EVALUATION AND DESIGN OF NON-LETHAL LASER DAZZLERS UTILIZING MICROCONTROLLERS

BY

KEITH JACK RICHARDSON

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Chairperson: Dr. Terry Faddis

Dr. Carl Luchies

Dr. Robert Umholtz

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The Thesis Committee for Keith Richardson
certifies that this is the approved version of the following thesis:

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ABSTRACT

Current non-lethal weapons suffer from an inability to meet requirements for uses across many fields and purposes. The safety and effectiveness of these weapons are inadequate. New concepts have provided a weapon utilizing lasers to flashblind a target's visual system. Minimal research and testing have been conducted to investigate the efficiency and safety of these weapons called laser dazzlers. Essentially a laser dazzler is comprised of a laser beam that has been diverged with the use of a lens to expand the beam creating an intensely bright flashlight.

All laser dazzlers to date are incapable of adjusting to external conditions automatically. This is important, because the power of these weapons need to change according to distance and light conditions. At long distances, the weapon is rendered useless because the laser beam has become diluted. At near distances, the weapon is too powerful causing permanent damage to the eye because the beam is condensed. Similarly, the eye adapts to brightness by adjusting the pupil size, which effectively limits the amount of light entering the eye. Laser eye damage is determined by the level of irradiance entering the eye. Therefore, a laser dazzler needs the ability to adjust output irradiance to compensate for the distance to the target and ambient light conditions.

It was postulated if an innovative laser dazzler design could adjust the laser beam divergence then the irradiance at the eye could be optimized for maximum vision disruption with minimal risk of permanent damage. The young nature of these weapons has lead to the rushed assumptions of laser wavelengths (color) and pulsing frequencies to cause maximum disorientation. Research provided key values of irradiance, wavelength, pulsing frequency and functions for the optical lens system.

In order for the laser dazzler to continuously evaluate the external conditions, luminosity and distance sensors were incorporated into the design. A control system was devised to operate the mechanical components meeting calculated values.

Testing the conceptual laser dazzlers illustrated the complexities of the system. A set irradiance value could be met at any distance and light condition, although this was accomplished by less than ideal methods. The final design included two lasers and only one optical system. The optical system was only capable of providing constant irradiance of one laser or the other allowing only single laser operation. For dual laser operation, the optical system was calibrated to offset the losses of each laser as distance was changed. Ultimately, this provided a constant combined irradiance with a decreasing green irradiance and increasing red irradiance as distance was increasing.

Future work should include enhancements to the mechanical components of the laser dazzler to further refine accuracy. This research was intended to provide a proof of concept and did so successfully.

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INTRODUCTION TO THE PROBLEM

Advancement in non-lethal weapon technology is needed. A non-lethal weapon is a tool intended to incapacitate or disable a human target with minimal risk of death or serious injury. These weapons can be used to limit the escalation of conflict or where engagement of lethal force is prohibited or undesirable.

Over the past two decades non-lethal weapons have been gaining attention politically, economically, environmentally and ethically. Currently, military and police are faced with scenarios including riot control, crowd control, self-defense and offensive operations requiring force, but have limited options to deal with these other than lethal force.

Recent political demands order that future operations either military or domestic minimize casualties while limiting collateral damage to the environment. The military's task of attacking or defending in a war setting is just as likely a task as conducting peacekeeping and humanitarian assistance missions. General John J. Sheehan has recognized this and spoke at the Non-Lethal Defense Conference to emphasize the need for non-lethal weapons as standard issue military equipment. The presence of non-lethal weapons shows the responsibility, policy and strategy our nation would want to exhibit to the media. New technology could create a life conserving strategy producing a diplomatic advantage. Situations in which the military was unable to act effectively due to the lack of non-lethal equipment may become possible. [13]

The development of non-lethal weapons to stop aggression while conserving life, resources, and the environment can provide the foundation of a new strategic principle of containing conflict and do so in an economically responsible manner. Engineering advancement of non-lethal weapons can become a real peace dividend if it is used to provide systems suited for domestic use, international use, peacemaking, and peacekeeping. The development and production of non-lethal weapons can provide new jobs market, trade market and encourage research and development.

There is also a need for self-defense at the civilian level. People have the right to bear arms, but many choose otherwise due to the inherent dangers of carrying a weapon. A safe and easy to use non-lethal weapon is needed to provide the peace of mind many people desire.

CURRENT TECHNOLOGY

There are multiple non-lethal weapons designed for specific purposes that utilize various methods to disable a human target. These weapons can affect the psychological, physical or both systems of a target. Current techniques include pain inducement or mental disorientation to weaken one's ability to focus through use of projectiles, chemicals, electricity, light and sound. The areas of attack eliminate the senses such as vision, hearing, smell and touch. The most widely used weapons are shown in Figure 1 and described below [11]:

Figure 1: Left to right; flash bang, pepper spray, rubber bullet, taser gun

- Stun grenades or flash bangs are small explosives that emit a very bright light to over stimulate light sensitive cells in the eye causing blindness for approximately 5 seconds. A loud bang also occurs and causes disorientation and ringing in the ears. A significant number of deaths have been reported due to the explosive nature of this device. The blast can also cause material to ignite and catch fire.
- Pepper spray, tear gas and mace are all intended to induce pain and temporarily eliminate vision. Intense pain and loss of vision instantaneously incapacitates a human. These chemicals sprays have come under scrutiny over the past few years. The respiratory system is affected with difficulty breathing and coughing. Breathing this chemical can be deadly due to inflammation of the respiratory tract and a number of fatalities have been recorded. If used in a windy situation it is difficult to aim and possible for the user of the weapon to be back-sprayed.
- Rubber bullets, wax bullets, bean bag projectiles are intended to cause blunt force trauma to the target and can be fired from a standard firearm. The kinetic impact induces severe pain to disable the target. Many cases have reported fractured bones, internal organ damage and death. Accurate marksmanship is required as any impacts to the head have a higher chance of fatality.
- Tasers use an electric shock to disrupt muscle function and induce pain. The effects of muscle dysfunction only occur when electricity is being administered and a target can be considered active when not applied. There have been cases of ventricular fibrillation causing death. Also the amount of electricity to cause ventricular fibrillation depends on the size of the target and the discharged energy from the electroshock is not adjustable.

Evaluation of the physical and psychological long-term effects of the pain-inducing non-lethal weapons on humans has not been studied in great detail. All of the above weapons are widely used today in situations where aggressive force is necessary. Law enforcement agencies have a difficulty dealing with the liabilities of using these weapons. Determining when these weapons can be fired at an individual is in a legal and ethical grey area and many lawsuits have occurred. Recently, some or all of these weapons have become illegal for use by military and law enforcement in certain countries and states. Within the European Union, every country has different laws on non-lethal weapons based on interpretations of International Humanitarian Law and public acceptance. These weapons have coined a new term of less-lethal weapons because of the possible risk of fatality. [6]

LASER DAZZLERS

A new type of weapon called a laser dazzler has been gaining attention from military forces and is truly non-lethal. A laser dazzler uses a beam of light shined into the eyes of a target to temporarily disrupt vision. Being hit is similar to looking directly at the sun. Limited research has been done on these weapons and they are still in the beginning stages of implementation. The typical laser dazzler consists of a laser and an optical lens. The optical lens increases the divergence of the laser beam to create a larger projected circular shape instead of a laser “point”. Light is produced by a laser diode powered by a battery or similar power source and is a very stable system. This weapon comes in many forms such as a handheld firearm, flashlight, rifle attachment, vehicle attachment, and naval ship attachment.

There are a number of benefits from this system. The speed of light allows essentially no delay from when the weapon is fired to the receiving end. Stun grenades have a delay after being deployed and allows time for the target to react. Rubber bullets, Tasers and chemical sprays travel at slower speeds creating difficulty when fired at moving targets at a long distance. The high speed of light also allows for increased accuracy with minimal aiming errors requiring no consideration of wind or leading aim of a moving target at a distance.

The tuning ability of the weapon allows for the variability between a low level warning strength to a high power permanent damage level of light. Theoretically this is achievable, but is not fully incorporated into any laser dazzler currently as will be discussed later. There is no collateral damage to the environment from the laser such as an explosions or hazardous chemicals.

The effects of the laser dazzler can last for an extended period of time unlike a Taser, which is only effective when electricity is being administered. Vision disruption continues after being hit in the eyes with the laser and can continue for 10 seconds to 2 minutes [17]. The duration of the effects depends on how direct and long the exposure occurred. The target's vision will have afterimages and become spotty. It is similar to getting a picture taken in a dark room with a flash, except severely amplified. This effect is also called flash blindness.

Another effect includes pulsing on and off of the laser, which produces nausea and disorientation. This will be called the flicker effect and occurs when the laser light is pulsed at a certain frequency for an extended period of time into the eyes. After the target closes their eyes, this effect can still be induced with the light shining through the eyelids. Dizziness, nausea and confusion can be produced and last for minutes after depending on the duration of exposure. This effect works similar in the brain to people that experience photo epileptic seizures except without such extreme side effects. [7]

These benefits allow laser dazzlers to be more widely used compared to the other non-lethal weapons discussed. Laser dazzlers could be used by the military, law enforcement or civilians. The military can use them for convoy protection and military only zones to notify a target at a long distance to not come closer. They can also be used for crowd control, detaining individuals, countering snipers, blocking line of sight and self-defense. The advantage of a bright light is that it has no language barriers and can be understood by anyone.

The current difficulty with these weapons is meeting the "sweet spot" to disrupt vision and not cause permanent damage. The United Nations held a convention on Certain Conventional Weapons and created the Protocol on Blinding Laser Weapons, also called Protocol IV (Appendix A). This prohibits the employment of a laser weapon specifically designed, as their sole combat function to cause permanent blindness to unenhanced vision. Any laser weapon must meet these requirements. Therefore, no laser weapons can be used by the United Nation's militaries unless it is proven to not have the purpose to cause blindness. [1]

The "sweet spot" where maximum disruption effect takes place without blinding is challenging to meet and no current system can without manual adjustments or firing at targets only within a given range. The trouble with current systems is the constant divergence of the laser beam. This means the weapon's effectiveness changes with the distance to the target as shown in Figure 2. When a target is near the weapon the projected area of the laser's light is smaller creating a higher radiant exposure. Conversely, when a target is far from the weapon the projected area of the laser's light is larger creating a lower radiant exposure. Essentially, the density of the diverged laser beam changes with respect to distance from the source.

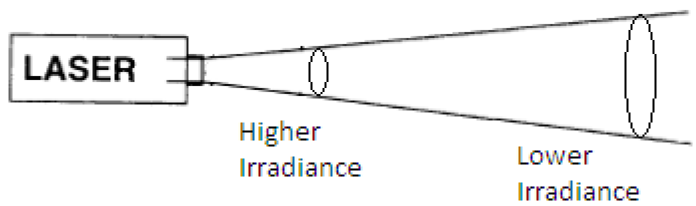

Figure 2: Decreasing irradiance with increasing distance

Radiant exposure and irradiance are two units of measurement to determine the strength of the laser weapon. Radiant exposure in Equation 1 is measured in energy per unit area, usually expressed as J/cm^2 or mJ/cm^2.

$$H = \frac{energy\ (J)}{area\ (cm^2)} \qquad (1)$$

Irradiance in Equation 2 is measured in power per unit area and is expressed as W/cm^2 or mW/cm^2.

$$E = \frac{power\ (W)}{area\ (cm^2)} \qquad (2)$$

Therefore, if a laser is outputting the same energy and the projected area is increased then the radiant exposure and irradiance decreases. Similarly if the projected area is decreased radiant exposure and irradiance is increased.

