2.25	2.75	3.625	4.25	1.25	47.6875	8
Concave lens	3.5	3.125	3.5	4	2.25	3.875	3.125	2.5	0.5	45.625	9
Truncated cone	3.5	2.625	3.25	3.25	2	3.125	3.625	2.875	1.25	45.1875	10
Short cylinder	4	2	2.75	1.5	1.75	3.5	3.625	4.5	0.5	45.0625	11
Bar	4	1.875	1.875	2	2	2.5	3.25	4.5	0.75	42.875	12
Prabolic	3	3.25	3.75	3.625	1.75	2.75	3.25	1.875	1	41.875	13
Convex lens	3.25	3.125	2.75	0.5	1.75	4	4	2.25	0.75	40.75	14
Hemisphere	3.5	3	3.25	3	2	2.5	3.25	1.625	0.25	39.0625	15

Table 1: Final Decision Matrix

Choosing Three Shapes

From the decision matrix, we took the top ten shapes from the matrix and narrowed them down to three final shapes that we would then develop into prototypes. In order to make the final decisions, we discussed these ten shapes and then took a final vote. The shapes that scored the highest in this final vote are displayed below with a basic overview of their benefits.

Rounded Bar: Simple structure, pretty appearance, and good focus function.

Jointed Bar: High innovation, great adjustability, wide light area, and an easy-to-print PCB.

Stepped Cone: Great innovation, pretty appearance, and collapsibility for changing light angle.

Heat Dissipation

Previous research shows that the major failure mechanism for LED's is heat[i]. Many current LED lighting fixtures have a published life expectancy of over 100,000 hours[ii]. That life expectancy is, however, based on the rated life of a single LED at 25°C and does not take into account the increased operating temperature of an LED enclosed in a fixture. As a result, the actual life tends to be much lower than the rated life[iii].

The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) has reccomends that the useful life of an LED ends when light output falls below 70% of its original value. Figure 2 shows, roughly, the correlation between operating temperature and light output for an LED fixture similar to ours.

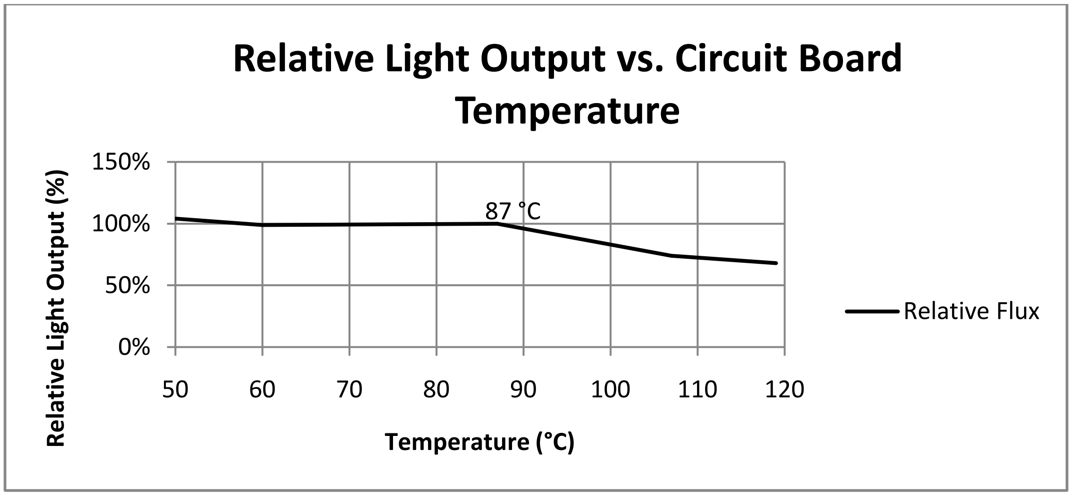


Figure 2: Relative Light output vs. Circuit Board Temperature[iv]

From Figure 2, it can be seen that light output remains consistent below 87°C, and, as a result, it is difficult to estimate their lifetimes. For fixtures operating above that temperature, however, the estimated lifetime is as low as 2100 hours[v], approaching that of an incandescent light bulb[vi]. Because of this, we will set the upper temperature limit for our fixtures at 87°C.

Because of this temperature limit, we designed an experiment to estimate the operating temperature of our final prototypes. In our experiment, we measured the operating temperature of our LED's at our circuit's operating current without any devices added to aid heat dissipation. If the LED temperature climbs above 87°C, then we would be required to add some sort of heat dissipation solution (i.e. heatsink, fan, or etc.) to our prototypes. If the temperature remains low, however, we would probably not need to add anything to increase heat dissipation because these add cost and complexity while we aim to create a light that is both cheap and simple.

Regardless of the outcome, we must still perform heat experiments on our final prototypes. The purpose of this experiment was simply to give us an idea of whether or not we needed to design a heat dissipation system into our first prototypes.

Initial Experiment Results

We performed the experiment according to the procedure laid out in Appendix H. Figure 3 below shows the temperature of the box, oil with LED's and the control oil over the course of the day, and Table 2 shows the average operating temperature both inside of the box and the oil.

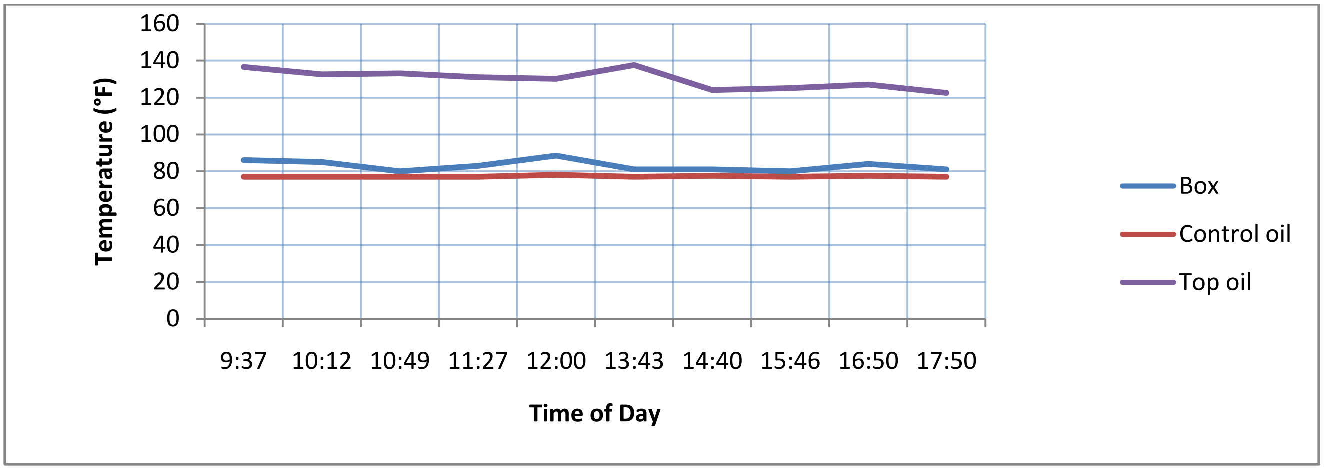


Figure 3: Time of Day vs. Temperature

	Box	Oil
Average Temperature (°C)	28.2	54.27

Table 2: Average Operating Temperature (°C)

Looking at the temperature of the LED's in both the box and the oil, we saw that the oil temperature was higher, and so we used the oil temperature to predict the worst-case scenario. The average oil temperature remained well below our limit of 86°C, so we concluded that heat dissipation would only be a minor problem for our prototypes.

Circuit Design DE

Introduction to AC Rectifying Bridge

Development

Experiments

Inductor vs. Capacitor

Structural Frame

Structural frame is the name we've given to the method by which a task light is held in place. For most machine tools, this boils down to an adjustable arm with the light head on its end. We took three steps to investigate this aspect of the light. First, we researched current structural frames. Second, we brainstormed for new designs, and finally we decided what kind of structural frame to use for our prototypes.

Factory Research

Since we didn't know much about different structural frame, we started by researching in the REM factory. We then used this information to form our brainstorming session. So we walked down to the REM Factory floor and found the six structural frames currently in use. We then analyzed each arm's degrees of freedom, stability, and method of attachment (if any) to the machine tool.

Figure 4: Incandescent fixture used on a lathe

Figure 4 shows and incandescent fixture that we found attached to an automatic lathe. This frame has five degrees of freedom and is kept stable by friction bearings located at each joint (there are four) of the arm. This frame is attached to the lathe by a simple L-bracket at the base of the arm.

An sidenote to this situation is that the lathes came with a different light installed in a completely different manner. The original light had two flourescent tubes mounted directly above the workpiece and tool area, and it was mounted inside of an immovable housing. When we asked why the lights had been switched, we were told that the flourescents had several issues: they were difficult to change, they weren't flexible enough to throw light where that they needed to, and the bulbs were expensive to replace and burned out often. While only the flexibility can be addressed by the structural frame, we kept the other two issues in mind as we designed our fixtures.

Figure 5: Planing Machine Halogen

In Figure 5 above, we show a halogen light mounted on a planing machine. This arm has only four degrees of freedom, the least of any arm that we looked at. Like the lathe incandescent above, this fixture is held in place by friction bearings at each of the joints. However, unlike the incandescent, this arm   The arm is attached directly to the machine tool's housing by four screws.

Figure 6: LED Flashlight used at the tapping and countersinking station

Figure 7: LED Flashlight in use

This next light (Figure 6) is a relatively recent addition to the factory. It is an LED flashlight that is used mainly at night by the tapping and countersinking stations (Figure 7). For degrees of freedom, it has four, and has only a single friction bearing to hold it in position. It also isn't actually attached to the machine, it just lays on the worktable during use.

Figure 8: Four-bar arm attached to a vertical milling machine

This next frame (Figure 8) is very similar to the setup seen on many drafting tables. The arm consists of two four-bar systems attached together and driven by springs. When properly adjusted, the springs can hold the arm in a variety of useful positions. This particular arm, however, was not very well adjusted, and thus it was difficult to get it to stay put.

In any case, the four-bar arm has five degrees of freedom and, in addition to the spring joints, two locking friction joints. It is attached to the machine in with the same L-bracket configuration as the incandescent on the lathe.

Figure 9: Halogen Gooseneck

The final structural frame that we analyzed was this gooseneck (Figure 9) used on several different machines throughout the factory. The gooseneck has five degrees of freedom: X, Y, and Z planar; and X and Y rotational.   It can be attached to a machine tool pretty easily via four bolts at its base. In our interviews with the workers in the factory, we found that they preferred this kind of arm because they can easily move the light to wherever it needs to be, and it stays there.

Brainstorm for new designs

From our research of current structural frames in the factory, we saw that there are essentially four important aspects of the structural frame: location of the attachment to the machine, method of attachment, adjustability of the arm, and the ability to lock the arm in place. So, in each of these areas, we listed all of the possible solutions that we could think of (Figure 10).

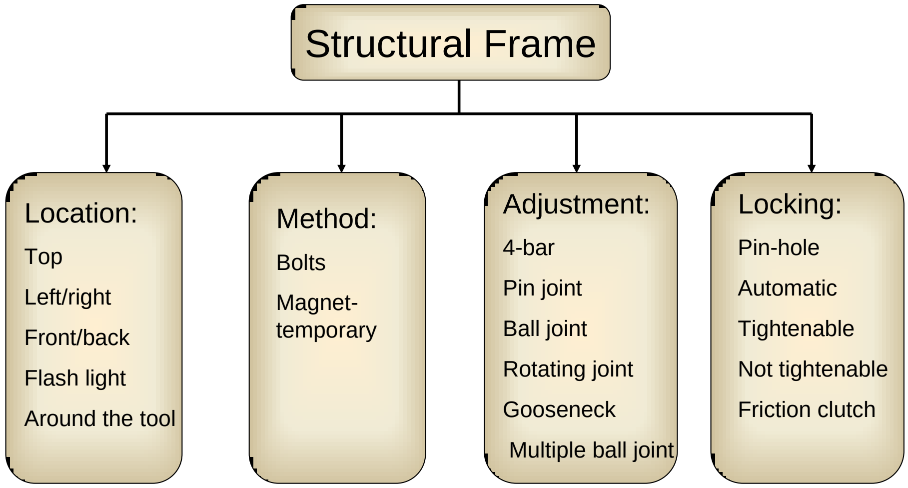


Figure 10: Structural Frame Possibilities

After we made this list, we brainstormed for some new ideas to add onto this list and came up with four basic ideas: fixing the arm to the machine with magnetic grips, attaching a ball joint to the light head, using segmented coolant tubes as a part of the frame, and putting a ball joint at the base of the arm.

Magnetic Grips

Magnetic grips are currently used to fix the workpieces to the worktable in the factory. We like it as a base because it is very stable when engaged, but can also be disengaged and moved if necessary

Ball Joint on the Light Head

This idea comes from talking with the workers in the REM factory. They said that, in addition to the arm being easy to adjust, the head of the light should separately adjustable. So we thought about putting a ball joint in the head of the light to make it more flexible and adjustable.

Flexible Coolant Tubing

We thought about using the flexible coolant tubing (shown below in Figure 11) that's commonly found in various milling machines for a few different reasons, foremost among them being that it is easy to find, stays in whatever position it is placed in, and has the additional feature of being able to fairly easily adjust the length of the arm.

Figure 11: Flexible coolant tubing segment

Final Directions

In our conversations with them, the workers let us know that, of the structural frames currently in use, their favorite was the gooseneck. So we took that idea and split into two directions when creating our prototypes. The jointed bar design used the segmented coolant tubing because it is relatively easy to attach and remove, while the stepped cone and rounded bar designs both use a regular gooseneck.

Light Quality CK

One of our main concerns as we began the design process was the quality of the light coming out of our fixtures. Will they be bright enough? Will the light be comfortable for the workers? If the answer to either of these questions is no, then our designs will have failed.

So we divided the planning phase of light quality into two sections. The first was an interview with the workers at REM about what they want to see in a task light, and the second was photometric measurements of current task lights that allowed us to create quantified requirements for our own prototypes to meet.

Research

Factory Interview

We interviewed the workers at REM to find out what they thought about the current lighting in the factory. We asked them several questions about the quality of the LED flashlights and incandescent task lights that are currently being used in the factory. For the full set of interview questions, see Appendix A: Experiments and Tests Opinions.

From the interview, we found that they want to see the following qualities in any new factory task lighting:

- Bright enough, but not too harsh
- Less heat output from the head
- Sufficient illumination area

Photometrics

In order to determine the illuminating parameters of the current lights quantitatively, we performed some basic photometric experiments. See Appendix XX for more information about how the tests were operated and Appendix XX for the results of these experiments.

Based on our measurements of the current lights and our interviews of the workers, we developed a set of specifications that we will use to evaluate the effectiveness of our prototypes.

- Brightness: Center brightness is about 10,000 lx at workpiece. (Average working distance is 20-40cm)
- Beam Angle: 50-60 degrees
- Harshness: LED's must not be directly visible while in the working position
- Beam Spread: soft transition between light and dark; the curve which shows the relationship between the luminosity and the angle should be widely spread.

Fabrication Stage

The fabrication stage of our project is, well, fairly self-explanatory. During the third, fourth, and fifth weeks, we worked at HUST to fabricate our designs for the structural frame and each of the three light head shapes. Most of the fabrication work was done with the tools at the HUST Engineering Training Facility, and the rest of it was done by either workers in the market of at the East 1 manufacturing facility. At the end of this stage, we had produced three different prototypes.

Structural Frame Fabrication

In fabricating the structural frame, we took two separate approaches for the different prototypes. In keeping with our earlier decision, both of these approaches were goosenecks. The first approach we'll call the segmented approach and we'll call the second approach the classic gooseneck approach.

Segmented Approach

The segmented approach used a special kind of flexible coolant tubing. In the States, this tubing is known as Loc-Line tubing, and can be found on almost all kinds of machine tools. The tubing is popular for a number of reasons, most of which make it prefect for application as a gooseneck. The first of these reasons is that it is both flexible and stable, and the second is its modularity. Loc-Line is composed of a series of small segments(XXX). A section of tubing can be lengthened or shortened as needed by simply attaching or detaching these segments.

One of our original goals with the Jointed Bar design was to make a series of light heads that could be attached and detached as required. The Loc-Line segments do this well, so we designed the Jointed Bar with a protrusion that's the same size and shape as the male tubing segments.

We made the base for the segmented structural frame from a simple piece of 1cm thick aluminum. The coolant tubes that we found came with a threaded section, so we just drilled a hole in our aluminum block and matched the threading (XXX).

Classic Gooseneck

For both the Stepped Cone and the Rounded Bar, we took a classic gooseneck approach to the structural frame. By classic gooseneck, we mean that we simply found an existing gooseneck and attached it to our light head. The only gooseneck that we could find in the market was another kind of coolant tube that was internally threaded on either end. Neither our lights nor the ball joint that we planned to used at the base had this threading, so we had to make a couple of additional attachment pieces.

The first piece that we made connected the gooseneck to the ball joint. Both of these pieces were internally threaded, so we made a double-threaded connector. The second piece attached the light head to the gooseneck. The gooseneck was, again, internally threaded, but the light head needed to be bolted flat. So, we made a piece that was threaded on one side and flat with holes in it on the other. The engineering drawings for both of these connectors can be found in Appendix B: Engineering Drawings.

Shape Fabrication

Rounded Bar

The first shape, the rounded bar, is was chosen for its simplicity. It is, in theory, just a rectangular prism whose back is rounded to provide a simple focusing mechanism for the LED's (see Figure 12 below). In addition to this simplicity, our prototype involves another layer of modularity with the PCB's being able to slide in and be replaced easily. This feature helps to strengthen a weak point in the circuit design by allowing any single leg of the circuit to be replaced easily. The creation of the prototype can be divided into three steps: printed circuit board (PCB) design, computer-aided housing design, and prototype fabrication.

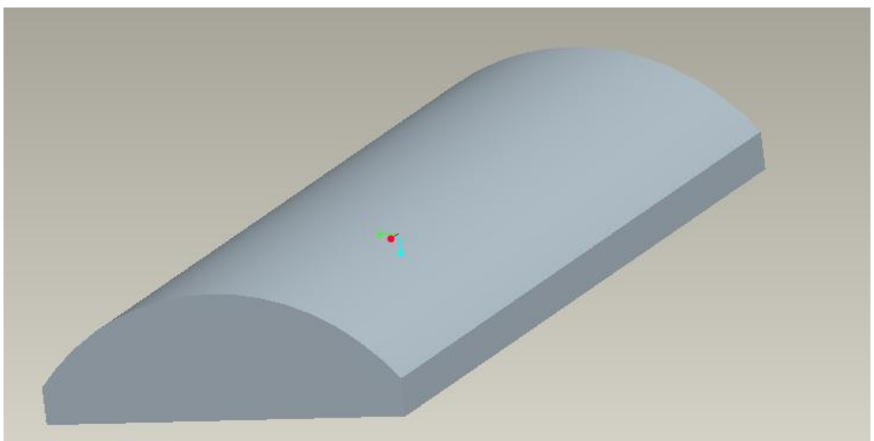


Figure 12: Rounded Bar Conceptual Shape

CAD Design CK

There are two basic parts of the rounded bar: the frame and the slide tracks. Below, in XXX, the final CAD model of the rounded bar is shown. Here, the ideal shapes of both the slide tracks and the frame are shown. Unfortunately, we weren't able to realize these exact shapes in our final prototypes.

PCB Design

When designing the circuit boards for the rounded bar, we pursued modularity. We split the circuit up into six simple segments and arranged them symmetrically across the inside of the bar. Four of these segments, representing the outer legs of the rectifying circuit, blink at 50 Hz, and the center leg is split into two constantly powered segments. With the PCB's split into these two groups, we will only have to print two different types of circuit boards.

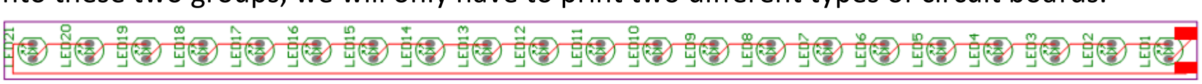


Figure 13: Protel Diagram of the blinking PCB

We created all of our design s using Protel 99 SE, a simple program that allows us to do both PCB design and basic simulations. In Figure 13 above, the PCB for the outer legs is shown. The wiring is shown in red, the edge of the board is shows in purple, and anything in red is the wiring on the board. There are 21 LED's lined up in series along the length of the board, and there are contacts on the right side that will allow the individual boards to be removed as necessary. Four of these PCB's will be used in each prototype.

Figure 14: Protel Diagram of the constant PCB

Figure 14 shows the Protel diagram of the constantly shining circuit board (see above for the color coding scheme. There are 18 LED's and one 50V, 22µF capacitor here. Putting two of these boards together will give is the center leg of the circuit board with a total of 36 LED's and 2 capacitors. This is a slight modification on the original circuit design, with two smaller capacitors instead of one larger one. To check for any problems before we realized the design, we set the modified circuit up with a breadboard and let it run for a few hours. There were no problems in that time period, so the modified design was accepted.

Fabrication Methods

We divided the fabrication of the rounded bar into three sections: frame, slide tracks, and attachment to the structural frame. Finally, we assembled each of these sections together to create the final prototype.

We created the frame of the rounded bar from a 9cm x 21 cm piece of .75mm sheet iron. First, we cut this piece from the stock sheet using a large sheet metal cutter in the HUST Engineering Training Facility. Then, we drilled holes: one in the center for wiring and two lines set 3 cm in from either end for attaching the slides. Please see XXX for detailed drawings.

Then, with the aid of one of the workers in the Facility, we bent our piece into an arc with a roughly 25cm diameter. We say roughly because there wasn't a bending tool available that could create a perfect 25 cm radius. Instead, we used a large die-bending machine to make seven small bends in the metal that apprximated a 25 cm radius. We used the same machine to make the final right angle bends along each side of the bar. The final frame is shown here in XXX.

The slide tracks hold the PCB in place. Originally, the slide tracks were supposed to be similar to the tracks shown in Figure XX. The LED strip lights that are currently being used in the REM facility use these same tracks for the exact same purpose (they are not, however, removable as we would like them to be). However, when we went shopping, we were unable to find a shop that sells these kinds of tracks so we were forced to come up with another plan.

The next idea for the slide tracks was to make them out of scrap sheet metal using the hand tools available in the Metal Forming Practice Room at the Training Facility. Since we were using small pieces of scrap for this design, we changed the shape of the tracks slightly. Instead of attaching each PCB with one long track, we made two separate pieces for each track (see XXX). We made several of these pieces and even got as far as attaching them to the frame before we realized exactly how difficult it would be to electrically isolate the circuit boards from the frame if everything were made of metal. So we finally nixed this idea in favor of the final one.

The slide tracks that we ended up using are shown here in XXX. We had seen them in the market when we were initially looking for slide tracks but dismissed them then because they weren't the exact shape that we had been looking for. When we realized the difficulties of using metal slide tracks, however, these were suddenly a pretty viable solution. This kind of track is actually household electrical conduit, commonly used to hide lower-power electrical cable. For us, it was convenient because it separates into two sections that can slide together, thus emulating the original design. We attached one side to the PCB and the other to the frame. This, however, is not ideal because if the PCB breaks, we'd have to discard one half of a length of conduit to replace it; but it demonstrated the functionality for our prototype.

Ideally, we would have put each PCB on its own track, but because of the size of the conduit that we used (1cm x 2 cm), six lengths of conduit simply would not have fit into the frame. So, on two of the pieces of conduit, we glued two PCB's right next to each other (See Figure XX).

The next pieces of the rounded bar that we created were the contacts and wiring. For the contacts, we used pieces from a PCI slot connector; the male pieces were pulled from inside the connector, and the female pieces were just sections of the connector that we cut off. For the wiring, we used .5mm copper wire. Figure 15 below shows the wiring diagram that we used and Table 3 shows how the contacts were connected.

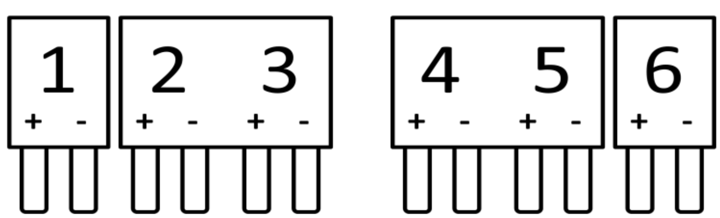


Figure 15:Wiring Diagram for Rounded Bar

	1	2	3	4	5	6
+	Black	1 , 3	White	5	2	5
-	2	5	2	White	4 , 6	Black

Table 3: Table showing the connections between contacts. White and Black refer to the two different sides of the AC power input

The final piece that had to be created was the connection between the structural frame and the light head. For this, we used a piece of .3mm sheet metal that we bent into a rough box. Holes in the bottom allowed for bolting to the light head frame and holes in one side allowed for connection to the structural frame.

Final Prototype

Finally, we assembled the whole prototype. The female contacts were glued in place on top of plexiglass spacers so that they mated with the contacts on the PCB's. All other assenbly was done with 3mm diameter bolts and nuts. The final prototype is shown in XXX below.

Stepped Cone

When we were brainstorming for different shapes, the stepped cone came up as an extension of the stepped pyramid design. It was originally intended to be focusable via a collapsible function. However, further investigation showed us that simply collapsing the frame wouldn't change the focus, so we abandoned that concept.