Another factor to hit the "sweet spot" is the ambient light conditions. The human eye reacts to light and dark conditions by adjusting the diameter of the pupil. This adjustment changes how much light enters the eye. In dark conditions the pupil is larger allowing more light to enter, therefore a lower radiant exposure would be required. In light conditions the pupil is smaller requiring a higher radiant exposure to achieve the optimal disruption in the same period of time.

Lux is another unit of measurement that will be discussed often in this report. Lux is a unit of illuminance, which is a measurement of intensity specific to the human eye. This unit can be converted to irradiance units with consideration of wavelengths using the luminous function.

Current laser dazzlers have inadequate considerations for distance to the target and ambient light conditions creating a less safe and less effective weapon. These incompetent weapons have been issued to military troops around the world. Director Anthony Salloum at Rideau Institute believes these weapons are underdeveloped and have potential to cause permanent damage [10]. For example, certain laser dazzlers can only be used within a specific distant to a target otherwise permanent eye damage can occur. This is due to the divergence issue discussed above. In a combat situation, conditions are not controlled and the distance to a target could occur at any length at any time.

This complication has created many legal issues with Protocol IV and similar treaties not allowing the use of permanent blinding weapons. Since 2007, governments have restricted the use of these weapons and have underpowered them to ensure minimal chance of blinding. The desire for advanced technology and new research on these weapons has been left unsatisfied. [18]

INDUSTRY BACKGROUND

The blinding effect has attempted to be accomplished through the use of different light sources. Incandescent and halogen bulbs used in rifle-mounted flashlights have been used to distract vision, but do not have sufficient power to cause intense disruption of vision.

Bright light emitting diodes (LED) have also been used in an attempt to achieve this affect. One of the first light dazzlers was the LED Incapacitator, which utilized many LEDs with a parabolic mirror to direct light in a forward direction [19]. The problem with these lights is the inability to maintain energy over distance. Light is created due to heat or energy build up on a filament then spontaneously emitting an excited photon. This reaction occurs independently from others and produces an overall light source of a jumble of waves with no relation of phase of waves. This lack of relationship is called incoherence.

Lasers create light in a different manner. In simple terms, excited atoms reflect between mirrors in a resonant like process. The atoms are stimulated to emit in phase with the existing waves preserving the phase over many cycles. This time coherence and spatial coherence between the mirrors allow lasers to emit more power per unit area than other sources. This relationship is called coherence. The difference between coherent and incoherent light is shown in Figure 3. A coherent light source only emits one wavelength or one color of light. Because lasers have the ability to maintain energy levels over long distances, they are the optimal light source to use for a light dazzler weapon. [12]

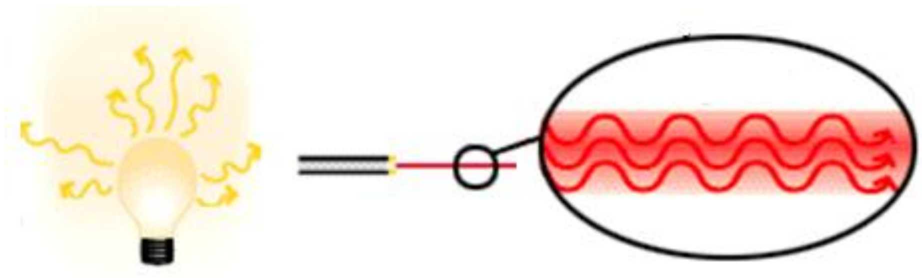

Figure 3: (left) Incoherent light with unaligned wavelengths and phases, (right) coherent light with aligned phase and single wavelength

Laser dazzlers have been gaining popularity, but are currently only used by the military and a few law enforcement agencies. No civilians are allowed to purchase these weapons. The most capable and advanced three systems to date are shown in Figure 4 and described below.

Figure 4: Left to right; CHPLD, Dazer Laser, B.E. Meyers GLARE GBD-IIIC

- Compact High Power Laser Dazzler (CHPLD) was invented in 2007 and is still in use today. It utilizes a 500 Milliwatt, 532 nanometer (green) laser. This device comes with a holographic diffuser. When applied this diverts the laser beam to allow for use on closer targets. To prevent permanent damage, the CHPLD can only be used on a target at a distance greater than 3 meters with the diffuser and greater than 20 meters without the diffuser. The maximum effective range is considered to be 200 meters in sunlight and 2 kilometers at night. Viewing the laser and measuring qualitatively and not quantitatively determined the maximum range. Actual visual disruptions with aftereffects are considered to be at a much shorter distance.

- Dazer Laser Defender (Appendix B) is the most current handheld model and the most developed of the three. The laser has a power of 500 mW and wavelength of 532 nm (green). This weapon has a day and night mode that takes into consideration the changes of ambient light conditions. It also has an optical lens system to create variable divergence to allow the use on targets at various distances while maintaining vision disruption values. The effective range is from 1 to 2400 meters with 14 predetermined interval settings. The problem is the lenses and light settings are changed manually. This weapon could not be used effectively in any element of surprise. If law enforcement were to rush into a room and the lights were off, but the weapon was set on day setting then there is no time to change the setting and there is a higher potential for injury. A similar scenario could occur if the distance is unknown to a target. This weapon also includes flashing to cause confusion and disorientation of the target.
- B.E. Meyers GLARE GBD-IIIC is the most widely used model by the military and can be rifle mounted. The laser has a power of 250 mW and wavelength of 532 nm (green). The effective range is 300 meters in the day and 4 kilometers at night. It cannot be used within a range of 39 meters. A number of accidents have been reported in Afghanistan of soldiers being blinded from being too close to the weapon. A new version, GLARE LA/9P, was developed with a safety control module (SCM) that can estimate the distance to the target. The SCM shuts down

the weapon if it determines the distance to be within 39 meters rendering the weapon useless. [6]

These weapons have made small advancements over the last five to ten years, but little research has been done to test their effectiveness and light energies. More research is needed to improve the safety and capabilities.

GOAL OF THIS RESEARCH

The goal of this research is to develop, define and prove new laser dazzler knowledge and equipment. The main issue with these weapons as briefly discussed was the inability to meet the optimum radiant exposure at a target of varying distance and ambient light conditions. Dazer Laser Defender is the only weapon to account for this, but requires manual adjustments, which are impractical in a combat situation. To improve on this idea a control system with the logic to evaluate distance and light conditions will be developed. This system will output the necessary light values to cause optimum vision disruption with no risk of permanent blinding. This control system will create a simple point and shoot system with no required input of the user besides activation of the system. The design will be considered a proof of concept and not intended for practical use. Meaning it will not have the proper ergonomics to fit in the hand and will not have proper aesthetic appeal.

To accomplish this proof of concept, the laser dazzler can be broken down into six main subsystems of lasers, optical lenses, distance sensor, luminosity sensor, control system and structural.

The lasers will need to deliver the specific wavelengths of light at the correct energy according to values determined through research. The optical lenses are comprised of a telescoping lens system with motor and mechanical components to drive the movement. The purpose of this subsystem is to change the divergence of the laser beam.

The distance sensor and luminosity sensor will read the external variables for use in the control system. These sensors will be secured in place by the structure. The structure will provide the connections of all subsystems and allow linear movement of the optical lenses.

The control system will contain the logic of the device. It will be comprised of functions including inputs from the distance sensor and luminosity sensor and will output data for optical lens position consequently changing the divergence. The logic of the system will have three inputs; distance to target, ambient light condition and an off on switch.

Research will provide values of the maximum permissible exposure (MPE), which is the maximum radiant energy the eye can accept before permanent damage. Values for the size of the pupil in different brightness levels will need to be found in order to determine how much energy is capable of entering the eye. To fully optimize the system, research will also be conducted on the frequency providing the best flicker effect and the color of the laser to cause the most disruption to vision. Green has been the current accepted color for laser dazzler based on simple assumptions. Research will discover how color affects the eye and determine the best color for a laser dazzler.

Calculations will be needed to determine the divergence of the optical lenses. The MPE will determine the calculated projected area of the laser, which will determine the required divergence. The divergence will provide the values for the telescoping lens system in turn defining motor movement and mechanical components. Testing will be conducted to confirm these values and enhance the system.

With these subsystems, calculations and research an optimized laser dazzler can be developed. The required radiant exposure can be met at any distance to the target and in any light condition with no input from the user. This proof of concept will contain all of the capabilities of current laser dazzlers plus the simplicity and safety of a point and shoot weapon.

LITERATURE RESEARCH

With the purpose of designing a superior laser dazzler the following research was conducted to fully comprehend the process of laser interactions with the physical and psychological mechanisms of the human eye and body. The subsequent information will cover:

1. Structure and mechanics of the eye
2. Photoreceptors reaction to light and color
3. Laser injuries and maximum permissible exposure (MPE)
4. Flicker effect and pulsing frequencies

1. STRUCTURE AND MECHANICS OF THE EYE

It is important to understand how light enters and interacts with the eye because this is the sole function of the laser dazzler. Seen in Figure 5 is the general structure of the eye. The eye allows light to enter through an aperture called the pupil. The diameter of the pupil can be changed by the iris, which responds to the intensity of light. In low light conditions the pupil will increase in size making laser exposure more dangerous and conversely in bright conditions the pupil will decrease in size.

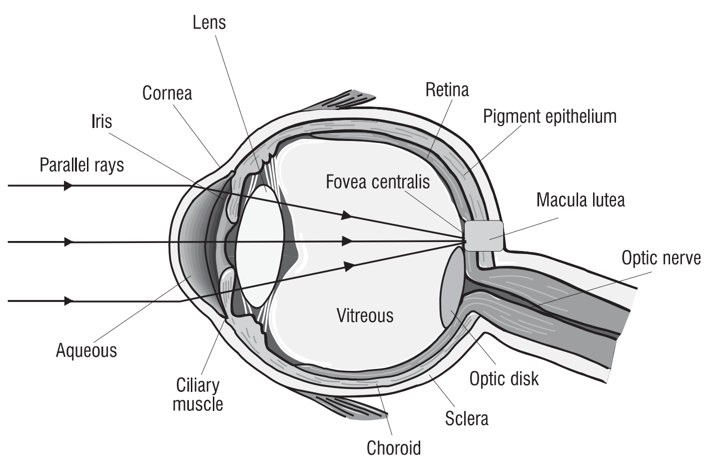

Figure 5: Structure of the human eye

In 1993, Barry Winn and his colleagues investigated the effect of luminance and the pupil size of humans at varying age, gender and iris color [24]. Various factors can affect the pupil size such as retinal luminance, state of the eye, and sensory or emotional conditions. Humans under the influence of certain drugs or with mental health conditions can have unpredictable pupil dilation occur no matter the lighting condition. All testing was conducted with the eye fully adapted to the environment. A problem encountered with measuring the pupil diameter is the pupil size is never entirely at rest, but experiences constant oscillations called hippus. 91 subjects were tested at 5 different luminance levels of 2.15, 10.5, 52.5, 263 and 1050 lumens per square meter (lum/m^2).

All but 2 of the subjects demonstrated a linear relationship between pupil diameter and log luminance. Pupil size showed no dependence of gender or iris color, but the age of the subject did have an affect as shown in Figure 6. It can be seen the average pupil diameter of a 20 year old can be up to 40% larger than the average 60 year old given the same luminance.