CAD Design

The stepped cone, shown in Figure 16 below, has three basic layers: the outer ring, the inner ring, and a disc-shape backplate. Each layer is 20mm deep, and from the disc to the top layer, the outer diameters are 110mm, 130mm, 150mm respectively. Finally, the outer and inner rings are both 10mm wide while the disc layer has a solid center.

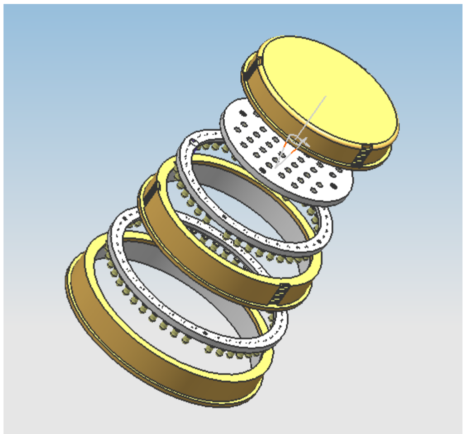


Figure 16: Exploded View of the stepped cone design

Different lights have different illumination areas, but the workers don't always need the same illumination area. We designed the stepped cone with this in mind. Each layer can be adjusted relative to the other layers in order to either narrow or widen the beam. In the CAD model, this was accomlished via a series of pawls and hooks at three locations on the edge of each layer (Figure 17).

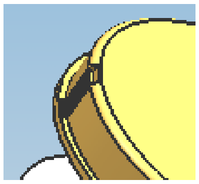


Figure 17: Adjustable Hooks

PCB Design

Our circuit design, as explained above consists of many LED's in series. This, unfortunately, means that if a single LED burns out completely, then all LED's that are in series with it will cease to function. In order to help mitigate this problem, we have designed the stepped cone's circuit board to be modular. Each layer of the design has a circuit board that can be easily pulled out and replaced.

Our circuit design can be divided pretty clearly into five groups: the four blinking outer legs, and the constant center leg. The backplate's circuit board has two of the blinking legs and the capacitor from the center leg on it. In order to help mitigate any blinking, the two legs on the backplate are out of phase with each other. That is to say that when one of them is on, the other is off. By putting these two opposite legs close to each other, we hope to make any blinkin less noticeable.

The 36 LED's in the middle layer all belong to the central, constantly shining leg. They are separated from the capacitor because, basically, the capacitor is too large to fit on the 10mm wide middle circuit board. Finally, the outer ring holds the remaining two legs which blink out of phase with each other, much like the backplate LED's.

Fabrication Methods

As we finally moved towards making a prototype of the stepped cone, we considered how to actually make it collapsible. The hooks in the CAD model required tolerances that were simply too difficult to realize, so we instead put a screw thread in between each layer. Making a full-scale model of this idea, however, proved to be too expensive, so we decided to make two different prototypes, a small one that would demonstrate the collapsibility, and full-scale one that we could install and test for light output.

Figure 18: Small Stepped Cone Prototype

The small prototype, shown in Figure 18 above, was milled out of 5cm bar stock aluminum. The individual layers are connected by a simple screw thread with a pitch of 2 mm. This threading would allow the the workers to adjust the beam of the light by simply screwing or unscrewing the individual layers. To keep the wires that hold the different layers together from becoming tangled during the unscrewing process, we plan to put connectors on the wires so that they can be removed during the screwing process.

Figure 19: Large prototype shell

The shell for the full-scale prototype (Figure 19) was made out of 0.75mm sheet metal and soldered together by a skilled worker that we hired in the Wuchang market. To attach the circuit boards to the shell, we found some plastic motherboard risers and attached them first to the shell and then to the PCB's.

To attach to the head to the structural frame, we first tried bolting on a ball joint (<HERE>) in an attempt to make the light more flexible. The ball joint, however, proved too heavy for the gooseneck, so we ended up fabricating a simple, inflexible connection to the light head similar to the rounded bar's connection.

We also considered attaching a plexiglass cover to the front of the light to protect it from chips coming off of the machine. However, with the plexiglass attached, the light was sealed, and the internal temperature increased, causing the capacitor to overheat and explode. We decided that this was bad and removed the plexiglass from our final design.

The Actual Prototype

Our final prototype of the stepped cone is shown here in <HERE>.

Jointed Bar DE

PCB Design

CAD Design

Fabrication Methods

Materials

Difficulties

Actual Prototype

Testing Stage

In the testing stage, we returned to the REM factory in Wuxi and performed several tests on each prototype, including operating temperature, photometrics, power consumption, and finally a field test in the factory.

Tests Done and Analysis

Modifications Made

Results

Structural Frame Decision

Final Design Choice

Heat Experiment Results

Light Output Results

Factory Worker Results

Interview Questions

Question		Light area (enough or not)	Housings (hot or not)	Luminous intensity (harsh or not)	Structural frame (flexible or not)	Light quality (blinking or not)	Comparison with common lights (better or worse)
Worker 1	Jointed Bar	Not enough	Not hot at all	Not enough but harsh	flexible	Not blinking	Better
	Rounded Bar						
	Stepped Cone						
Worker 2	Jointed Bar						
	Rounded Bar	Enough	Not hot at all	Enough and not harsh	flexible	Not blinking	Better
	Stepped Cone	Enough	Not hot at all	Enough and not harsh	flexible	A little blinking	Better
Worker 3	Jointed Bar	Good, but not enough	Not hot at all	Enough and not harsh	Flexible	Not blinking	Better
	Rounded Bar	Enough	Not hot at all	Enough and not harsh	Less flexible because of heavy head	Not blinking	Better
	Stepped Cone	Enough	Not hot at all	Enough and not harsh	Less flexible because of heavy head	Not blinking	Better

Table 4: Results of final factory interview

Conclusions

What we've learned

Future Recommendations

This section gives our suggestions for what future work should be done with our designs. We've divided this into three parts. First, we'll talk about the problems that we've noticed with our designs (mistakes we've made, design choices that could be better, etc.), and then we'll talk about other ideas that we've had, but didn't have the time, resources, or expertise to explore in this project. And finally, we'll give some advice about how future work, experiments, etc. in general should be conducted.

Current Issues

There were a number of issues with each design; some of them we were able to fix, and others will need to be fixed in a future iteration. The section below details these issues and our suggestions for each design.

Rounded Bar

First off for the rounded Bar, both the frame and the PCB's were designed to be 21cm long. So when we installed the slot connectors on the end, which took up about 2 cm, the PCB's stuck out of the end of the frame. This should be fixed future iterations by simply making the frame a little bit longer.

Another problem that we ran into was that the flange that we had designed to prevent glare simply wasn't long enough. So, in future iterations, these flanges should be made long enough to prevent the light from directly reaching the workers' eyes.

The next issue came up in the worker feedback. The light coming from the fixture was visibly blinking in both the rounded bar and stepped cone designs, but not in the jointed bar design. We think that this is because the blinking LED's in the Jointed Bar were placed so close together. So to address this, we suggest changing the PCB design to have mix to have LED's that blink out of phase next to each other(XXX). This would not change the modularity of the design, as all of the individual strips of LED's would still be identical.

In fact, the only difficulties that this change could produce would be with the contact design. Because two separate legs would be running on the same circuit board, each PCB would need four contacts. As it stands, the contacts are too wide to fit four on a board, so a new, smaller kind of contact would have to be found.

Structural Frame

Ball Joint Attached to the Light Head

We tried attaching a ball joint to the head of the stepped cone prototype, but that failed because the gooseneck could not support the extra weight. To solve this, we suggest that either a plastic ball joint be used or the weight of the light head be reduced.

Reducing the weight of the light head could be achieved in a couple of different ways. The simplest would be to make the frame out of a lighter material. This would work especially well for the stepped cone and rounded bar designs because their prototype frames were made out of sheet iron, which is a very dense material. If they were made out of aluminum or even plastic, their weights would be cut significantly.

The second weight reduction method that we suggest is to remove unnecessary material from the frames. In every one of the designs, there are places where holes could be added into the frame simple for the sake of removing material. For the stepped cone design, these holes would serve the second purpose of providing ventilation when a cover is atttached.

Gooseneck

The only gooseneck material that we could find in the market was an oil tube. As such, it was not really intended to hold weight in the way that we were using it and it was difficult to get it to stay in position without falling down. When we attached the ball joint to the head in the stepped cone design, the head became far too heavy and fell nearly every time. There are two approaches to fixing this problem, and we believe that any future work on these designs should use both of them.

The first approach would be to make the light head weigh less. This could be done to both the stepped cone and rounded bar designs by removing unnecessary material or making the fixture out of a lighter material.

The second approach would be to strengthen the gooseneck. Upon inspecting the current fixtures, we found that few of their arms were completely made of the gooseneck material; many of them had a short (10-12 cm) section of rigid tubing at their base. If we found a gooseneck with a similar design, it might be more stable

Magnetic Grips

When brainstorming for the structural frame, we thought about attaching the arms to the machine via a magnetic grip. Ideally, this grip would be strong enough to hold the weight of the entire fixture, and it could also be easily disengaged. Similar magnets are already used in the factory to fix a workpieces to worktables, and adapting those magnets should be relatively simple.

Spring Board Idea DYJ

Experiments

Models

Other Reccomendations

Retail Price

After interview the purchaser and foremen at REM, we found that they have only ever used four kinds of lights, the incandescent light, the halogen light, the fluorescent light and the LED flashlight. The price of the lights is shown in

	Bulb price	Light price	Average Bulb Life
Incandescent light	1 RMB	20 RMB	Less than 1 week
Halogen light	15 RMB	50 RMB	More than 1 year
LED torch	n/a	32 RMB	Unknown

Table 5: Price of the lights currently used in the factory

Many of those We also did some research on the internet to find more information about the cost of a new fixture. The lights that we found (see Table 6 below) varied in price from 50 RMB to 300 RMB.

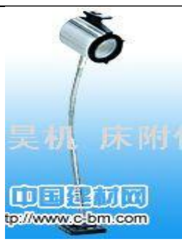
	Price	Structural frame	Features
	50 RMB	Many ball joints and a gooseneck	Many degrees of freedom
	80RMB	One ball joint and a gooseneck	Long Life
	300RMB	Many ball joints and a gooseneck	Many degrees of freedom Long Life

Table 6: Research on the current price of lights

From this research and suggestions from our sponsor, we suggest that, in order to be competitive in the marketplace, Future LED products should be sold at a price of 60 RMB. If sold in the United States, that price should be increased by a significant margin. Compared with the prices for our prototypes (See Table 7 below and Appendix D: Accounts for more detailed information), this is an ambitious goal, but we feel that with a larger-scale production scheme, it will be an attainable one.

Design	Final Prototype Cost
Jointed Bar	¥396.39
Stepped Cone	¥221.92
Rounded Bar	¥160.67

Table 7: Final Protoype Costs

More rigorous photometrics testing

Improvements to Heat Dissipation Expt.

Thermocouples attached directly to the leads

References

Appendix A: Experiments and Tests

Power Test

Workers' Opinions

We designed our interviews with the workers to focus on five different areas: Bulb life, illumination area, brightness, heat output, and the number of defects produced while using task lights. We also asked a few questions that were specifically about the LED flashlights currently used in the factory.

Interview Questions

Lifetime

- How often do the bulbs need changing?
- Why do the bulbs break?

Heat

- Are they hot or not?

Brightness

- Do they illuminate enough now?
- and the illumination area enough or not?
- Are they too bright or not?
- Do you want to be able to see the bulb?

Usage

- We've notice that currently lights don't get used very much. Why?
- Are there any methods currently used to clean the fixture?
- Is the fixturing convenient?
- How often do you use the lights?
- Why don't you use the light?

Quality Control (this question was only asked to the quality control workers)

- Is there different in the average number of defects produced by the day shift vs. that of the night shift

Yellow Flashlight

- Charge time/battery life
- More convenient than traditional solution?
- How could it be better?
- Do you prefer the LED color over the incandescent/halogen color?
- What do you use the light for?
- How much area needs to be illuminated?