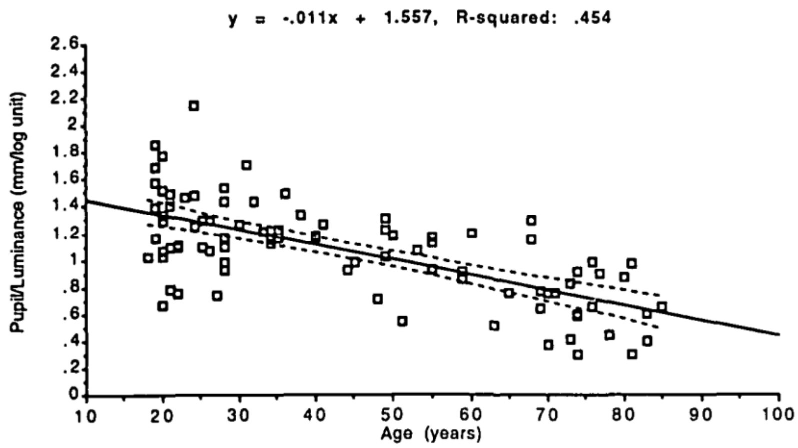

Figure 6: Pupil size versus age

In 2002, MacLachlan performed studies of the pupil diameter with illumination. The relationship found was again log linear with the pupil size decreasing with illumination increasing. Equation 3 was found to fit this relationship.

$$Pupil\ Diameter\ (mm) = 2.3 - 0.7 * \log[luminance\left(\frac{cd}{cm^2}\right)] \qquad (3)$$

The rate at which the pupil changes size was also noted. From complete illumination of 2100 lux to total darkness the pupil will reach 98.8% of its final diameter within 60 seconds. Subjects showed 80-90% of the total change in pupil diameter was accomplished in the first 3 seconds. [15]

Previously, Groot and Gebhard [9] also studied the relationship between luminance and pupil diameter. They collected data from eight separate studies and fit a function to describe the results. Pupil size generally ranged from approximately 2 to 7 mm. The best-fit result is shown in Figure 7 and in Equation 4:

$$\log[d\ (mm)] = 0.8558 - 0.000401 * (\log[luminance(millilamberts)] + 8.1)^3 \qquad (4)$$

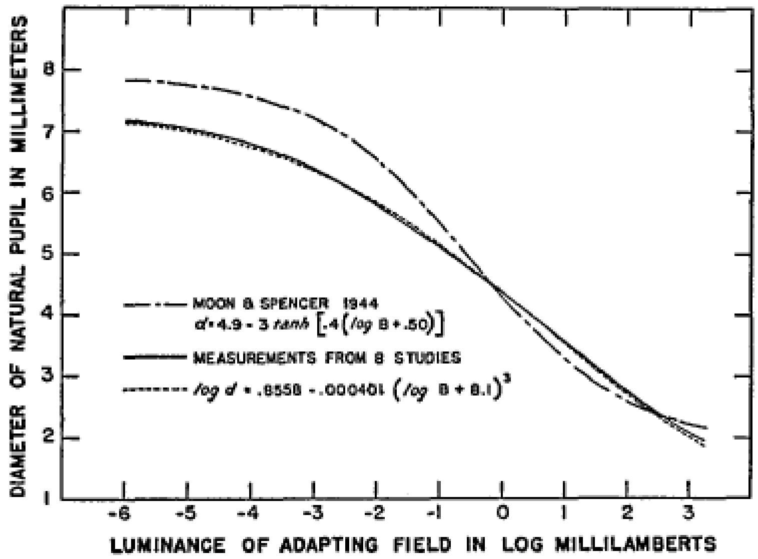

Figure 7: Pupil diameter size versus luminance

The cornea is the outermost surface of the eye protecting it from environmental damage such as dust. Mild injuries to the cornea heal quickly because corneal cells replace themselves about every 48 hours. The cornea absorbs infrared light at wavelengths greater than 1400 nm. This prevents vision and retinal injuries from these wavelengths of light. [16]

The lens is a transparent structure located behind the pupil and focuses light onto the retina. The intensity at the focal spot on the retina can be 100,000 to 200,000 times greater than the intensity affecting the iris [5]. This increase of intensity can cause photochemical damage and thermal damage. Ultraviolet light wavelengths below 400 nm are absorbed by the lens and cornea not allowing this light to reach the retina. Therefore, these wavelengths cannot be seen or cause a blinding effect.

The aqueous humor and vitreous humor is a liquid and jelly like substance that helps maintain the shape of the eye. They can absorb heat to protect the internal portion of the eye from thermal radiation. [16]

The retina, macula and fovea are the main areas of focus because these parts absorb visible (400 – 700 nm) and near infrared (700 – 1400 nm) light and are susceptible to laser damage. The absorption of photons in these parts creates a chemical reaction sending messages to the brain for interpretation. The macula and fovea are located on the retina and have the highest density of photoreceptor cells to provide acute vision. The lens densely focuses light onto these parts, which can cause permanent damage if the energy is too great. [20]

2. PHOTORECEPTORS REACTION TO LIGHT AND COLOR

Vision begins with absorption of light by a photoreceptor cell in the retina. These cells allow phototransduction, the conversion of light radiation to electrical signals to stimulate biological processes. The photoreceptor contains pigment made of a protein, which determines the wavelength of light that can be absorbed and trigger a change in the cells potential.

The two main photoreceptor cells contributing to vision are called rods and cones. Rods are very sensitive and support vision at very low light levels. The proteins in these cells are most sensitive to a wavelength of 498 nm. This explains why it is difficult to view colors in low light situations because only this type of cell is triggered. In a changing light condition, as from bright to dark, it can take up to 30 minutes for these cells to fully adjust.

Cones require brighter light to produce a signal. Human vision is trichromatic meaning any color can be created by a mixture of three primary colors. Subsequently, there are three different proteins that a cone photoreceptor could have with each being most sensitive to a specific wavelength. The three types of cones cells are simply called short (S-cone or blue), medium (M-cone or green) and long (L-cone or red). S-cones contain a protein that more readily absorb short or blue wavelengths of light and are most sensitive to 420 nm (blue). M-cones are most sensitive to 534 nm (green) and L-cones are most sensitive to 564 nm (red). Figure 8 shows the respective linearized frequencies of light each type of cone can absorb. [3]

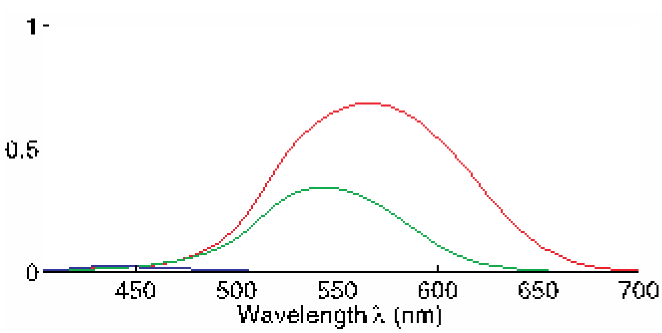

Figure 8: S, M, and L cone sensitivities to wavelength

Depending on the amount of each type of photoreceptor that is stimulated and actively producing a signal will be interpreted as a color by the brain. For example, if red and green photoreceptors in close proximity of one another are stimulated then the brain takes these signals and interprets it as a mixture creating yellow. The human retina has approximately 120 million rods and 5 million cones with the rods contributing very little to color interpretation. [3]

In 2011, Li Zhaoping reevaluated the cone density ratios [27]. Throughout the retina, S, M and L cones are distributed in certain locations and in different quantities. The cone density ratio normalizes the quantity of each type of cone to the other types.

Previous research has estimated the cone density ratios to be $d_L : d_M : d_S = 6:3:1$. Evidence suggests densities can vary up to $d_L : d_M : d_S = 30:15:1$. His findings discovered an average of $d_L : d_M : d_S = 13:9:1$ due to the variation and range of possible densities in humans. Hence, L (red) and M (green) cones significantly outnumber the amount of S (blue) cones in the retina.

Only L and M cones are found within the fovea, the region of the retina for acute vision. There are no S cones because this would defocus vision. The lens of the eye acts as a prism and will refract short wavelength light more than long wavelength light. The refracted short wavelength light would stimulate a different area of photoreceptors than long wavelength light. Therefore, to prevent sharp images from distorting no S cones are within the fovea. Figure 9 shows the approximate density population on the retina with no S cones in the center fovea. [21]

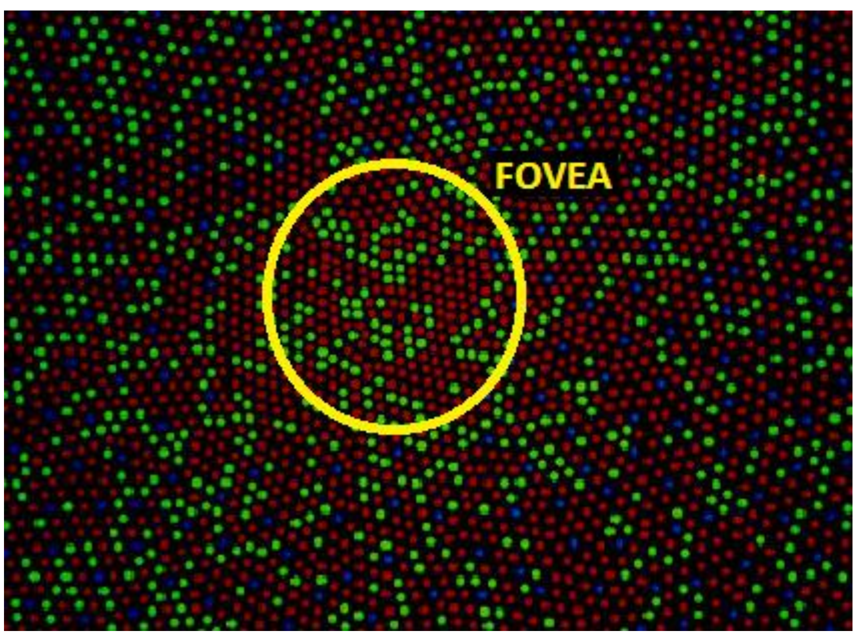

Figure 9: Cone density representation

A human's brain defines colors in values of hue, saturation and brightness. Hue is the psychological dimension of color, which relates to wavelength. Saturation is essentially the purity of the color. Brightness is the dimension corresponding with the color intensity. The eye and brain determine brightness by the number of photoreceptors reacting to photons. The retina consists mostly of L (red) and M (green) cones and this makes up what is called the luminance channel. The level of activity in the luminance channel determines the brightness that is interpreted by the brain. Different from the luminance channel is the red-green opponent channel, which determines color along a red and green scale. This psychological effect inhibits humans from seeing a reddish green color, because it is an opponent channel. Half of the neurons in this channel stimulate to red light and inhibit green light and half of the neurons stimulate to green light and inhibit red light. Since they cannot be stimulated simultaneously the perception of yellow is created. The blue-yellow opponent channel works in the same manner. Figure 10 is a diagram of luminance and color interpretation from photoreceptor cells. [21]

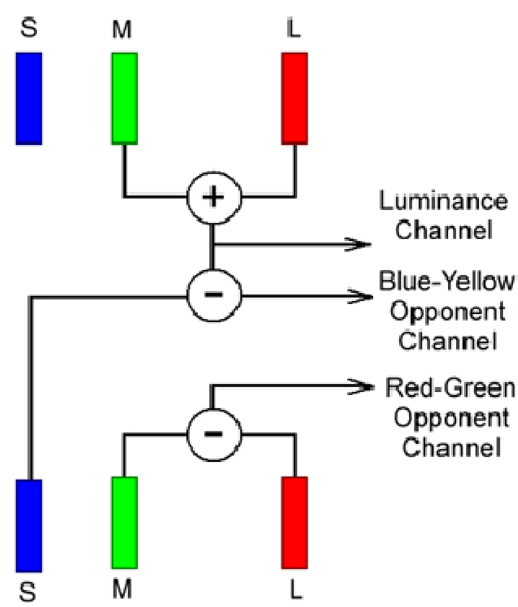

Figure 10: Luminance and opponent channels for color interpretation

The luminosity function describes the overall average spectral sensitivity of the human eye. It is used to describe the relative sensitivity to light of different wavelengths. Equation 5 utilizes the luminosity function and can be used to convert radiant energy into luminous energy.

$$B = 683.002\ \frac{lumens}{Watt} \int_0^{\infty} \bar{y}(\lambda) J(\lambda) d\lambda \qquad (5)$$

Where B is lumens, $J(\lambda)$ is watts per m, $\bar{y}(\lambda)$ is the luminosity function and λ is wavelength.