We made the following form to record the findings of our interviews

<table>
<tr><th colspan="3">Questions</th><th>Worker 1</th><th>Worker 2</th><th>Worker 3</th></tr>
<tr><td rowspan="6">Fixed light</td><td>1</td><td>Hot or not</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>Parts that need light</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>Light area (enough or not)</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>Frequency of changing bulbs</td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>Luminous intensity</td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>The ratio of defects</td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Yellow torch</td><td>8</td><td>Light area (enough or not)</td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>Convenient or not</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>Hot or not</td><td></td><td></td><td></td></tr>
<tr><td>11</td><td>Luminous intensity</td><td></td><td></td><td></td></tr>
</table>

Photometrics Test

Appendix B: Engineering Drawings

Appendix C: CAD Models (.stl)

Appendix D: Accounts

Here we have included an spreadsheet of our spending for each prototype

Jointed Bar

Item	Qty.	Price per Item (¥)	Extended (¥)
Light Head			
Rapid Prototype Housing	1	250.00	250.00
2mm Nails (for hinges)	4	0.05	0.20
2mm Acrilic Sheet	1	10.00	10.00
PCI Slot Connector	1	11.00	11.00
PCB	1	25.00	25.00
White LED	120	0.30	36.00
Capacitor (100µF, 100V)	1	1.00	1.00
Single-strand Copper Wire, .5mm Ø (per meter)	0.25	0.56	0.14
Coaxial Wire	5	0.50	2.50
2 Prong Electrical Connector	1	2.50	2.50
220 Volt AC to 12 Volt DC Transformer	1	15.00	15.00
12 Volt, .26 Amp DC fan	1	5.00	5.00
AB Glue (per gram)	4	0.09	0.35
Solder			3.00
		Total	361.69
Structural Frame			
Jointed Arm	1	10.00	10.00
Hose Clamp	1	3.00	3.00
Aluminum Connector (material, per kg)	0.05	33.00	1.65
Aluminum Connector (labor)	1	10.00	10.00
3mm philips head bolt	2	0.05	0.10
Aluminum Baseplate (material, per kg)	0.15	33.00	4.95
Aluminum Baseplate (labor)	1	5.00	5.00
		Total	34.70
		Grand Total	¥396.39

Rounded Bar

Item	Qty.	Price per Item (¥)	Extended (¥)
Light Head			
.75 mm White Iron (9 cm x 21 cm)	1	6.3	6.3
.3 mm White Iron (14 cm x 7 cm)	1	3	3
84 cm Square Plastic conduit (1 cm x .5 cm)	1	4.2	4.2
PCI Slot Connector	1	11	11
Blinking PCB	4	7.5	30
Constant PCB	2	7.5	15
White LED	120	0.3	36
Capacitor (22µF, 50V)	2	0.2	0.4
Bolt, 3mm	16	0.05	0.8
Nut, 3mm ID	16	0.01	0.16
Pop rivet, 3mm	4	0.1	0.4
Single-strand Copper Wire, .5mm Ø	0.5	0.56	0.28
Electrical Tape (per meter)	0.2	0.15	0.03
Stranded Copper Wire, 1mm Ø (per meter)	3	1.1	3.3
Solder			3
		Total	113.87
Structural Frame			
Gooseneck	1	15	15
Ball Joint assembly	1	5	5
Bolt, 6mmØ	4	0.1	0.4
Nut, 6mmØ	4	0.05	0.2
Washer, 6mm ID	4	0.05	0.2
White Iron Sheet, .75mm, 9cm x 14cm	1	6	6
		Total	26.8
Gooseneck Connector A (Threads and Bolts)			
Aluminum	1	2.5	2.5
Labor	1	7.5	7.5
		Total	10
Gooseneck Connector B (Double-Threaded)			
Aluminum	1	2.5	2.5
Labor	1	7.5	7.5
		Total	10
		Grand Total	**¥160.67**

Stepped Cone

Item	Qty.	Price per Item (¥)	Extended (¥)
Light Head			
Iron Shell	1	50	50
LED's	0.3	120	36
PCB's	3	24.5	73.5
Capacitor(47µF,100V)	1	1	1
Metal Motherboard Riser A	6	0.2	1.2
Metal Motherboard Riser B	3	0.5	1.5
Plastic Motherboard Riser	9	0.2	1.8
Aluminum(Right Angle)	1	3.6	3.6
Single-strand Copper Wire	0.5	0.56	0.28
Stranded Copper Wire	2	1.1	2.2
Solder			3
		Total	174.08
Structral Frame			
Gooseneck & Ball Joint	1	15	15
Ball Joint Assembly	1	5	5
Bolt(ϕ6mm)	8	0.1	0.8
Nut(ϕ6mm)	8	0.05	0.4
Washer, 6mm ID	8	0.05	0.4
White Iron Sheet, 0.75mm, 9cm x 14cm	1	6	6
Bolt(ϕ3mm)	4	0.05	0.2
Nut(ϕ3mm)	4	0.01	0.04
		Total	27.84
Gooseneck Connector A (Threads and Bolts)			
Aluminum	1	2.5	2.5
Labor	1	7.5	7.5
		Total	10
Gooseneck Connector B (Threads and Bolts)			
Aluminum	1	2.5	2.5
Labor	1	7.5	7.5
		Total	10
		Grand Total	**¥221.92**

Appendix E: Weekly Work Schedules

Week 2

<table>
<tr><th colspan="2">Monday</th><th colspan="2">Tuesday</th><th colspan="4">Wednesdays</th><th colspan="4">Thursday</th><th colspan="3">Friday</th></tr>
<tr>
<td colspan="2" rowspan="2">In REM
Visit and discuss
The lecture of
MR. Barry</td>
<td colspan="2" rowspan="2">Trip to the electric shops/ market
(A+B+C)</td>
<td rowspan="4">Bread board Test
(A)</td>
<td rowspan="4">LED Heat Test
(C)</td>
<td rowspan="2">Collect the decision matrix
(B)</td>
<td>Collect current solution of S.F.(C)</td>
<td rowspan="4">Bread board test
(A)</td>
<td rowspan="4">LED Heat Test
(C)</td>
<td rowspan="4">Photometry of the light quality
(C)</td>
<td>Create decision matrix of shapes
(B)</td>
<td rowspan="4">Bread board Test
(A)</td>
<td rowspan="2">Analyze the decision matrix of shapes
(B)</td>
<td rowspan="2">Decide if HD is a problem
(C)</td>
</tr>
<tr>
<td>Research on the H.D and LQ(C)</td>
<td rowspan="2">Interview the workers
(B)</td>
</tr>
<tr>
<td>Bread board
(A)</td>
<td>Work plan
(C+B)</td>
<td rowspan="2">Bread board Test
(A)</td>
<td>BS of interview questions
(C+B)</td>
<td colspan="2">Analysis of current design
(C+B)</td>
<td colspan="2">Organize the problem sheets(C+B)</td>
</tr>
<tr>
<td colspan="2">Brainstorm of the shapes
(A+B+C)</td>
<td>Analyze possible shapes
(C+B)</td>
<td colspan="2">Brainstorm of structural frame
(A+B+C)</td>
<td>Analyze the result of interview
(B)</td>
<td colspan="2">Preparation to the presentation
(A+B+C)</td>
</tr>
</table>

Date: June 23th ---June 27th plan

Groups: A =David B=Lu Wei & Deng Yujun C=Chris & Guo Huimin

Brief Introduction:

1. S.F. = structural frame 2. H.D. = heat dissipation 3. L.Q. = light quality

Week 3

<table>
<tr><th></th><th>Monday</th><th colspan="3">Tuesday</th><th>Wednesday</th><th>Thursday</th><th>Friday</th></tr>
<tr><td rowspan="2">Morning</td><td rowspan="4">Travel from Wuxi to HUST</td><td colspan="3">Travel to HUST</td><td rowspan="4">CAD: Build model of each each shape</td><td>CAD</td><td>Presentation</td></tr>
<tr><td colspan="3">Buy capacitors at the market</td><td>Choose shapes</td><td></td></tr>
<tr><td rowspan="2">Afternoon</td><td rowspan="2">Finish circuit design</td><td rowspan="2">Discuss design specifications (L.Q)</td><td rowspan="2">Research epoxies and polycarbonate (Fabrication)</td><td>PCB Design</td><td rowspan="2">Plan next week (Week 4)</td></tr>
<tr><td>PPT work</td></tr>
</table>

Week 4

<table>
<tr><th></th><th colspan="2">Monday</th><th>Tuesday</th><th>Wednesday</th><th colspan="2">Thursday</th><th>Friday</th></tr>
<tr><td rowspan="2">Morning</td><td rowspan="2">Print PCB's in market</td><td rowspan="2">Make and plan shopping list</td><td rowspan="4">Go to Market for material in 2 groups</td><td>Application for machines in training center</td><td rowspan="2">Fabrication housing (rounded bar & stepped cone)</td><td rowspan="2">Presentation preparations</td><td rowspan="2">Presentation preparations</td></tr>
<tr><td>Fabrication housing(rounded bar)</td></tr>
<tr><td rowspan="2">Afternoon</td><td colspan="2">Review structural frame brainstorm</td><td rowspan="2">Fabrication housing(rounded bar & jointed bar & stepped cone)</td><td rowspan="2">Fabrication housing (jointed bar)</td><td rowspan="2">Decide Final solution for structural frame</td><td rowspan="2">Give presentation</td></tr>
<tr><td colspan="2">Fabrication of housing preparation</td></tr>
</table>

Week 5

Week 6

Week 7

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning	Everyone does preparations for the final document	Continue the final document	Prepare for the final presentation and finish the PPT	Distribute the task and modify the PPT	Final Presentation
Afternoon	Prepare the questions for the final presentation	Discuss the main part of final document		Rehearsal	Continue the final document

Appendix F: Original Project Proposal

MQP Proposal

REM LED Lighting

David Embree
Christopher Kingsley

Registration #MQP YR – CH85

Sponsored by: Dr. Yiming Rong
Mechanical Engineering

Al Barry
Rapid Engineering Manufacturing

Submitted: 4/28/08

Abstract

This proposal will describe, in detail, the plan and basis for the Rapid Engineering Manufacturing (REM) LED Lighting MQP. We first introduce the theoretical basis of how LED's work, and then the economic justification for switching to LED-based lighting systems. We also present some background information on REM, the company that we will be working with to design these LED fixtures. Then, we will present an outline of how and where we plan to spend our time in China, and what our final goals for the project will be.

Introduction

Since the invention of **L**ight **E**mitting **D**iodes (LED's) in the late twentieth century, the uses of these devices have been constantly multiplying. They have gone from being simple indicator lights to seven-segment display applications, and more recently have been applied to huge architectural projects. Only recently, however, have people begun to think about LED's as illuminating devices for work and living spaces. Our goal with this project is to begin designing and prototyping a product that will effectively bring LED's into the industrial workspace.

So why aren't LED's used to light most workspaces around the world? The answer is that the fixtures and power sources that house and drive the LED's are still very expensive. The cost of the LED's themselves, however, has been decreasing. There is an opportunity here to design LED-driven lighting fixtures that are cost-effective.

LED's are attractive to businesses for two reasons: long lamp life and low power consumption. The light output per unit of power input for an LED is typically at least twice that of current incandescent or fluorescent equivalents, and the lamp life is approximately ten times greater.

For this project, we will focus on creating several different prototype lighting fixtures that will light workspaces within the REM facility. We will then evaluate the performance of these fixtures with respect to both cost and quality of lighting. Then, we will modify these prototypes and test them again.

Most LED products are still very expensive because they are focused towards retrofitting existing lighting systems rather than installing a system that is designed to drive LED's. LED's need their own power systems because they are so different from other forms of lights. LED's only function at very specific voltages and they can only be powered by a DC circuit. These two requirements have, thus far, kept the cost of the LED systems high while the cost of the LED's themselves remains relatively low.

Our project will take advantage of a simple, unique circuit that will power three banks of LED's, one at full power and two at half power. This circuit will be able to attach directly to an AC power supply without needing many additional parts. Overall, we want to create a modular LED system that can be applied in several forms to a number of settings.

Background Information

LED's

Light Emitting Diodes, more commonly known as LED's, were invented in the second half of the twentieth century. The earliest LED's were only able to emit light in the infrared range, and thus their applications were limited. Since then, LED technology has developed into the visible spectrum, and LED's are finding all kinds of applications, from flashlights to jumbotrons.

LED Benefits

The advantages that LED's hold over existing lights are both economic and environmental.

Economically, LED's consume much less power than both incandescent and fluorescent lights. In terms of efficiency, LED's can produce about 90 lumens per watt of power consumed, and this number is steadily increasing. A standard incandescent light generally produces a maximum of 20 lumens per watt, and a standard fluorescent light only produces up to 40 lumens per watt. In addition, the lifespan of an LED is far longer than that of other lights. Most manufacturers rate the life of their LED's at approximately 100,000 hours, where incandescents are generally rated for a 1,000 hour life, and fluorescent lights are at 20,000 hours. This increase in lamp life decreases lamp replacement costs.

LED's hold a strong environmental advantage over modern fluorescent lights because production and disposal are environmentally friendly. Fluorescent lights must contain a certain amount of mercury in order to work. Mercury is toxic, so fluorescent lights require special handling for disposal, which adds to their overall cost.

LED Technology

LED's are semiconductor chips. They emit light at a very specific frequency when electrons jump between separate p-type and n-type semiconductors. The point of contact between these chips is called the p-n junction. Both the specific frequency of light emitted and the electric potential needed cause the jump depend on atoms of exotic elements being substituted for a small percentage of the silicon atoms. The process of exposing pure silicon to atmospheres containing high concentrations of these elements is called "doping", and the material's charge and conductivity are very dependant on the elements that they've been doped with.

In order to understand how the electrons jump from one side to the other, one must first understand how materials conduct electricity. Electrons in the atoms of most materials are gathered in two different "bands": the valence band, and the conduction band. The conduction band corresponds to the outermost electron shell and, in accordance with its name, is where transfer of electrons between atoms takes place. The valence band, on the other hand, refers to the outermost shell of electrons that is filled to capacity with electrons. The difference in distinct energy levels between these two shells is known as the band gap. Metals have no distinct band gap, therefore electrons are free to move to the conduction band at no energy cost, and therefore metals conduct electricity well. Nonmetals have a large band gap, so valence electrons can't get to the conduction band easily, and thus nonmetals do not conduct well. Semiconductors, as their name implies, have a medium band gap, and so their electrons can jump to the conduction band with only a little energy input. Doped semiconductors, in addition to having different numbers of electrons, have different band gaps than their non-doped counterparts.

P-type semiconductors have been doped so that they are lacking in electrons (p stands for positive here). As a result, their valence bands are not full, and their conduction bands are empty. Each location in the p-type material that is missing an electron is known as a hole. N-type semiconductors, on the other hand, have been doped to have an excess of electrons. These excess electrons stay in the conduction band of the semiconductor.

Both p- and n-type semiconductors are normally electrically stable, however when an electric potential is applied across the two, electrons travel easily between them, jumping from the crowded n-type conduction band to the empty p-type valence band. For the individual electrons, this jump, in addition to switching atoms, means a change in energy level. As we know from basic physics, when an electron falls from a higher atomic energy level to a lower energy level, the excess energy leaves the electron in the form of a photon and thus light is emitted.

The exact color of the light emitted depends directly on the amount of energy lost in the jump from the n-type to the p-type, and thus the band gaps associated with the two. As a result of that, the choice of doping materials for both the n and p sides of the LED controls the color output of the LED. Since the band gap associated with a given doping material is very consistent for all samples of a doped semiconductor, LED's of a given type emit only very specific frequencies of light, which generally come across as the primary colors of light (red, green, and blue). In order to create white LED's, manufacturers dope the LED materials with several different materials to create a mixed light output that comes across as white.

The supply voltage that is required to get the electrons over the band gap is also directly proportional to the size of the band gap, so differently colored LED's require slightly different input voltages to emit light. Supplying too great of a voltage will cause electrons to move through the material too quickly, and the LED will burn itself out. Without enough voltage, the electrons will not make the jump, and nothing will happen. It should also be noted that if the supply voltage is attached backwards, and enough voltage is supplied to make the electrons flow backwards, then the doping of the n-type and p-type semiconductors will break down and the LED will become unusable.

Existing LED Applications

Lighting as a field began to develop in the early twentieth century with the advent of the electric light bulb. Finally, there was a source of lighting with a relatively constant light output. Light is measured in several different ways. The most basic unit is intensity, measured in candela or millicandela. Intensity is generally only measured for a single light source, so any fixtures that incorporate more than a single light source (i.e. most LED systems) are measured differently. Luminosity is a measure of the total light reflected per unit area off of a surface that has been placed at a specified distance. Luminosity is a useful measure because it can be measured on a per-fixture basis rather than on a per-light source basis.

Most existing LED applications can be categorized into two basic categories: small-scale and large. Small-scale applications, such as flashlights, reading lights, and indicator lights usually only make use of very few LED's and are intended for very specific purposes. They are also generally powered by batteries. Large-scale applications involving multiple thousands of LED's include LED jumbotrons in sports arenas and architectural lighting showcases, like the Fremont Street experience in Las Vegas. Neither of these categories provides light on the scale that we will be designing for; however both of them contribute something to our knowledge of the problem.

Most of the early uses for LED's were in small-scale applications, they were especially useful as indicator lights because the are small, work for hundreds of thousands of hours with very little decrease in light output, consume little power, and give off very little heat when compared to incandescent bulbs. More recently, LED's have found their way into small portable task lights, especially flashlights. Their low power consumption makes them ideal for this because they make better use of their batteries. To relate this to the goals of our project, these small-scale applications exploit the simplicity of LED's. Our goal is to make our fixtures as simple to power and rearrange as possible.

Large-scale applications of LED's showcase both their versatility and their durability. One of the best examples of large-scale applications is the Fremont Street Experience in Las Vegas. The Experience uses 1.4 million individual LED's to illuminate the underside of a large pavilion in Las Vegas. The LED's are controlled by a set of computers and are used for shows underneath the pavilion. The Experience has been running with LED's and without any major interruptions since 2004, even with external components exposed to the weather.

While both of these applications give off light, neither of them is concerned with illumination. Smaller products are focused on lighting individual tasks, while larger products don't really provide illumination as much as they provide a lighted screen on which to display images. The smaller products emphasize power advantages of LED's and larger products emphasize the durability and versatility advantages of LED's. With our fixtures, we want to emphasize both of these characteristics.

Rapid Engineering Manufacturing

Rapid Engineering Manufacturing (REM) is a small metal-working company that is based in Wuxi, China. They have a relatively new facility and are looking at the long-term costs of maintaining it. One way that they want to cut down on operating costs is to install highly efficient LED lighting systems throughout the factory. Since they have a new factory, installing a new system should be relatively easy to do.

REM has already begun the changeover to LED illumination with their overhead lights. We will be furthering the changeover by developing fixtures to be used as task lighting on specific machine tools. Currently, most of the task lighting that they have is incandescent; the bulbs frequently burn out and don't always get replaced. With our LED fixtures, we would like to see that change. Specifically, replacement costs and maintenance time will be reduced or eliminated.

REM's business is specialty nuts, pins, and rivets, and the machine tools that we will be designing our fixtures for will be working metal. As a result, the fixtures that we design will have to be able to withstand flying metal chips and other dangers that are associated with the shop environment.

Method of Research and Development

Over the course of the last term, we have developed a simple, modular circuit design that can be used with Alternating Current (AC) power delivered directly from standard wall 120 volt or 220 volt outlets. The physical shape of the circuit depends entirely on the mounting location, or locations, within the individual machines at the factory. This means that actual designs of the lights must wait until we have seen the machines in person and determined possible mounting locations within them. Additionally, a light intensity sensor should be employed to gather data about current lighting conditions so that quantitative comparisons can be made at the conclusion of this project.

Some work can be done before arriving in China, however. LEDs have been ordered to begin the process of testing the circuit design on a breadboard with AC power, with variations on the number and arrangement of LEDs being the primary focus. Strength and placement of inductors will also be investigated. The basic design is a rectifying bridge created completely with LEDs, with the addition of an inductor to maintain the current through the primary LEDs during the periods of low voltage in the AC waveform.

When we arrive at the factory, each machine will be individually evaluated. Pictures will be taken of each, highlighting the areas we want to illuminate with the LEDs and positions where mounting is possible. Measurements and sketches of these locations must be made as well, so that circuit designs and housing molds can be created precisely. Interviews of the employees responsible for each machine should also be conducted, so that areas they think are important can be given extra consideration. A folder containing all information on each machine will keep the data organized.

Once all machines have been evaluated, we will return to HUST and begin design and fabrication of the prototypes. The first step is to compare all the information gathered about the machines and determine the minimum number of shapes necessary to be used among all machines. Ideally, this will be between 3 - 6 shapes. Prototype circuit boards can then be designed in an electrical engineering program that produces diagrams which will be sent to the circuit board printing company for production. While the boards are being fabricated, complimentary housing molds can be designed and fabricated from aluminum.

Each light will be a circuit board embedded in solid plastic. The type of plastic is subject to the results of testing; primary candidates are Plexiglas, polycarbonate and two part epoxy. Each will be evaluated for clarity, robustness, ease of preparation and use, possible interference with LEDs or circuits, and affect on light focusing. Once the best material has been selected, production can begin on all shapes.

Soldering the LEDs into the circuits will be a time consuming part of fabrication, since every light will have between 55 – 80 LEDs which all need to be soldered into place, along with the inductor and power wires. Fortunately, soldering becomes very quick and easy with practice, and there should be time between the testing of the housing materials and full scale production for each team member to become proficient in the art of soldering LEDs into a circuit board.

Once there is an example of each of the shapes fully manufactured, a trip should be made back to the factory to test them in actual machines. If there are any problems with the fit, changes can be made to the mold, without wasting assembled circuits. Evaluations by factory employees can also be made at this time to determine preliminary effectiveness of each design. Any problems can be addressed before time is wasted, and while there is time correct them. Pictures and light intensity measurements should also be made for each design.

Full scale production can begin at this point. Jigs and holders can be fabricated to decrease assembly time, and the advice of manufacturing majors can be pursued and utilized. Extra prototypes can be assembled if time permits for hands on demonstration at the final presentation. The last phase is the writing of the final report, which will include graphs, diagrams and images created during the project, and a presentation based on it.

Tentative Timeline

Before arrival in Shanghai, research can be completed on the configuration of LEDs on a breadboard circuit. 100 LEDs have been ordered to complete a test circuit, and various inductors will be purchased from Radio Shack.

Arrive in Shanghai on Sunday, June 15th in the afternoon. Professor Rong will meet us at the airport and accompany us to the hotel in Shanghai where we will spend the night. In the morning, (Monday, June 16th) several groups will travel to Wuxi to visit their respective companies. We will be getting a tour of the REM facility and given the details on where LEDs need to be installed. Introductions to the employees will also be made.

Travel overnight to Wuhan by train to arrive on the 17th at HUST. We will meet our Chinese partners at this point, and compare notes and objectives. Preliminary presentations will be made at this point to the HUST professors and sponsors, outlining the objectives for the project and the tentative schedule. Tours of HUST will also be made during this time. Total time for the REM team in Wuhan: 2 days.

Travel back to Wuxi on Friday, the 20th to categorize the machines at the factory. Each machine will have detailed pictures taken, with precise measurements of possible LED mounting locations. Initial ambient light readings at locations of interest will also be made.

Additionally, light readings at inspection stations outside the machines (at desks or work benches, for example) must also be made. This will take approximately two weeks.

Return to Wuhan by train on Friday the 4th of July. On Monday, the 6th, begin creating shapes for each machine's mounting location. Combine shapes until only 4-6 shapes remain. By Tuesday, the 7th, develop prototype circuits in the electrical engineering program that match the final shapes. Work should be finished by Tuesday, the 7th so that prototypes can be fabricated at a local circuit printing company. At least 5 of each shape need to be ordered so that alternate configurations of LEDs can be tested. On Wednesday, the 8th, purchase enough LEDs, inductors and wiring for prototypes. Begin CAD designs for housing molds in SolidWorks, until prototype circuit boards arrive. Work on the prototypes should begin immediately; LEDs, inductors and wires need to be soldered into the boards so that light quality tests can be conducted. Once optimal configurations are determined, circuit designs are modified to reflect the changes. By Friday, the 11th, final circuit designs are submitted to the circuit printing company for fabrication. Any extra time must be devoted to housing mold design and fabrication.

The week of Monday, July 14th, should be devoted to fabrication and testing of the housing molds. Polycarbonate, Plexiglas and epoxy materials will be tested for ease of use, strength, scratch resistance, effect on LEDs, effect on light transmission/refraction/etc, and weight. The best substance will be used for the final production. The prototype circuit boards will be used for these tests, so that they are not wasted. On Wednesday, the 16th, additional LEDs, inductors and wires should be purchased; enough for all final designs. When the final circuit boards are delivered on Thursday or Friday, final production can begin.

The week of Monday, July 21st, full scale production of each shape should start. Each team member will rotate through each stage of production:

1) counting of individual components and sub assembly into "jigs" to hold parts in place;

2) soldering LEDs, inductors and wires onto the circuit board;

3) testing of lights to assure full functionality, and troubleshooting any problems;

4) pouring of plastic around circuits in the molds.

Any improvements to the processes will be noted and passed on to the next workers at each station. The team members should rotate stations once an hour to stretch, and to alleviate boredom. If one station gets significantly ahead of the next station in the sequence, members of that station should move to the other station and help until caught up.

Production should be finished by Friday, July 25th. Prototypes will be packaged and transported to Wuxi, and team members will travel by train overnight on Sunday, the 27th. Installation and testing will begin on Monday the 28th. Tests of lighting conditions will be made, and interviews with machine operators will be conducted. Installation should be complete by Wednesday, the 29th. Team will return to Wuhan that night.

Remaining time from Thursday, July 24th to the presentation date on Friday, August 1st, will be dedicated to documentation of the project. Light intensity data must be analyzed, responses of machine operators will be compiled, and representative images for the presentation shall be selected. Final circuit diagrams will be prepared, power requirements will be measured, lumen to wattage ratios will be calculated, total cost of the project will be counted, material cost of an individual unit will be determined, and fabrication processes will be documented.