Phototransduction in cones is unique because when a photoreceptor is stimulated by light this actually reduces the cells activity. Photoreceptor cells are constantly opening and closing chemical channels to send signals. An advantage of this is in a dark room all cells will be actively open and any random closing will not affect the signal thereby limiting noise. The disadvantage of this is once a cell has closed due to being stimulated by a photon it takes time for it to regenerate and open to produce the chemical signal. If a very bright light stimulates many cells at one time the length of time to regenerate can be seconds to minutes [14]. This is called photopigment bleaching and produces afterimages.

In 1971, Jack Loomis [14] investigated photopigment bleaching and afterimages. It was known at this time the afterimage produced from colored light appeared as the complimentary color. For example, if a subject were exposed to green light and then the viewer stared at a white wall a red afterimage would appear. This is due to the green photoreceptors inability to send a signal while the red photoreceptors are stimulated by the white wall consequently making the white wall appear red. Loomis tested multiple light color combinations on subjects and recorded the intensity and duration of the afterimage as described by the subject. A red light had the longest afterimage duration of 90 to 120 seconds. Blue and green light had shorter durations of approximately 10 seconds. Also in his work he tested low light bleaching conditions and deliberated the possibility of neural adaptation afterimages. Neural adaptation includes psychological afterimages produced in the brain rather than the physical adaptation of the photoreceptors.

In 2012, researchers at The University of Chicago's Department of Surgery [26] added to Loomis's work. They agree that the proposed physiological mechanisms for afterimages are both due to bleaching of cone pigments and neural adaptation. Afterimages proved to have significant effect on selective attention and consciousness. They found cone adaptation able to occur within milliseconds and the time constant for exponential decay of the image to be 5 to 12 seconds.

3. LASER INJURIES AND MPE CALCULATION

There have been a number of reports and case studies of retinal injuries from lasers. Brief exposure to a common Class I laser pointer poses little threat of permanent eye damage. Laser classifications can be found in Appendix C. The Food and Drug Administration requires warnings to be placed on laser pointers to warn of the dangers. The British government has completely banned the use of all Class 3 lasers for people's safety. [4]

Pain is not a symptom of being flashed with a laser because there are no pain receptors in the retina. Psychological symptoms consist of discomfort, confusion, disorientation and loss of situational awareness and can persist for an extended period following exposure. [17]

A case report from 2010, [22] describes a retinal injury obtained from a 20 mW green laser. The patient gazed at the laser for approximately 1 second with no disturbing immediate symptoms. A few hours later the patient noticed mild loss of vision in one eye. Retinal damage had occurred, but over the next two months vision improved. It is likely once the patient perceives danger from exposure, the damage has already occurred.

Another report in 2007 [25] came from a 5 mW green laser. The patient received two flashes of about one to two seconds each. The patient noticed a scotoma or a dark spot in their vision. Pictures of the retina revealed lesions. Sight recovered over the next two months.

There are two types of injuries from a laser, delayed photochemical reaction injuries and acute thermal damage from laser energy absorption. The lens ability to focus light on the retina concentrates the laser causing injuries to the eyes to be much more likely than injury to the skin. Infrared lasers are especially dangerous because this light is absorbed by the retina, but is not visible and gives no warning of exposure. The only immediate indication that damage is being done by an infrared laser is a clicking sound in the eye or loss of vision. Only wavelengths of 400 – 1400 nm can cause damage to the retina. Other wavelengths are absorbed by the cornea or lens. Delayed photochemical injuries typically occur more than thermal injuries and cause scotomas. Thermal injuries are burns on the retina causing hemorrhaging and permanent loss of vision is probable. Figure 11 shows these injuries on the retina. [20]

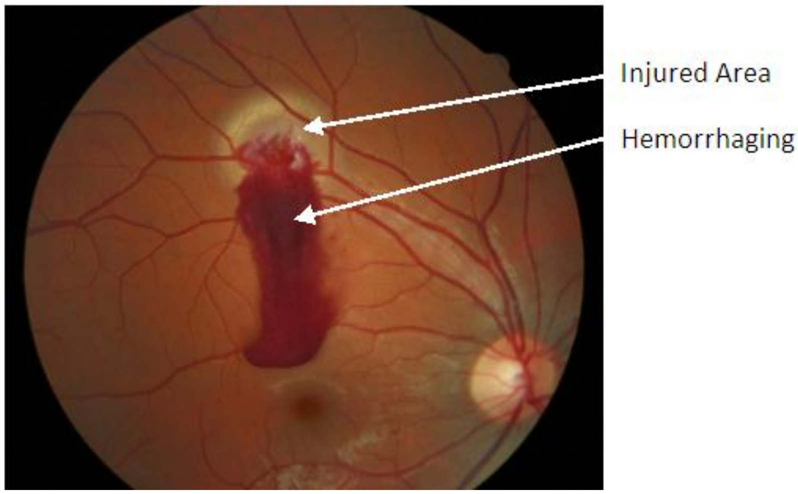

Figure 11: Retinal damage from laser pointer

To prevent these injuries the American National Standard for Safe Use of Lasers was developed [2]. A compilation of research and studies defined what radiant exposures are safe for the eye to be exposed to. The maximum permissible exposure (MPE) is the level of laser radiation exposure a human can accept without injury. This value is measured at the front of the cornea and includes the effect of optical gain from the lens focusing the beam on the retina. Exposure from more than one wavelength at the same time are additive. Each wavelength can be evaluated independently and summed for a combined MPE. The MPE includes characteristics of wavelength, output power, pupil size and duration of exposure.

In order to calculate MPE from a pulsed laser both photochemical and thermal injuries need to be considered. ANSI Z136.1-2007 has developed three rules for laser safety to protect the eye. The equations and assumptions for these rules are provided in Appendix D. These rules provide the radiant exposure, $MPE\!:H$, in mJ per square cm or energy per unit area. Also, the irradiance, $MPE\!:E$, in mW per square centimeter or power per unit area.

Rule 1: Single-Pulse MPE. Exposure from a single pulse in a group of pulses must not exceed the MPE. This case protects against thermal damage when the single pulse is greater than the average energy. Exposure time is considered to be 0.25 seconds, which is determined from the blink reflex.

Rule 2: Average Power MPE. The exposure from a group of pulses delivered before the blink reflex must not exceed the MPE. That is, the total radiant exposure over time must not exceed the MPE. This rule protects against cumulative injury from photochemical damage and heat buildup for thermal damage.

Rule 3: Multiple-pulse MPE. The exposure for a group of pulses must not exceed the single-pulse MPE multiplied by a multiple-pulse correction factor. All pulses occurring within the blink reflex are treated as a single-pulse to protect against sub-threshold pulse-cumulative thermal injury.

Using Table D3 with a wavelength between 400-700 nm and exposure duration of 0.25 seconds provides Equation 6 and 7 to calculate the MPE.

$$MPE\!:H\ \left[\frac{\mathrm{mJ}}{\mathrm{cm}^2}\right] = 1.8 * t^{0.75} \qquad (6)$$

$$MPE\!:E\ \left[\frac{\mathrm{mW}}{\mathrm{cm}^2}\right] = \frac{MPE\!:H}{T} \qquad (7)$$

Where t is the time for a single pulse and T is the time for a cycle. A cycle is considered the on and off time combined or the inverse of the frequency.

Figure 12 is a plot of radiant exposure versus exposure duration. This plot illustrates the amount of energy the eye is capable of accepting for a given time. The shorter the exposure time, less total radiant exposure can be delivered safely in that time. The longer the exposure time, the eye can handle more cumulative energy over a longer time.

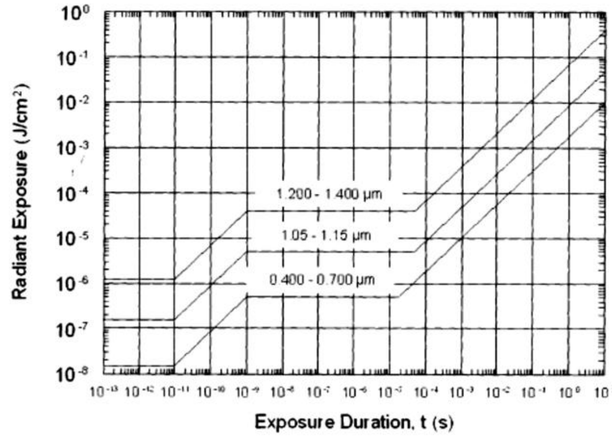

Figure 12: Radiant exposure versus exposure duration

Figure 13 is a plot of irradiance versus exposure duration. The higher the power or irradiance the less exposure time the eye can accept. The lower the irradiance the more exposure the eye can handle safely. The dashed line indicates photochemical effects and the solid line indicates thermal effects.

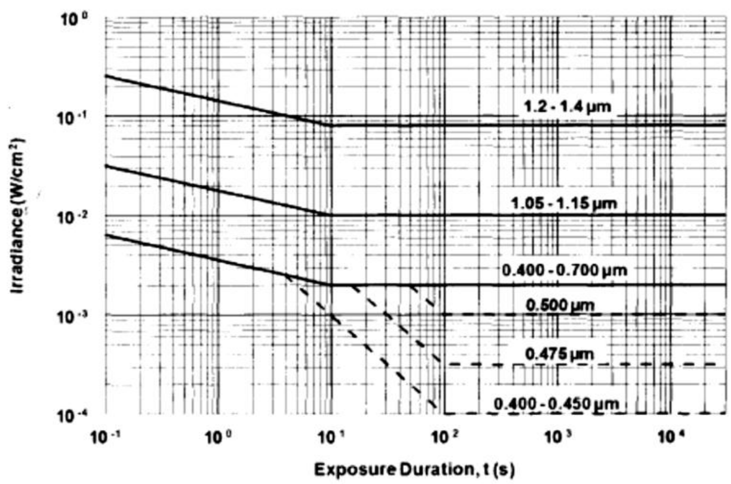

Figure 13: Irradiance versus exposure duration, solid line is thermal MPE and dashed line is photochemical MPE

The above rules apply to intrabeam viewing and diffuse reflections. Intrabeam viewing is the laser directly entering the eye and diffuse reflection is the laser beam reflected off a wall and into the eyes. Figure 14 and Figure 15 portrays the differences and displays the variables of the two.

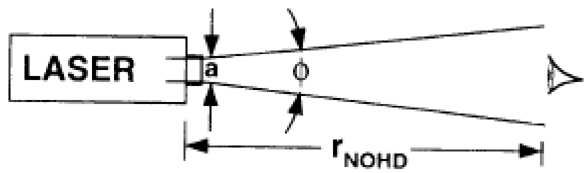

Figure 14: Intrabeam viewing

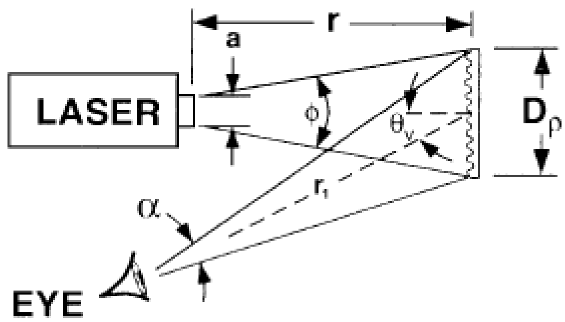

Figure 15: Diffuse reflection viewing

The nominal ocular hazard distance (NOHD) needs to be calculated for intrabeam viewing. This is the threshold distance at which exposure without injury can occur for 0.25 seconds and is calculated by Equation 8. This equation can be used after the MPE has been determined.

$$r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{1.27\Phi}{MPE{:}E} - a^2} \qquad (8)$$

Where r_{NOHD} is the nominal ocular hazard distance, ϕ is the beam divergence, Φ is the power of the laser, $MPE{:}E$ is the maximum irradiance and a is the exit diameter of the laser beam. This equation applies to pulsed lasers and not continuous wave lasers.

For a diffuse reflection the nominal hazard zone (NHZ) needs to be calculated. This is the distance at which the reflection of a laser beam can be viewed with respect to the power of the laser and the angle it is viewed upon. Equation 9 can calculate NHZ after the MPE has been determined.

$$r_{NHZ} = \sqrt{\frac{\rho * \Phi \cos\theta}{\pi * MPE{:}E}} \tag{9}$$

Where r_{NHZ} is the nominal hazard zone, ρ is the reflectivity of the surface, Φ is the power of the laser, θ is the angle the viewer is from the surface and $MPE{:}E$ is the maximum irradiance.

A laser beam that is diffused by optical lenses does not project a flat top distribution of energy. The projection is Gaussian beam, which has higher energy values in the center than at the edges as shown in Figure 16. For proper safety measurements the laser beam's energy should always be measured in the peak region.

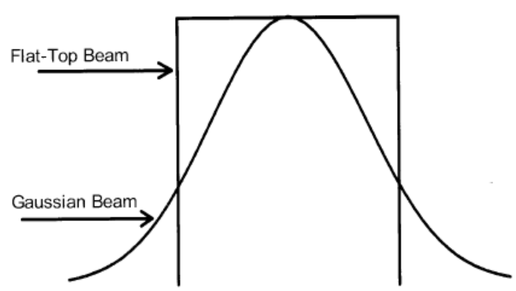

Figure 16: Flat-Top beam versus a Gaussian beam

When light is transmitted through a medium such as air or optical lenses some of the light intensity is absorbed decreasing the strength of the beam. The absorption is minimal in air over short distances and is virtually negligible. Lambert's Law in Equation 10 provides the amount of irradiance lost in a system.

$$E_x = E_0 e^{-\sigma x} \tag{10}$$

Where E_x is the irradiance after travelling through the medium, E_0 is the irradiance entering the medium, σ is the absorption coefficient dependent on the material and x is the thickness of the medium.

4. FLICKER EFFECT AND PULSE FREQUENCIES

Numerous studies have been done on the effects of flashing or pulsing light effects on humans. This has been mainly due to people with a certain condition called photo epileptic seizures (PES). Certain frequencies of pulsing light can cause an overstimulation of the nervous system and an interaction of conflicting stimulation of different receptors. An individual that does not have PES can still experience symptoms of nausea and confusion similar to motion sickness. Research on these effects has also been conducted on helicopter pilots. Reports have shown a large number of pilots have experienced this effect from the sun shining through the blades of the helicopter causing flashing.

In the 1950s, Dr. Ulett studied these effects and called them flicker sickness. It is noted this photic stimulation can cause immediate sensations of spinning and vertigo. His testing was conducted on over 500 subjects. He found the symptoms appeared when the frequency of the light flashing matched the frequency of the subject's brain waves. Many subjects experienced headaches long after stimulation of only five minutes. Frequencies other than that of the brain waves have little to no effect. Frequencies were varied from 2 to 30 Hz with the most effective being approximately 10 to 12 Hz. [23]

In 1964, Robert Benfari conducted his own research to better understand what helicopter pilots were experiencing. Pilots were placed in front of a projector and the light was pulsed at a range of frequencies. Two thirds of the subjects he tested could not continue testing after 9 minutes of exposure due to various symptoms and the other third suffered from profuse sweating, dizziness and blood pressure disturbances. His test was not to determine the exact frequency although it was noted to vary from 5 to 15 Hz. [7]

In 2011, John Cass studied how flicker frequency can be used to capture attention. He notes there are two temporal channels, one low frequency and one high frequency. The fundamental idea of his research was to have multiple flashing objects at different frequencies on a screen in front of a subject and then determine if one frequency stands out amongst the others. The high frequency channel peaks between 8 to 12 Hz and the low channel is around 1 to 3 Hz. The results show the high frequency channel to be the most affective at capturing attention. [8]

SUMMARY AND EVALUATION OF LITERATURE

In order to design a superior laser dazzler the existing research must be evaluated and applied to the proposed solution. First taking the pupil's variable size into consideration would require the laser dazzler to vary the output energy depending on the illuminance of the current situation. To simplify the design and functionality of the control system two settings of a light condition and dark condition will be created for the variation of pupil size. The system will be optimized for the range of a 25 to 40 year old person according to Barry Winn's studies. It will be assumed the pupil diameter will maintain a size of 7 mm in dark conditions and 4 mm in standard room light conditions according to the pupil dilation functions. Hippus, continuous pupil fluctuations, can be neglected because the variation in size is insignificant. Pupil size is not completely determined by the ambient light, but rather the brightness of the point in the center of vision. For example, if someone was in a dark room with only one light and they were staring directly at the light then the pupil size would likely vary from the estimated diameter determined from the ambient light condition. This situation will be neglected as well as it will be virtually impossible to determine what a target could be staring at before the weapon is discharged and the likelihood of a large variation in pupil size from ambient condition is considered minimal. No other conditions such as gender, iris color or visual aids such as glasses will be considered at this time.

Light interacting with the retina creates vision. The only wavelengths reaching the retina are visible (400-700 nm) and infrared (700-1400 nm). Infrared light cannot be visualized due to the photoreceptors insensitivity to this wavelength. This could pose a serious danger because no blink reflex could be initiated until damage has already occurred. The visible light wavelengths are the best for a laser dazzler for this reason.

The sensitivity and the density of the photoreceptors determine the optimum wavelengths in this region. Rods contribute little to color and acute vision making them not the ideal target for a laser dazzler. Cones are sensitive to color and are responsible for acute vision. S cones (blue) make up a very small portion of the photoreceptor population, less than 5% according to Zhaoping [27]. Because the number of cones stimulated mainly determines brightness, the S cones small percentage makes them less than the ideal target for vision disruption. M (green) and L (red) cones make up the vast majority and are the only type of cone in the fovea. The level of activity of red and green cones is interpreted by the luminance channel and generates psychological brightness. Therefore, these are the photoreceptors to target.

M (green) and L (red) cones are most sensitive to wavelengths of 534 nm and 564 nm. These are the wavelengths the laser dazzler must produce to have the maximum disruption of vision. It is now easy to see why current laser dazzlers have green lasers, although these lasers are operating at a wavelength of 532 nm. This one wavelength is stimulating most of the M cones, but only a fraction of the L cones. L cones outnumber M cones by nearly 2 to 1. Therefore, current dazzlers are not meeting the optimal frequencies. Two frequencies should be incorporated at the peak sensitivities of 534nm and 564 nm.

Eye injuries can occur in fractions of a second depending on the strength of the laser. Permanent vision loss or scotomas ensue when the MPE is exceeded. In the design of the laser dazzler calculations must be done to evaluate the maximum radiant exposure and irradiance acceptable for the specific lasers used. Analysis will be done using American National Standard of Safe Use of Laser equations. The calculations will be done under the assumption that the duration of exposure is the length of the blink reflex of 0.25 seconds.

For intrabeam viewing, the nominal ocular hazard distance should be at the targets distance. This will be achieved by varying the divergence of the laser beam by a telescoping optical lens system. The divergence will change according to the distance to the target. The nominal hazard zone does not pose a serious threat to eye safety due to the system being optimized for intrabeam viewing. This calculation can provide a value to determine how strong the beam is after reflecting off a surface such as a cotton shirt. This could be beneficial because if the target put their head down to avoid the laser, the reflection could still have a slight disorienting effect.

A laser beam diverged by optical lenses creates a Gaussian beam with the highest power in the center. All testing measurements will be taken from the center or maximum point of the laser beam. This will ensure the maximum possible exposure is being accounted for. Calculations of Lambert's law (Equation 10) will be neglected due to the minimal absorption value of the optical lenses. Although, this equation can provide useful values in determining the effectiveness and safety of protective eyewear or for systems used in long-range applications.

Pulsing the laser could amplify the disorienting affects along with flash blinding. The research studies are all in agreement with the range of frequencies causing nausea and motion sickness like symptoms. A frequency of 12 Hz falls within the range of optimal frequencies. Although serious symptoms are not likely to occur in the short period of exposure of 0.25 seconds but, the weapon can still be affective once the eyes are closed or not staring in the direction of the weapon. This intense light can go through the eyelids and reflect off clothing.

From this research a laser dazzler can be designed with the optimal settings. The calculations will be accomplished once all the component properties are defined.

EQUIPMENT AND ASSEMBLY

Briefly described earlier, this proof of concept laser dazzler will consist of six subsystems of lasers, optical lenses, distance sensor, luminosity sensor, control system and structural elements. The subsystem components were either custom built or purchased and are described below. A full list of equipment is included in the bill of materials in Appendix E. All of the individual part specifications can be found in

Appendix F. The electronic schematics are shown in Appendix G. The completed system with all components attached is shown in Figure 17 and multiple figures of the completed system are in Appendix H.

Figure 17: Complete assembled system

1. LASERS

Two lasers were purchased and the complete specifications are in Appendix F1. The first laser is a 150 mW and 532 nm (green) laser module. The second is a 200 mW and 660 nm (red) laser module. These laser modules include the diode, driver and casing to ensure proper current is delivered and limiting temperature fluctuations. The operational voltage is 3.7 to 4.2 V. Increasing the voltage increases the intensity of the laser beams. The modules have a simple focusing system to collimate the beam with minimal emitted divergence. The emitted beam is approximately 2 mm in diameter with an initial divergence of < 5 mrad. These lasers are classified as 3B and protective eyewear is required for testing.

These lasers were chosen based on their power output, wavelengths and cost. The power output is comparable to current laser dazzlers and can create the necessary energy to cause flash blindness. The green laser's wavelength of 532 nm is consistent with current research and matches closely to the M cones peak sensitivity of 534 nm. The red laser's wavelength of 660nm was not ideal and somewhat distant from the peak wavelength of the L cones sensitivity of 564nm. This was the closest available wavelength for purchase with consideration of cost. A krypton gas-ion laser can have an output of 568 nm, which would be much closer to the L cones peak sensitivity of 564 nm.

Class 3B lasers are capable of permanent blinding in short periods of time. The MPE calculations can confirm the allowable radiant exposure and irradiance levels from these lasers. The control system provided the ability to pulse the lasers. The electronic schematic is shown in Figure G1. An electronic switch allowed the system to be changed from a pulsing beam to a constant beam.

2. OPTICAL LENSES

The optical lenses allow variable divergence of the laser dazzler. Each laser has a telescoping lens system. The telescoping lens system consists of a convex lens and a concave lens. The distance between these two lenses can change the divergence. The lenses specification can be found in Appendix F2.

The first lens is plano-convex with a focal length of 30 mm. It has a diameter of 11 mm and is grade 1, meaning very high quality with no scratches or chips. This lens also has an anti-reflective coating to minimize any reflective energy loss in the lens.

The second lens is plano-concave with a focal length of -15 mm. It has a diameter of 15 mm and is also grade 1 with an anti-reflective coating. These lenses were chosen to be plano (one side is flat) because this helps to minimize spherical aberration in compound lenses. Spherical aberration is the lens inability to focus all light rays on to one point. The farther from the center of the lens the greater this effect becomes, causing distortion and can increase the negative properties of a Gaussian beam.