Expected Results

1. At the end of this project, we expect to have designed and fabricated a number of prototype fixtures. We also expect to have made at least a few revisions to the prototypes after having tested them in the REM factory.
2. Complete, simple circuit design to drive the LED's off of an AC power source.
3. Possibly the most important outcome of this will be a cost-analysis for each prototype.
4. We plan to have quantitative results for increased light intensity at critical locations within the machines.
5. Images of each design and its effectiveness.

References

luminous efficacy:

-LED

-Incand

-Fluor

Lamp Life:

-LED

-Incand

-Fluor

Fluor. Hg

P-type def.

N-type def.

banding, etc.

def. of luminosity, etc.

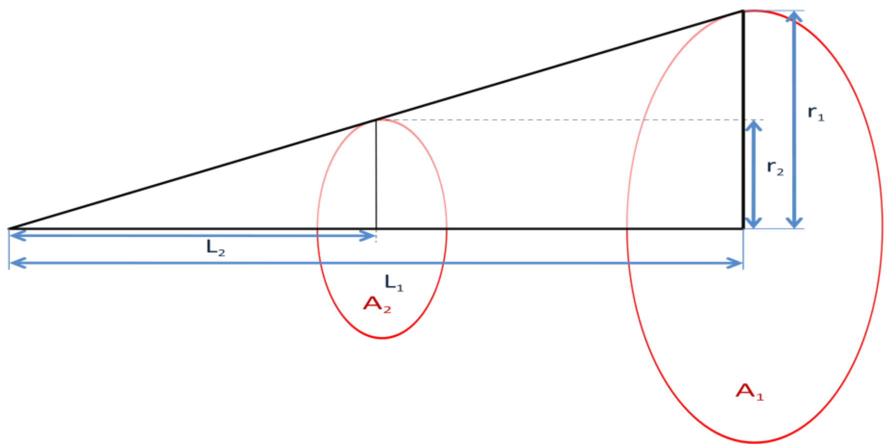
Fremont St.

Jumbotrons

Casiday, Rachel and Frey, Regina. Bonds, Bands, and Doping: How Do LEDs Work?

Appendix G: Proportionality of Light Flux

Assuming that across a small area within a beam of light, illuminance is constant. Proportionality of light flux (lumens) between two distances within the same beam Assuming that a beam of light is a cone shape,



For two different distances,

$$\frac{L_1}{L_2} = \frac{r_1}{r_2}$$

If the area of the base at a give distance is,

$$A = \pi r^2$$

then

$$\frac{L_1}{L_2} = \sqrt{\frac{A_1}{A_2}}$$

From the definition of illuminance, we know that

$$I_v = \frac{F}{A}$$

or

$$A = \frac{F}{I_v}$$

where I_v is illuminance, F is luminous flux, and A is area. Substituting, we now have a relationship between intensity, illuminance, and distance.

$$\frac{L_1}{L_2} = \sqrt{\frac{I_2}{I_1} \times \frac{F_1}{F_2}}$$

If we assume that the total amount of luminous flux in the given area is the same at both distances (F2=F1), then we have

$$\frac{L_1}{L_2} = \sqrt{\frac{I_2}{I_1}}$$

or

$$\frac{I_2}{I_1} = \left(\frac{L_1}{L_2}\right)^2$$

Appendix H: Heat Experiment Procedure and Equipment List

Procedure

1. Place the LED's on the breadboard in lines of 3 attached in series. Then attach 5 of these lines together in parallel at each end of the breadboard. You should end up with two sets of 5 lines of LED's (Figure 20)

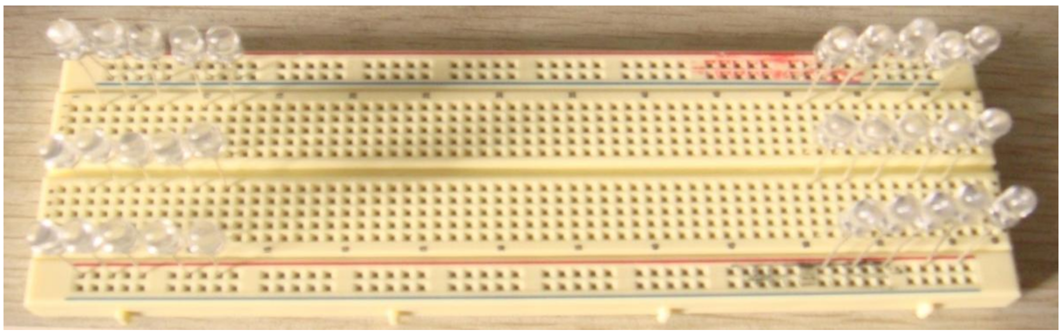


Figure 20: Breadboard arrangement

2. Prepare the oil and control oil cups by filling them partway with oil.

3. Prepare the box by cutting a hole near the top that is just big enough for the breadboard to be put through and assemble all pieces as shown (Figure 21). Make sure that one half of the breadboard is inside of the box and that the LED capsules on the other half are immersed in water.

Figure 21: Overall Assembly

4. Attach the breadboard to the DC power source (9.2V) and confirm that all LED's are functional.

5. Using the thermometer, take and record initial readings for the following: air temperature, temperature inside the box, temperature of the oil, and temperature of the control oil.

6. Record the temperatures of the ambient air, the air inside the box, the control oil, and the oil with the LED's in it. When measuring the oil with the LED's in it, be sure to measure the temperature near the base of the LED's in order to best approximate the junction temperature.

7. Repeat step 6 every thirty minutes for eight hours.

Equipment Used

Items	Manufacturer	Part #	Serial # (if applicable)
30LED's	Shenzhen City Mizuhiro Optoelectronic Equipment Co.	5W4DC-WG-WR008	
DC power supply	Shenzhen Zhaoxin Electronics	TXN-1502D	2N3055 - O5U3D
Digital Thermometer	Uni-Trend	UT70A	3080096352
Breadboard			
Plastic Cup			
Cooking oil			
Cardboard box			

Appendix I: Shape Matrices

Final Matrix

	Feasibility	Innovation	Appearance	Focus function	Adjustability	Heat dissipation	Light area	Printing PCB	Collapsible function	**Total**	**Rank**
Weighting Factor	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
2 hinged rectangle	3.375	3.5	3.125	2.5	4.25	3.75	4.125	5	4.25	**59.68**	**1**
Jointed bar	3	4.25	2.625	2.25	4.5	4	4.25	4.5	3.75	**59.25**	**2**
Ziggurat	3.25	4.5	4.5	2.5	2	3.625	3.75	4	3.25	**55.43**	**3**
Stepped cone	3.25	4	4.5	2.5	2	3.125	3.75	3.5	3.25	**52.43**	**4**
Torus	3.75	4.5	3.625	2.75	2	4.25	3.75	3.5	0.25	**51.12**	**5**
Round bar	3.75	3	3.75	3.75	2.5	3.5	3.5	3.75	0.5	**49.50**	**6**
Cage	2.5	4	3.25	3.5	1.5	4.5	3.875	2.375	2.25	**48.75**	**7**
Right tetrahedron	2.875	3.375	3.5	2.5	2.25	2.75	3.625	4.25	1.25	**47.68**	**8**
Concave lens	3.5	3.125	3.5	4	2.25	3.875	3.125	2.5	0.5	**45.62**	**9**
Truncated cone	3.5	2.625	3.25	3.25	2	3.125	3.625	2.875	1.25	**45.18**	**10**
Short cylinder	4	2	2.75	1.5	1.75	3.5	3.625	4.5	0.5	**45.06**	**11**
Bar	4	1.875	1.875	2	2	2.5	3.25	4.5	0.75	**42.87**	**12**
Parabolic	3	3.25	3.75	3.625	1.75	2.75	3.25	1.875	1	**41.87**	**13**
Convex lens	3.25	3.125	2.75	0.5	1.75	4	4	2.25	0.75	**40.75**	**14**
Hemisphere	3.5	3	3.25	3	2	2.5	3.25	1.625	0.25	**39.06**	**15**

Individual Shape Matrices

Lu Wei

	Feasibility	Innovation	Appearance	Focus function	Adjustability	Heat dissipation	Light area	Printing PCB	Collapsible function	Total	Rank
Weighting Factor	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
2 hinged rectangle	4	5	5	0	5	5	4	5	4	64	1
Jointed bar	5	5	3	0	5	5	4	5	4	64	2
Ziggurat	3	5	4	0	0	4	4	5	5	56	3
Short cylinder	5	3	5	0	0	5	5	5	0	53.5	4
Stepped cone	3	5	5	0	0	3	4	4	5	53	5
cage	4	5	4	3	0	5	3	4	0	51.5	6
Convex lens	4	5	5	0	0	5	5	3	0	50.5	7
Torus	4	5	4	0	0	5	4	4	0	49.5	8
Round bar	4	3	5	3	0	4	3	5	0	49.5	8
Concave lens	4	3	5	4	0	4	4	3	0	48.5	10
Truncated cone	4	4	5	3	0	4	3	3	0	46.5	11
Hemisphere	5	3	5	4	0	3	3	3	0	46.5	12
Bar	5	3	3	0	0	4	3	5	0	45	13
Parabolic	4	3	5	5	0	3	3	2	0	43.5	14
Right tetrahedron	3	3	4	2	0	3	3	4	0	41	15

Deng Yujun

	Feasibility	Innovation	Appearance	Focus function	Adjustability	Heat dissipation	Light area	Printing PCB	Collapsible function	Total	Rank
Weighting Factor	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
2 hinged rectangle	5	5	4	0	5	5	5	5	4	67.5	1
Jointed bar	4	5	4	0	5	5	4	5	4	63	2
Ziggurat	3	5	4	0	0	3	4	5	5	54.5	3
Stepped cone	3	5	5	0	0	4	4	4	5	54.5	4
cage	4	5	4	3	0	5	4	3	0	51.5	5
Short cylinder	5	3	5	0	0	5	4	5	0	51	6
Torus	4	5	5	0	0	5	4	4	0	50.5	7
Round bar	4	3	5	3	0	4	3	5	0	49.5	8
Concave lens	4	4	5	4	0	5	3	3	0	49.5	8
Convex lens	4	4	5	0	0	5	5	3	0	48.5	10
Truncated cone	4	3	5	3	0	3	4	4	0	48	11
Right tetrahedron	4	4	4	2	0	3	4	4	0	47.5	12
Parabolic	4	3	5	4	0	3	3	3	0	44.5	13
Hemisphere	5	3	5	4	0	3	3	2	0	44	14
Bar	5	2	4	0	0	4	3	5	0	44	15

David

	Feasibility	Innovation	Appearance	Focus function	Adjustability	Heat dissipation	Light area	Printing PCB	Collapsible function	Total	Rank
Weighting Factor	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
2 hinged rectangle	3	4	2	1	3	4	4	5	4	55	1
Stepped cone	3	4	4	3	3	3	4	3	2	50.5	2
Torus	4	5	3	3	2	4	4	2	1	50	3
Ziggurat	3	4	4	3	2	3	4	3	2	49.5	4
Round bar	4	4	3	4	4	3	3	2	2	49	5
Convex lens	3	3	3	1	3	4	5	2	3	47.5	6
Concave lens	3	3	2	3	3	4	3	3	2	45.5	7
Jointed bar	2	3	2	1	3	4	4	4	2	45.5	8
Short cylinder	3	3	2	2	2	3	4	3	2	44	9
Parabolic	3	3	3	2	2	3	4	2	2	42.5	10
Hemisphere	4	3	3	2	2	2	4	2	1	41.5	11
Right tetrahedron	3	2	2	2	3	2	3	4	2	41.5	12
Truncated cone	3	3	2	2	2	3	4	2	2	41.5	13
Bar	3	2	2	4	3	1	3	3	2	40.5	14
cage	2	2	2	2	2	3	3	2	2	35	15

Chris

	Feasibility	Innovation	Appearance	Focus function	Adjustability	Heat dissipation	Light area	Printing PCB	Collapsible function	Total	Rank
Weighting Factor	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
Jointed bar	3	5	2	4	5	4	4	4	5	62.5	1
Ziggurat	4	4	5	4	3	4	4	5	2	61.5	2
Right tetrahedron	4	4	5	4	3	3	4	5	0	57	3
2 hinged rectangle	2	2	2	5	5	3	3	5	5	54.5	4
Stepped cone	4	3	5	4	3	2	4	4	2	54	5
Round bar	4	2	4	4	3	4	4	5	0	53.5	6
cage	1	5	2	5	1	5	5	2	3	52	7
Torus	3	4	3	3	2	5	3	5	0	51	8
Truncated cone	4	1	4	4	3	3	4	4	0	47.5	9
Parabolic	2	4	4	5	3	2	4	2	0	44.5	10
Bar	3	2	1	2	3	2	4	5	1	44	11
Short cylinder	4	1	2	2	3	3	3	5	0	42.5	12
Concave lens	3	2	4	4	3	3	4	2	0	42.5	13
Hemisphere	2	2	3	3	3	2	3	1	0	31.5	14
Convex lens	3	2	1	1	3	3	2	2	0	30	15

David

	Feasibility	Innovation	Appearance	Focus function	Adjustability	Heat dissipation	Light area	Printing PCB	Collapsible function	Total	Rank
Weighting Factor	2	2	1	1.5	1	1.5	2.5	2.5	1.5		
Jointed bar	4	4	3	4	5	3	5	5	4	65.5	1
2 hinged rectangle	4	3	4	4	4	3	5	5	4	63.5	2
cage	3	4	5	4	3	5	4	2	4	56.5	3
Ziggurat	3	5	5	3	3	4	3	3	4	55.5	4
Torus	4	4	4	5	4	3	4	3	0	53.5	5
Stepped cone	3	4	4	3	2	4	3	3	4	51.5	6
Right tetrahedron	1	4	3	2	3	3	4	4	3	48	7
Round bar	3	3	3	4	3	3	4	3	0	46	8
Concave lens	4	4	3	5	3	4	2	2	0	45.5	9
Truncated cone	3	3	2	4	3	3	3	2	3	44.5	10
Bar	5	1	1	2	2	3	3	5	0	42.5	11
Short cylinder	4	1	2	2	2	3	3	5	0	41.5	12
Hemisphere	3	4	2	3	3	3	3	1	0	38	13
Parabolic	3	3	3	3	2	3	2	1	2	36.5	14
Convex lens	3	3	2	0	1	4	4	2	0	36	15

Appendix J: Photometrics Sheets

For each of our prototypes and also for each of our current fixtures, we created a photometrics sheet that showed several values, including beam angle and a rough luminosity distribution curve. Beam angle measurements were taken according to the procedure set forth in Appendix A: Experiments and Tests.

Light output at a given working distance was calculated usingcombination of the beam angle, luminosity measurements taken at an arbitrary distance, and simple proportions.   For a detailed explanation of these calculations, please see Appendix G: Proportionality of Light Flux

Yellow Flashlight

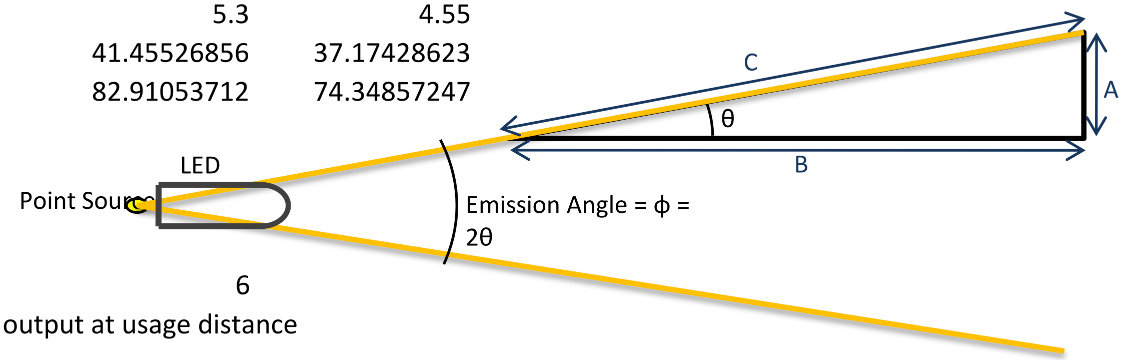
Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output		lux meter area:	12.08105	cm^2
6					0.001208	m^2
Center	3000	3.624315096				
Top	1000	1.208105032				
Left	290	0.350350459				
Bottom	1000	1.208105032				
Right	290	0.350350459				

Beam Angle

Trial #	Distance from Wall (cm)	Beam Width (cm)	Beam Height(cm)
1	0	3.5	7
2	6	14.1	16.1

	Beam Width	Beam Height
Side B (cm)	6	6
Side A (cm)	5.3	4.55
θ	41.45526856	37.17428623
ϕ	82.91053712	74.34857247



General Usage Distance (cm): 6

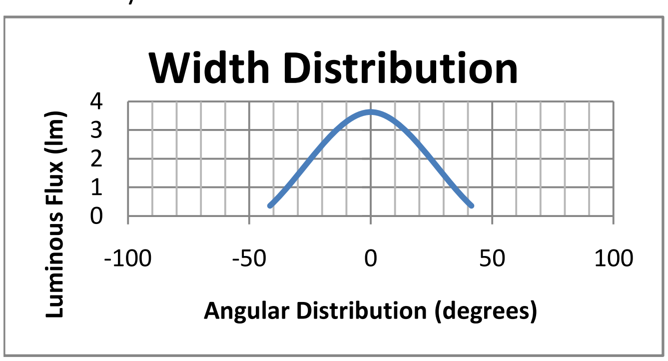
Projected light output at usage distance

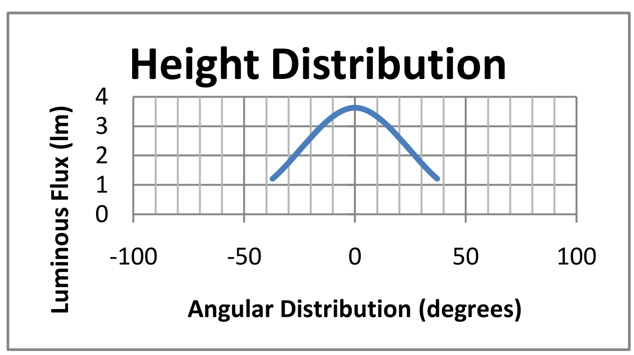
I2=I1(L1/L2)^2

I2 (lux) 3000

Beam Distribution

	Width			Height		
Location (deg)	-41.45526856	0	41.4552686	-37.17428623	0	37.174286
Luminosity	0.350350459	3.624315096	0.35035046	1.208105032	3.624315	1.208105





FourBar Incandescent

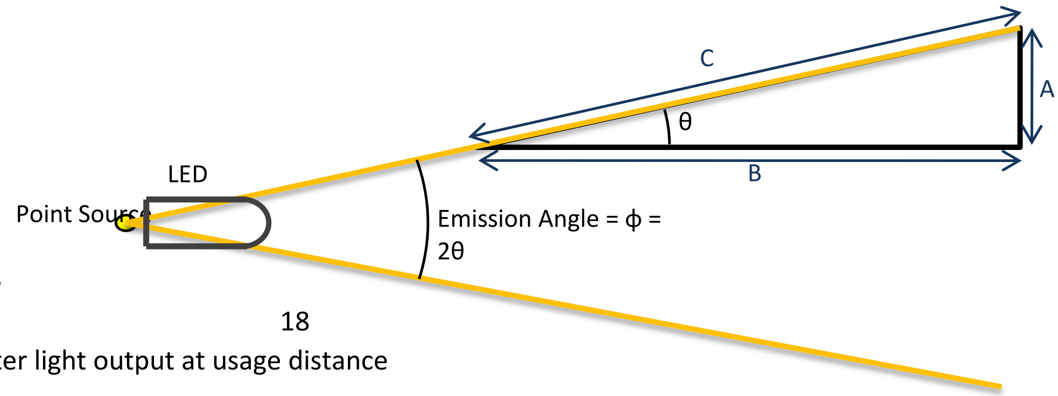
Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output	lux meter area:	12.0810503	cm^2
82				0.00120811	m^2
Center	299	0.3612234			
Top	4	0.0048324			
Left	Not Testable	#VALUE!			
Bottom	6	0.0072486			
Right	5	0.0060405			

Beam Angle

Trial #	Distance from Wall (cm)	Beam Diameter (cm)	Side B	Side A	θ	ϕ
1	0	17.3	1.5	3.85	68.7136529	137.4273
2	1.5	25				

Average ϕ:	137.4273



General Usage Distance (cm): 18

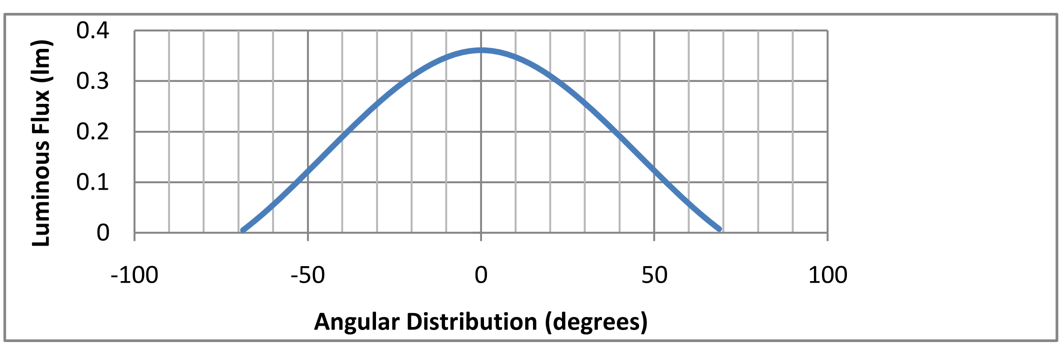
Projected center light output at usage distance

I2=I1(L1/L2)^2

I2 (lux) 6205.17284

Beam Distribution

Location (deg)	-68.71365293	0	68.71365
Luminosity	0.00483242	0.3612234	0.007249



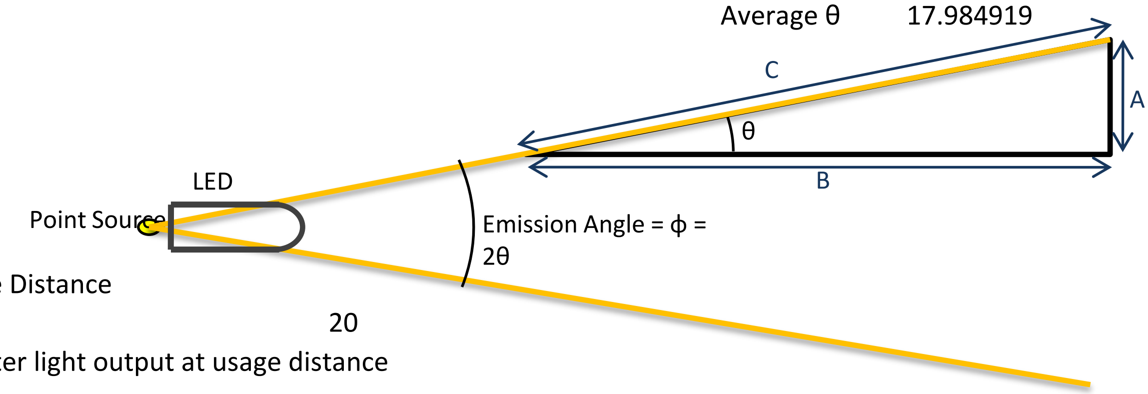
Gooseneck Halogen

Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output	lux meter area:		
126.2				12.08105	cm^2
				0.0012081	m^2
Center	970	1.171861881			
Top	123	0.148596919			
Left	83	0.100272718			
Bottom	110	0.132891554			
Right	85	0.102688928			

Beam Angle

Trial #	Distance from Wall (cm)	Beam Diameter (cm)	Side B	Side A	θ	ϕ
1	0	7.6	12.4	3.2	14.470306	28.94061
2	12.4	14	14.1	5.5	21.309329	42.61866
3	26.5	25	26.5	8.7	18.175121	36.35024
					Average ϕ:	35.96984
				Average θ	17.984919	



General Usage Distance (cm): 20

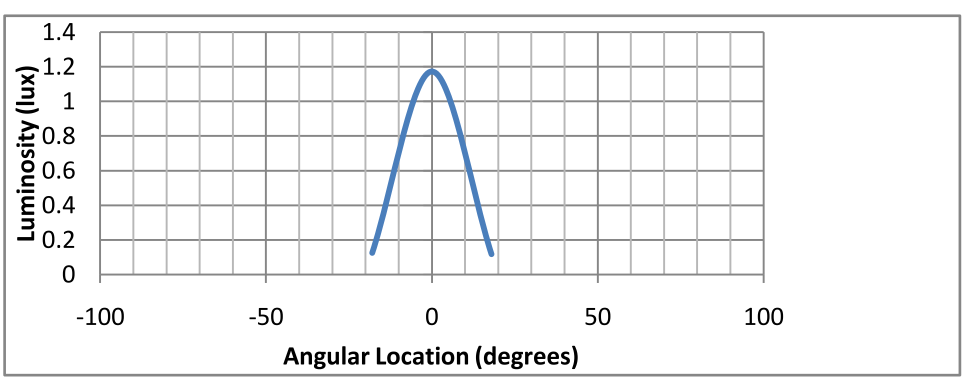
Projected center light output at usage distance

I2=I1(L1/L2)^2

I2 (lux) 38621.617

Beam Distribution

Location (deg)	-17.98491869	0	17.98492
Luminosity	0.124434818	1.171861881	0.11779