The focal point of compound lenses, as a function of distance between the lenses, is determined by the thin compound lens equation.

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \qquad (11)$$

Where f is the focal length of the system, f_1 is the focal length of the first lens, f_2 is the focal length of the second lens and d is the distance between the lenses. Values to determine the projected area or diameter can be determined by geometry once focal length has been found.

3. DISTANCE SENSOR

The distance sensor is a Sharp GP2Y0A710K0F measuring unit. The specifications can be found in Appendix F3. It utilizes an infrared beam, position sensor unit, receiver and the logic of triangulation to determine distance. It is capable of detecting a range of 100 cm to 550 cm accurately. This range may not be ideal for real world applications, but is useful for the purpose of proof of concept.

The sensor has an output voltage terminal for input into the control system. The Sharp distance sensor provides the output voltage compared to distance. This relationship is non linear and is displayed in the distant sensor specifications. An analogue to digital converter (ADC) will be used to convert the signal from the sensor and improve overall performance. The distance sensor electronic schematic is shown in Figure G2.

4. LUMINOSITY SENSOR

The luminosity sensor was constructed using a simple photoresistor. A photoresistor changes its resistance according to the amount of light it is exposed to. These devices are limited on their accuracy. Since it was determined the proof of concept laser dazzler will only need to detect a light and dark condition, the photoresistor is acceptable for this application. When fitted into an electrical circuit, this device will be able to output a voltage that depends on external light intensity. An ADC will also be used for this system to increase the overall performance. The luminosity sensor electronic schematic can be found in Figure G3.

5. CONTROL SYSTEM

The control system is a Parallax BASIC Stamp microcontroller. The output voltages from the distance and luminosity sensors are input into the program. Equations described in the calculations section are the foundation of the code written in PBASIC. The code shown in Appendix I outputs a position for the motor, consequently changing the distance between the lenses to ultimately change the laser divergence. The electronic schematic for the device is shown in Appendix G.

6. STRUCTURAL

The structure will provide the proper interactions between all of the subsystems. The model was built in Autodesk Inventor then printed by a 3D rapid prototyper. The rapid prototyper uses fused deposition modeling and constructs the object out of plastic. This method allowed for prompt testing and quick turnaround of design iterations. The dimensions and CAD drawings are illustrated in Appendix J. The assembled structure is shown in Figure 18.

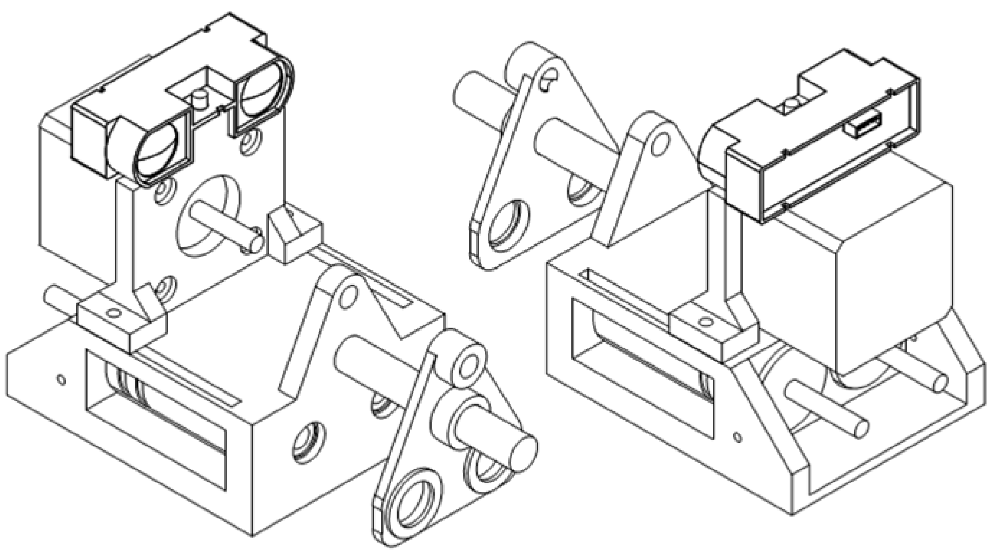

Figure 18: CAD of laser dazzler concept

The structure is made up of three pieces. The base has locations for the lasers to be inserted and directed forward. It has mounting locations for the plano-convex lenses directly in front of the laser beams. There are adjustable slots on top for the motor mount piece and a support hole for the camshaft. A rod in the front creates only linear movement for the lens slide piece.

The motor mount connects to the top of the base and can be adjusted forward and backward to fit all other components such as the motor, coupler and camshaft. There is a location on the top of the motor mount for the distance sensor to provide a direct undisturbed view in front of the laser dazzler.

The lens slide holds the plano-concave lenses and is attached to the base by the rod. The top of the lens slide has a location for the camshaft to fit and drive the movement of this piece changing the distance between the telescoping lenses.

7. OTHER EQUIPMENT

The stepper motor has a step angle of 1.8 degrees or 200 steps per rotation. It is small and lightweight making it acceptable for this application. The stepper motor control was simplified with the help of the Easy Driver stepper motor controller. The motor specifications can be found in Appendix F4 and the Easy Driver stepper motor controller specifications can be found in Appendix F5. A coupler was used to connect the motor shaft to the camshaft.

The camshaft was simply a 1/8-inch drill bit. The measured pitch was 1.093 inches. The pitch determines the linear movement of the lens slide for one rotation of the camshaft. One rotation of the motor is equal to 1.093 inches or 1 step equals 0.0055 inches of lens slide movement.

A Digital Lux Meter LX1330B was used for test measurements. It is capable of measuring 0 to 200,000 Lux. This maximum value exceeds the amount of light required to cause permanent eye damage thereby making it suitable for this testing. The output values of the LX1330B are in units of Lux, which are converted to radiant exposure

(mJ/cm^2) or irradiance (mW/cm^2) using the luminosity function in Equation 5. The lux meter is calibrated to the sensitivity of the human eye and provides adjusted values to enter in the luminosity function.

It should be noted other equipment included a personal computer used to write the program code for the Basic Stamp microcontroller, a voltage supply for the lasers, A/D converters, resistors, transistors, potentiometers and wiring.

CALCULATION RESULTS

This section discusses the resulting functions and evaluates them for use in the laser dazzler system. All example calculations including full-length derivations with assumptions can be found in Appendix K.

Pulsing will occur at a frequency of 12 Hz or 0.0833 seconds per pulse group. The lasers will be on for 0.0500 seconds and off for 0.0333 seconds. This will create higher peak irradiance than average irradiance allowing for more light energy to enter the eye before the blink reflex of 0.25 seconds.

The ANSI Z136.1-2007 three-rule system was followed to determine the MPE. Rule 1 (single pulse limit) had an irradiance of 2.2839 mW/cm^2. Rule 2 (average power limit) had an irradiance of 2.5456 mW/cm^2. Rule 3 (repetitive pulse limit) was calculated with the correction factor and had an irradiance of 1.7352 mW/cm^2. Rule 3 is the lowest value making it the limiting rule to be followed. Therefore, a radiant exposure of 0.1446 mJ/cm^2 or irradiance of 1.7352 mW/cm^2 must not be exceeded within 0.25 seconds to prevent permanent damage to the eye.

These values are for a pupil with a dilation size of 7 mm. ANSI bases its calculation on the worst-case scenario, which would be in a dark room where the pupil size is a maximum. Adjustments to the value need to be made for a light condition when the pupil size is 4 mm. The aperture area decreases by 67% from a 7 mm diameter pupil to a 4 mm diameter pupil; this blocks a significant amount of light from entering the eye. Irradiance is power per unit area and accounting for this loss in area amounts to a total irradiance of 5.3140 mW/cm^2. This equates to a radiant exposure of 0.4428 mJ/cm^2.

The 150 mW green and 200 mW red lasers with a combined power of 350 mW must not exceed these values. Using the nominal ocular hazard distance (Equation 8) and substituting in values for the MPE, laser power and initial beam diameter provides a relationship between the distance to the target (r_{NOHD}) and the beam divergence (ϕ). Equation 12 shows the relationship for the dark condition and Equation 13 shows the relationship for the light condition.

$$\phi_D = \frac{16.0039}{r_{NOHD}} \tag{12}$$

$$\phi_L = \frac{9.1437}{r_{NOHD}} \tag{13}$$

Using the distance to the target and divergence the projected laser beam diameter was determined to be 16 cm for the dark condition and 9.14 cm for the light condition. The projected area should theoretically remain the same at any distance because of the lasers ability to transmit energy through air with minimal loss. Therefore, the irradiance or power per unit area will remain the same. This projected area would be for an ideal system with no losses and the lasers operating at full power.

To achieve the calculated projected area the optical lens system will need to adjust accordingly. Following the compound thin lens equation with inputs of focal length, projected diameter and distance to target the distance between the lenses can be calculated. The distance to the target to create the required projected diameter when the focal point of the first lens crosses over the second lens is 240 cm for the dark condition and 137 cm for the light condition. Therefore two equations are needed for the dark condition and light condition, totaling four equations. The following equations define the required distance between the two optical lenses in centimeters for a known distance to the target in centimeters and for a given light condition. Equation 14 describes the relationship for a target distance of 100 cm to 240 cm for the dark condition.

$$d_{DC}(x) = \frac{360}{x} + 1.5 \qquad (14)$$

Equation 15 describes the relationship for a target distance of 240 cm to 550 cm in a dark condition.

$$d_{DF}(x) = \frac{364.5}{x} + 1.5 \qquad (15)$$

Equation 16 describes the relationship for a target distance of 100 cm to 137 cm in a light condition.

$$d_{LC}(x) = \frac{205.7}{x} + 1.5 \qquad (16)$$

Equation 17 describes the relationship for a target distance of 137 cm to 550 cm in a light condition.

$$d_{LF}(x) = \frac{210.2}{x} + 1.5 \qquad (17)$$

Where d is the distance between the lenses in centimeters and x is in the distance to the target in centimeters.

Equation 18 describes the relationship between the number of steps of the motor relative to the distance to the target for lengths 100 cm to 240 cm in a dark condition.

$$N_{DC}(x) = \frac{25937}{x} + 108 \tag{18}$$

Equation 19 describes the relationship of motor steps relative to distance to target for lengths 240 cm to 550 cm in a dark condition.

$$N_{DF}(x) = \frac{26261}{x} + 108 \tag{19}$$

Equation 20 describes the relationship of motor steps relative to distance to target for lengths 100 cm to 137 cm in a light condition.

$$N_{LC}(x) = \frac{14820}{x} + 108 \tag{20}$$

Equation 21 describes the relationship of motor steps relative to distance to target for lengths 137 cm to 550 cm in a light condition.

$$N_{LF}(x) = \frac{15144}{x} + 108 \tag{21}$$

Where N is the number of steps and x is the distance to the target in centimeters. The steps are calculated from an initial position of the lenses touching with no distance between them. These are the functions that will provide the basis for the logic of the control system.

The nominal hazard zone is used to determine the safe distance from a reflected light beam off a surface. This was calculated based on a scenario of a human target looking down out of the direct line of laser light. The laser dazzler light is reflecting off of a white cotton shirt and then into the eyes of the target. The angle of reflection off of the shirt and into the eyes is estimated to be 70° and the reflectivity of the shirt is estimated to be 50% [2]. This provides a nominal hazard zone of 3.31 cm in a dark condition and 1.9 cm in a light condition. These values are small are likely to never be exceeded, but should be considered for any laser weapon system.