Planer Halogen

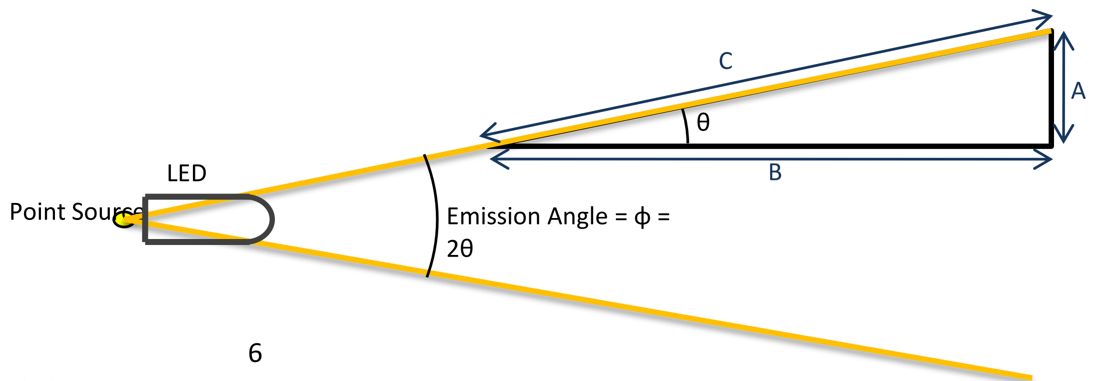
Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output	lux meter area:	12.0810503	cm^2
126.3				0.00120811	m^2
Center	170	0.205377855			
Top	Machine in way	#VALUE!			
Left	36	0.043491781			
Bottom	33	0.039867466			
Right	34	0.041075571			

Beam Angle

Trial #	Distance from Wall (cm)	Beam Diameter (cm)	Side B	Side A	θ	ϕ
1	0	7	26	9	19.0935081	38.18702
2	26	25				

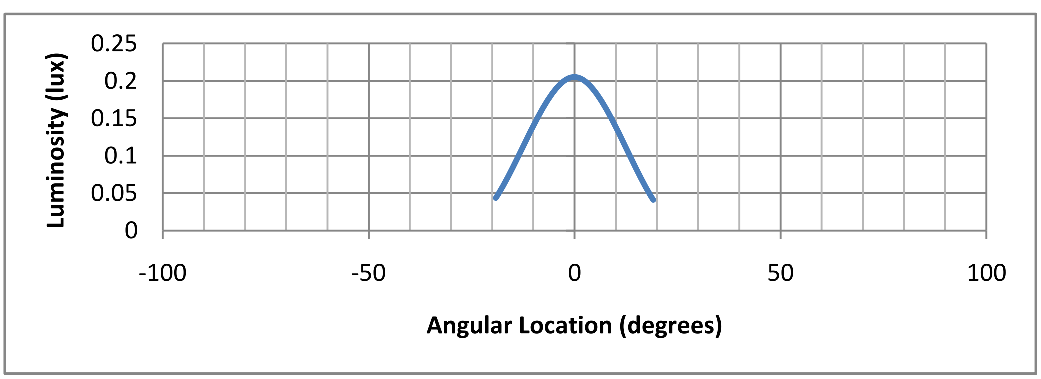
Average ϕ:	38.18702



General Usage
Distance (cm): 6
Projected center light output at usage distance
I2=I1(L1/L2)^2
I2 (lux) 75327.425

Beam Distribution

Location (deg)	-19.09350813	0	19.09351
Luminosity	0.043491781	0.205377855	0.041076



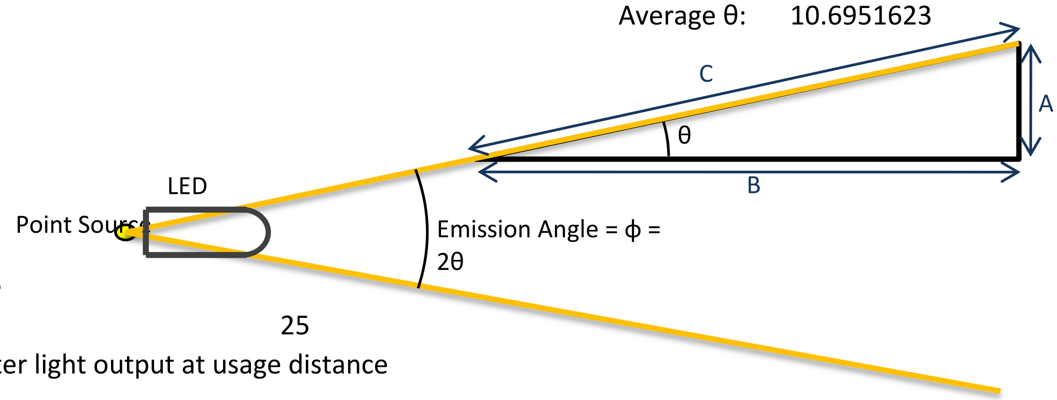
Jointed Rectangle

Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output	lux meter area:		
107				12.0810503	cm^2
				0.00120811	m^2
Center	445	0.5376067			
Top	150	0.1812158			
Left	230	0.2778642			
Bottom	150	0.1812158			
Right	220	0.2657831			

Beam Angle

Trial #	Distance from Wall (cm)	Beam Diameter	Side B	Side A	θ	ϕ
1	0	8.5	13	2.75	11.9441873	23.88837
2	13	14	32	5.5	9.75243318	19.50487
3	45	25	45	8.25	10.3888666	20.77773
					Average ϕ:	21.39032
				Average θ:	10.6951623	



General Usage Distance (cm): 25

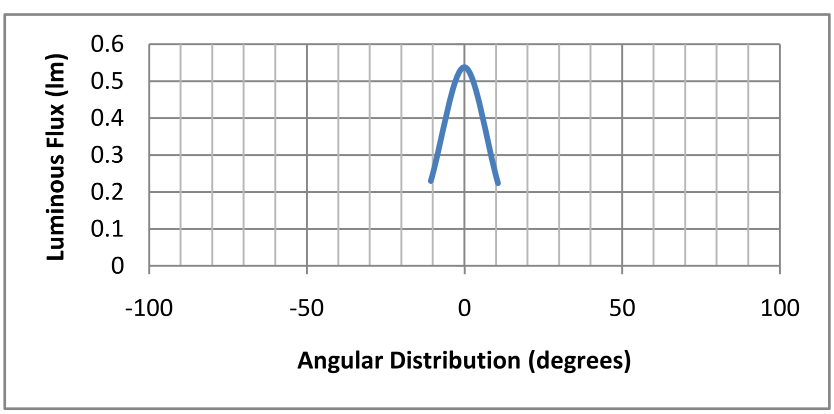
Projected center light output at usage distance

I2=I1(L1/L2)^2

I2 (lux) 8151.688

Beam Distribution

Location (deg)	-10.69516235	0	10.69516
Luminosity	0.229539956	0.5376067	0.223499



Rounded Bar

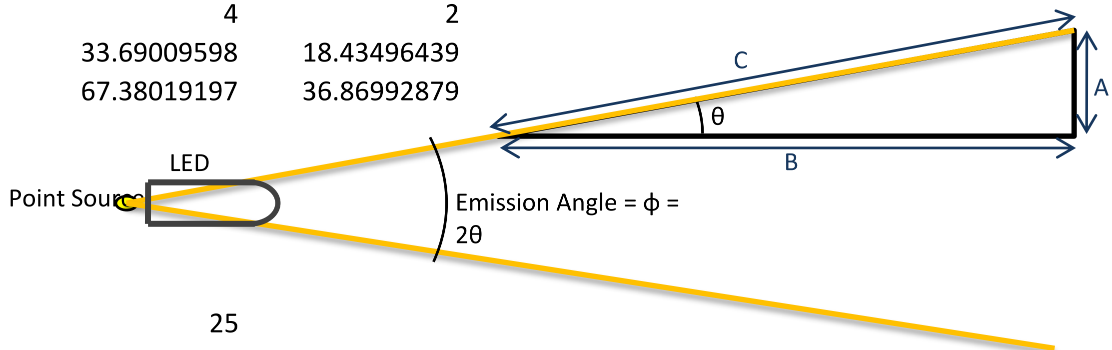
Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output		lux meter area:	12.08105	cm^2
25					0.001208	m^2
Center	2230	2.694074221				
Top	1100	1.328915535				
Left	700	0.845673522				
Bottom	900	1.087294529				
Right	570	0.688619868				

Beam Angle

Trial #	Distance from Wall (cm)	Beam Width (cm)	Beam Height(cm)
1	0	8	21
2	6	16	25

	Beam Width	Beam Height
Side B (cm)	6	6
Side A (cm)	4	2
θ	33.69009598	18.43496439
ϕ	67.38019197	36.86992879



General Usage

Distance (cm):	25

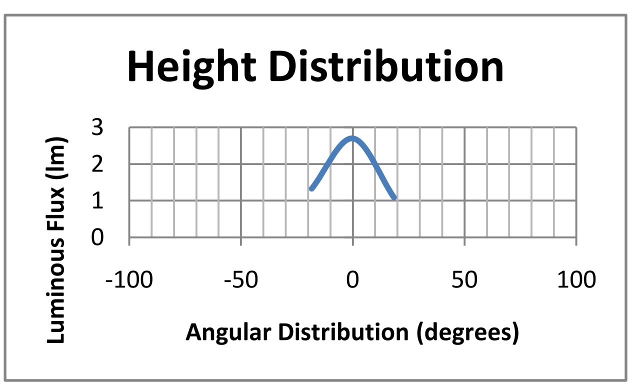
Projected light output at usage distance

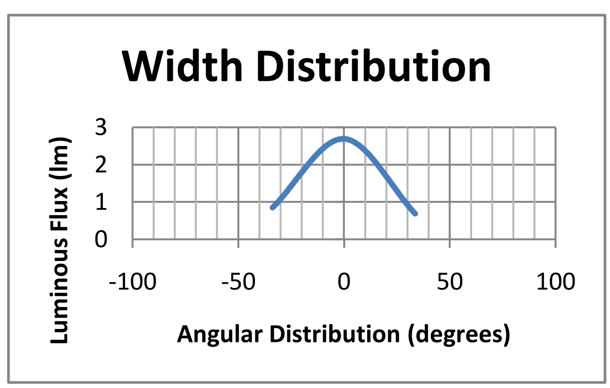
I2=I1(L1/L2)^2

I2 (lux)	2230

Beam Distribution

	Width			**Height**		
Location (deg)	-33.69009598	0	33.690096	-18.43496439	0	18.434964
Luminosity	0.845673522	2.694074221	0.68861987	1.328915535	2.694074	1.0872945





Stepped Cone

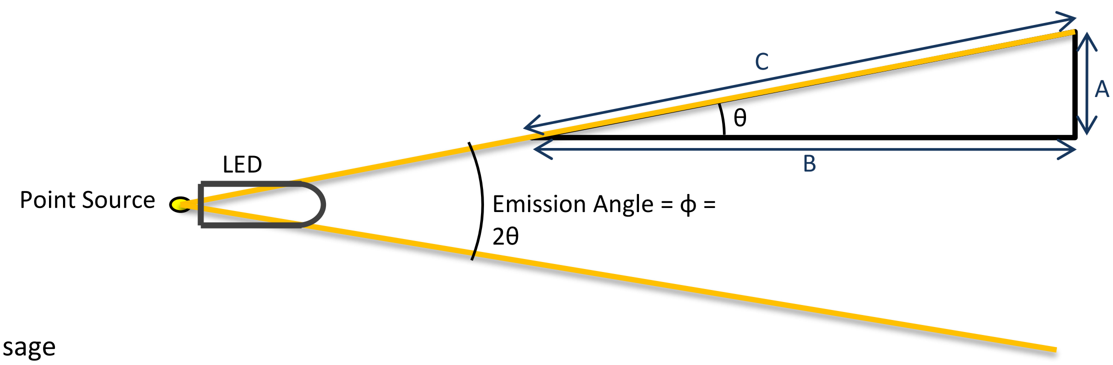
Light Output

Measuring Distance (cm)	Luminosity (lux)	Lumens output		lux meter area:	
76.00					12.08 cm^2
					0.00 m^2
Center	350.00	0.42			
Top	150.00	0.18			
Left	70.00	0.08			
Bottom	180.00	0.22			
Right	73.00	0.09			

Beam Angle

Trial #	Distance from Wall (cm)	Beam Diameter (cm)	Side B	Side A	θ	ϕ
1.00	0.00	16.00	20.00	4.50	12.68	25.36
2.00	20.00	25.00				

Average ϕ:	25.36



General Usage Distance (cm): 18.00

Projected center light output at usage distance

I2=I1(L1/L2)^2

I2 (lux) 6239.51

Beam Distribution

Location (deg)	-12.68	0.00	12.68
Luminosity	0.15	0.42	0.13