The irradiance MPE units need to be converted to Lux for comparison to the testing values. Using the luminosity function, MPE was determined to be equivalent to 11850 Lux. This means, if 11850 Lux are exceeded and shined into the eyes with a 7 mm dilated pupil for over 0.25 seconds permanent damage is probable. As well, if 11850 Lux are reflected off a shirt and into the eyes that are within 3.31 cm for a dark condition or 1.9 cm for a light condition then damage is probable.

TESTING PROCEDURES AND RESULTS

Multiple tests were conducted to calibrate and verify the capabilities of the laser dazzler. All laser illuminance values were held well below MPE values. For safety during testing, the illuminance values were kept at a safe level in most circumstances unless otherwise described in which extra safety precautions were taken. Illuminance values could easily be increased to meet the calculated MPE values with the proper system calibration. All testing data are compiled in Appendix L. The order of testing was as follows:

1. Distance sensor calibration
2. Gaussian laser beam shape
3. Constant diameter in light conditions
4. Constant illuminance in light conditions
5. Constant diameter in dark conditions
6. Constant illuminance in dark conditions
7. Control system standalone operation
8. Constant divergence

1. Distance sensor calibration:

This test was used to verify the voltage reading into the control system at varying distances. Distances from 100 cm to 550 cm were marked in increments of 50 cm from the sensor. The laser dazzler system was constructed as previously described. A large white box was moved to each distance from the sensor to mimic a human target. The output voltage was recorded. The results are shown in Appendix L1.

The results are similar to the provided data from Sharp and only varied slightly. With this test the distance could be accurately evaluated with meaningful values of voltage. As the distance is increased the voltage decreases in a nonlinear manner. The control program linearly interpolates between data values.

2. Gaussian laser beam shape:

This test indicates the shape of the laser beam. This was useful for later tests in order to capture the maximum value of illuminance. The projected shape of the beam was circular and by nature of the lens system was most powerful in the center. The diameter of the projected laser beam was set to approximately 15 cm at a distance of 200 cm. Measurements were taken 4 cm, 8 cm, and 13 cm from the center of the beam. Measurements were taken in six locations at each distance from the center of the beam. The results are shown in Appendix L2.

Figure L2 and L3 reveal the general shape of the laser's projected area. It can be seen that the laser's illuminance can decrease by up to 85% at a distance of 13 cm from the center. The green laser is shown to have a higher illuminance than the red laser even though the red laser has a higher power rating. This is due to the wavelength sensitivity of the digital lux meter matching the luminous function of the human eye, therefore having a higher sensitivity for green wavelengths. Testing was conducted with the lasers at a constant voltage of 4 volts. Varying the voltage significantly changes the illuminance. Pulsing of the laser was not active for these tests and later tests in order to get accurate measurements.

3. Constant diameter in light condition:

This test provides the illuminance output of the laser dazzler in a light condition. The illuminance should remain constant if the projected area remains constant as discussed earlier. The data reveals further complexities of the mechanical components inabilities to achieve a constant projected area.

Measurements were taken from 100 cm to 550 cm in increments of 50 cm. The red lasers projected area was set to 15 cm. This was done by adjusting the optical system manually. 15 cm was chosen because it is similar to the calculated value for MPE although the measured values are lower than expected. A light condition is considered when the ambient illuminance was measured to be greater than 300 Lux. Standard lighting exceeded this value when the lights were on.

The illuminance in Lux of the red and green laser, distance between optical lenses and diameter of red and green lasers’ projected beams were recorded. The illuminance values for each color laser were recorded individually due to accuracy difficulties. The red laser projection could not be precisely placed over the green laser projection. It was especially challenging to match the highest illuminance point of the Gaussian beams with one another. ANSI Z136.1 states multiple laser systems of different wavelengths are additive and should be linearly compounded. Therefore, each laser's illuminance was measured individually then summed to calculate the total illuminance of the laser dazzler.

The unexpected complexity of the system can be easily seen in the results in Appendix L3. The red laser illuminance remained at a constant value of approximately 1620 Lux at every distance with only slight variation. The data reveals a problematic decreasing illuminance of the green laser. This occurred because the diameter of the projected area is increasing as the distance is increased. Each laser has a different initial divergence, which creates inconsistent diameters between the two.

The optical lens system is accommodating the red laser, but not the green laser. This test could have been done in the opposite manner where the green laser's diameter is held constant and a similar relationship would show for the red laser. This is occurring possibly because each of the laser modules has a different initial divergence and beam diameter. This was inherent in the laser devices and could not be adjusted to match one another.

This issue has the combined illuminance of the lasers decreasing. The green laser diameter increased 7 cm and lost 78% illuminance from 100 to 550 cm. The red laser diameter was always set to 15 cm and the illuminance never varied more than 6% from the average.

4. Constant illuminance in light condition

This test was conducted to prove the ability of the laser dazzler to meet a specific combined illuminance at any distance. It was completed in a similar manner to test 3. The distance between the lenses, illuminance and diameters of the red and green lasers were recorded. The optical lens system was manually adjusted until the combined illuminance was approximately 5000 Lux. This value was chosen based on safety concerns. This system is capable of producing higher values. The goal of this test and research can still be accomplished if the illuminance values are below MPE.

The results can be seen in Appendix L4. The same issue was exposed. The initial divergence of each laser is different, rendering the optical system to be instable for either one laser or the other. The control system cannot accommodate both lasers at the same time. The plot shows a decreasing illuminance of the green laser and an increasing illuminance of the red laser. The red laser diameter decreased 12.5 cm and illuminance increased over 400%. The green laser diameter increased 8 cm and illuminance decreased over 400%. These fluctuating values can offset one another to create a constant combined illuminance. The combined illuminance was held constant with less than 3.5% deviation from the average.

5. Constant diameter in dark condition

This test is essentially the same as test 3 except it was conducted in a dark condition. The same values were recorded and it was conducted in the same manner as test 3. The constant diameter was set to 20 cm for the red laser. This value was chosen to demonstrate the how illuminance values change with respect to the projected diameter. A dark condition was considered to be when the ambient illuminance was less than 300 Lux. Appendix L5 illustrates the results.

The results showed a lower illuminance compared to the constant diameter light condition. The light condition testing had a smaller projected diameter of 15 cm creating a higher illuminance. The red laser held a constant illuminance value of 1150 Lux while the green laser's illuminance value continually decreased with distance. Again, this created a decreasing combined illuminance with increasing distance. The green laser diameter increased 6 cm and lost 68% illuminance from 100 to 550 cm. The red laser diameter was always set to 20 cm and the illuminance only varied more than 3.5% from the average on one occasion.

6. Constant illuminance in dark condition

This test is similar to test 4 except done in a dark condition. The same parameters were recorded and were gathered in the same manner. The constant illuminance attempted to meet was 3000 Lux. This value was again chosen for safety issues and also to demonstrate this system can meet lower illuminance values when required by the light condition. Appendix L6 presents the results.

The data showed similarities to the previous test. The red laser's projected area decreased with distance, which produced increasing illuminance values. Inversely, the green laser projected area increased with distance, which produced decreasing illuminance values. This scenario provided offsetting values to generate a constant combined illuminance. The red laser diameter decreased 17 cm and illuminance increased over 400%. The green laser diameter increased 3 cm and illuminance decreased over 250%. These fluctuating values can offset one another to create a constant combined illuminance. The combined illuminance was held constant with less than 4.3% deviation from the average.

7. Control system standalone operation

This test allowed the system to operate on its own with no manual adjustment of the lens slide. The lens positions were taken from tests 3 through 6. Then these distances were converted to motor steps and inserted into the control system program. Both the constant diameter and constant combined illuminance cases were tested. Table L12 and L13 show the values of motor steps for light and dark conditions. The number of steps was normalized to the same initial starting position. This allows the program to maintain track of the motor position when switching from light and dark conditions. A sheet of white cardboard was moved to every position that had been previously tested and the laser dazzler system would adapt. The diameter and illuminance was recorded.

First, the constant diameter program was tested. The results can be seen in Table L14 and Figure L8. Only the red laser values were recorded. The green values were determined to be insignificant because a constant diameter at varying distance could not be simultaneously met with the red laser.

In comparison to test 3 and 5, the measured values were very similar. The control system constantly evaluated the external inputs and adjusted accordingly. There was a "shake" to the system due to noise from the distance sensor. The system would continuously make small adjustments back and forth. The peak difference from average illuminance was 9.8% for the light condition and 10% for the dark condition. There was a little slippage in the connection from the lens slide to the camshaft and was likely the cause for the higher variability.

Next, the constant combined illuminance motor step values were entered in the program and tested. The results are shown in Table L15 and Figure L9 for the light condition and Table L16 and Figure L10 for the dark condition. Again, there was more variance than compared to manually adjusting the lenses. The same relationships were seen. The peak difference from average illuminance was 5% for the light condition and 5.3% for the dark condition. The average illuminance was 5001 Lux with a target of 5000 Lux for the light condition. The average illuminance was 3156 Lux with a target of 3000 Lux for the dark condition.

8. Constant divergence

This test was conducted to illustrate the weaknesses of current laser dazzlers on the market and the effects of a constant divergence system. It was also done to prove the advantages of the concepts of this design of laser dazzler.

First, the optical lens system was set to a distance of 2.200 inches, where the red laser region was approximately 15 cm in diameter at a distance of 50 cm. The distance between optical lenses was not adjusted during this test. Illuminance measurements were taken at every distance from previous tests including 50 cm. The laser diameters were not measured because this was not possible at longer distances. The results are shown in Appendix L7, Table LT7 and Figure L13.

The illuminance decreases dramatically with an increasing distance. This renders the laser dazzler virtually useless at a long distance when optimized for a close distance. The red laser illuminance decreased 77% and the green laser illuminance decreased 86% from 50 cm to 150 cm.

Next, the optical lenses were set to a distance apart of 0.670 inches, where the red laser region was approximately 15 cm in diameter at a distance of 550 cm. Again, measurements were taken at every distance recorded previously while the optical lenses are not adjusted. The results are shown in Table LT8 and Figure L14.

At 550 cm the illuminance values are reasonable and do not exceed the MPE. As measurements were taken closer to the laser dazzler, illuminance values increased dramatically. At a distance of 50 cm the projected area was less than 5 cm with a combined illuminance value of 125300 Lux. This value is extremely high and dangerous, therefore extra safety precautions were taken. This value can cause permanent damage quicker than the blink reflex can protect the eye. This demonstrates the dangers of laser dazzlers incapable of adjusting divergence. The illuminance increased 2500% from a distance 550 cm to 50 cm.

TESTING SUMMARY AND DISCUSSION

The tests have proven the capabilities and complexities of this conceptual laser dazzler. The system was successful in meeting a set irradiance at any distance and could adjust according to light conditions. Testing provided data describing the positive and negatives of this system.

The calculated MPE determined the projected area of the lasers needed to be 16 cm diameter. Testing was done with the projected area at 15 cm diameter. Therefore, testing values should have shown higher irradiance than the calculated MPE value. The MPE value was equivalent to 11850 Lux. The actual combined measured value of the lasers was around 5000 Lux when both red and green lasers were approximately 15 cm diameter. The lasers were unable to meet the theoretical calculations.

There are many reasons this occurred. The lasers are stated to have a combined power of 350 mW from the manufacturer and are recommended to operate at a voltage of 4 Volts for longevity and low risk of burning out the diode. This voltage is not the peak voltage hence the lasers were not operating at the peak power of 350 mW. Due to the high expense of the lasers, the maximum voltage that could be applied was not determined due to apprehension of burning out the laser diode. The theoretical values could be met if the power output of the lasers was increased or if the divergence of the beam was decreased.

Also, the optical lenses were not perfectly aligned; therefore some of the laser light was reflected. When the system was operating the laser light could be seen on the back of the lens slide, an indication of scatter of the beam. The first lens diverged the beam larger than the size of the second lens. Only the very edge of the beam where the energy was minimal was larger than the second lens and projected on the back of the lens slide. There was also a reflection back towards the laser dazzler unit that could be seen on the base. These problems allow the laser's energy to escape the system and not be projected in the direction of the target. The majority of the energy was clearly projected forward, but these losses of energy likely account for the offset from the theoretical calculations.

The connection between the camshaft and the lens slide was not a perfect fit. There was a slight gap between the two allowing for small movements of the lens slide.

This could have caused the higher variability when the system was in standalone operation.

Appendix L9 illustrates the comparison of the theoretically calculated distance between the lenses and the actual measured values in order to achieve a constant projected diameter. This comparison was only done for the red laser at a diameter of 15 cm. The theoretical equations were derived for a diameter of 15 cm. The theoretical and measured values show the same relationship with respect to distance. The measured values appear to be slightly less than the theoretical. This is more than likely do to the initial divergence of the beam.

A comparison of every test that recorded the diameter of the projected area and the illuminance is shown in Appendix L10. The plot shows the consistency of the gathered data from testing. As the projected area increases the illuminance decreases. The closely packed data demonstrates low variability of testing.

The motor adjusting to the inputs rather than the sensor's ability to adjust to the external variables limited the reaction time of the system. The distance sensor responded quickly and could easily detect the distance to a human body. The inputs to the control system update four times a second. When the system is optimized for a distance of 550 cm and then the distance is cut to 100 cm, the time for the motor to adapt was approximately 1 second. This is acceptable for a proof of concept, but needs significant improvements for practical use.

It was difficult to determine the exact edge of the projected laser region. It would fade out over a few centimeters and the actual size had to be estimated. Measurements should be consistent with one another because they were taken with the same method every time.

There was a significant challenge to align of the two laser's projected regions on top of one another. This method was abandoned and the illuminance of each laser was measured individually. The red and green laser diameters could not be synced at every distance. This is because each laser has a different initial divergence. A constant illuminance could be obtained by combining the lasers illuminance to cancel out the gains and losses of one another. At farther distances red would be more prominent and at closer distances green would be more prominent. This is a disadvantage of this design.

The voltage supplied to the lasers determined the output power and the illuminance requirements for light and dark conditions were met by changing the divergence. It is not ideal for the diameter to change in a light and dark condition. In a real world situation this could prove difficult for a user and their accuracy in using the laser dazzler. Instead it may be possible for the input voltage to be varied with light conditions in order to maintain the same projected diameter in any situation. A change in voltage changes the output power and does not affect the projected diameter.

Overall the system operated successfully. All components and subsystems interacted correctly and proved this concept is possible. A specific irradiance could be met at any distance. The flashing effect was not tested, but is incorporated into the final system. The lasers are capable of pulses at a frequency of 12 Hz as needed. The pulsing effect was not tested for obvious safety reasons.

CONCLUSION AND RECOMMENDATIONS

New laser dazzler technology can provide an effective and safe form of true non-lethal weapons. Current laser dazzlers operate well below MPE, because they cannot adapt to external conditions and their weakness is demonstrated by test 7. Only one laser dazzler varies divergence and requires it to be done manually, which is not ideal for a user in a high stress situation. The conceptual laser dazzler in this study contains the logic to automatically adjust for conditions of distance to the target and light variations.

The concept was shown through testing to meet a specified irradiance at any distance and adjust to varying light conditions. However many areas need improvement and further testing before being ready for safe and practical use.

Future work would consist of changes to the physical components of the system. An independent focusing system is needed for each laser. The ability to specifically control each laser would correct the issue of different laser projected diameters. Each optical lens system could be optimized for each laser's initial divergence.

The maximum irradiance allowed to safely enter the eye changes in different light conditions. Adjusting the divergence effectively compensates for this. An alternative method would be to adjust the voltage to the laser. This would allow the projected region to remain the same, but the output power would adjust according to the necessary irradiance.

More powerful lasers could be used to increase the size of the projected area making it easier to hit a target. The wavelengths of the lasers need to be adjusted as well. The green 532 nm laser is appropriate, but the red 620 nm laser is not. A more ideal laser on the market has a wavelength of 564 nm, which is closer to the peak sensitivity of the L cones.

The overall structure of the system would need significant improvements. Obviously the size needs to be decreased and all electrical components need to operate with an embedded computer system.

Safety elements should be included into the dazzler control system logic. For example a laser shut off if someone suddenly walks into the path of the laser beam when it is currently set for a farther distance.

The Gaussian beam effect would also create a difficulty for the user. To deliver the maximum vision disruption the user would have to accurately hit the eyes with the very center of the beam where the power is the strongest. An optical lens system with increased complexity may be able to deliver a projected area with a top hat style irradiance distribution rather than a Gaussian distribution.

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APPENDIX A: Protocol IV

Article 1:

It is prohibited to employ laser weapons specifically designed, as their sole combat function or as one of their combat functions, to cause permanent blindness to unenhanced vision, that is to the naked eye or to the eye with corrective eyesight devices. The High Contracting Parties shall not transfer such weapons to any State or non-State entity.

Article 2:

In the employment of laser systems, the High Contracting Parties shall take all feasible precautions to avoid the incidence of permanent blindness to unenhanced vision. Such precautions shall include training of their armed forces and other practical measures

Article 3:

Blinding as an incidental or collateral effect of the legitimate military employment of laser systems, including laser systems used against optical equipment, is not covered by the prohibition of the Protocol.

Article 4:

For the purpose of this protocol “permanent blindness” means irreversible and uncorrectable loss of vision, which is seriously disabling with no prospect of recovery. Serious disability is equivalent to visual acuity of less than 20/200 Snellen measured using both eyes.

APPENDIX B: Dazer Laser Defender Specifications

Dazer Laser® DEFENDER
Light Fighting Technologies™

Key Specifications	
Power of Laser	500 mW (nominal)
Wavelength	532 nm
Operating Temperature	- 5 ° C to + 45 ° C
Storage Temperature	- 40 ° C to + 80 ° C
Laser Operating Mode (Incorporates proprietary M.E.A.N. Beam Technology* Day/Night mode button)	**Day mode:** Special combination of CW & modulated lasing for daylight **Night mode:** Special combination of CW & modulated lasing for night *Combination of CW and modulated light emitted from the laser (Patents Pending)
Effective Dazing Range	LFP MB5HPL LR: ~ 1 - 2400 meters
Maximum Range (Warning)	LFP MB5HPL LR: ~ 4000 meters
Cooling System	Laser is conductively cooled with a built-in heat sink which allows heat to be drawn away from the laser more efficiently incorporating a built-in thermo-electric cooling system for both CW and modulated lasing.
Security Features	Programmed 12 or 24 hour time clock. System has unique code which must be programmed each day. Built-in kill switch allows for instant shutoff.
Dazer Laser® Beam	
Beam Divergence	Variable divergence (0.4 mrad - 200 mrad)
NOHD	1 meter [10 second exposure (1 mW/cm^2 AEL)]
Beam Diameter	Beam diameter varies. The beam diameter is ~ 1 m (39 inches) at each of the 14 predetermined range settings of 5, 10, 15, 25, 50, 100, 200, 300, 400, 600, 800, 1200, 1600 & 2400 meters.
Safety	Class IIIB laser device (<500 mW) Meets ANSI (Z136.1) when operated as trained and specified
Physical Characteristics	
Dimensions	6.3" L x 6.1" H x 1.9" W
Weight	~ 24 ounces (batteries included)
Colors	Matte finish: Black (optional Green or Camouflage)
Housing	High impact engineering thermo plastic System is hermetically sealed with O-Rings at all entry points Ergonomically comfortable finger grips
Mounting	MIL–STD 1913 Picatinny rail adaptor easily mountable along top of device
Power and Durability	
Power Source	(4) x CR123A Batteries (3V Lithium)
Battery Life	2 hours of constant use in nominal conditions > 1 hour of constant use in extreme temperature use Built-in warning light indication (~10 minutes battery life left) Battery good ~ 600 Dazings @ 10 second intervals
Warm-up Time	Instant-on operation with no warm up time
Durability	Fully water-proof to 20 meters (65.6 feet) (2 atmospheres) Salt spray (Clean with soap and water) Shock & vibration: transport and gunfire

APPENDIX C: Laser Classifications

The International Electrotechnical Commission (IEC) has published these international standards for the safe use of laser products.

Class 1: These laser products pose no risk to eyes or skin under normal operations and conditions, including occasions when users view the beam directly with optics that could concentrate the output into the eye.

Class 1M: Class 1M laser products have a wavelength range of 302.5 to 10^6 nm. Like Class 1 laser products, Class 1M products are safe to eyes and skin under normal conditions, including when users view the laser beam directly. However, users should not incorporate optics that could concentrate the output into the eyes (e.g., a telescope with a 1M laser emitting a well-collimated beam).

Class 2: Class 2 lasers emit visible (400 to 700nm) output below 1mW. These products emit light that poses very little risk to the human eye, even when viewing the beam directly with optics that could concentrate the output into the eye. The eye's natural aversion response to bright light prevents injury to the eye. However, these lasers do pose a dazzle hazard.

Class 2M: Laser products classified as 2M emit visible output below 1mW in the 400 to 700nm range. Like Class 2 laser products, Class 2M products pose relatively little risk to eyes and no risk to skin under normal conditions, including when users view the laser beam directly. The eye's natural aversion response to bright light prevents damage to the eye. However, users should not incorporate optics that could concentrate the output into the eyes (e.g., a telescope with a 1M laser emitting a well-collimated beam).

Class 3R: This class is similar to CDRH's 3A class. Class 3R lasers emit between 1 and 5mW of output power in the 302.5 to 10^6 nm wavelength range. IEC reserves the 3R classification for those laser products that yield output of up to a factor of five over the maximum allowed for Class 2 in the 400 to 700nm wavelength range and up to a factor of five over the maximum allowed for Class 1 for other wavelengths. Designation "R" indicates "reduced requirements," requirements that are less stringent than those reserved for 3B lasers. The risk of injury from directly viewing a Class 3R laser beam remains relatively low, but users should take greater care to avoid direct eye exposure, especially when handling invisible output.

Class 3B: Class 3B lasers emit between 5 and 500mW of output power in the 302.5 to 10^6 nm wavelength range. They are hazardous to the eye when viewed directly, even when taking aversion responses to light into account. However, scattered light is typically safe to the eye. Higher power 3B lasers are a hazard to the skin, but the natural aversion response to localized heating typically prevents skin burns.

Class 4: Class 4 lasers emit output power above 500mW. Direct exposure to Class 4 laser output is hazardous to both eyes and skin. Scattered light may also be hazardous to eyes. These lasers may be fire hazards.

APPENDIX D: ANSI MPE Evaluation Tables

Table D1: Exposure duration for 400-700 nm wavelength

Recommended Limiting Exposure Durations for CW and Repetitive-Pulse MPE Calculations

Visible 0.4 to 0.7 μm	600	0.25**
NIR 0.7 to 1.4 μm	600	10
FIR 1.4 μm to 1 mm	10	10

* For single pulse lasers (PRF < 1 Hz) use actual laser pulse duration.

** For unintended or accidental viewing only. For other conditions, use the time of *intended* viewing.

Table D2: MPE calculations are evaluated according to a pupil size of 7 mm

Limiting Apertures (Irradiance and Radiant Exposure) for Hazard Evaluation

Spectral Region (μm)	Duration† (s)	Aperture Diameter (mm) Eye	Aperture Diameter (mm) Skin
0.180 to 0.400	10^{-9} to 0.3	1.0	3.5
	0.3 to 10*	$1.5\,t^{0.375}$	3.5
	10 to 3×10^4	3.5	3.5
0.400 to 1.400	10^{-13} to 3×10^4	7.0	3.5
1.400 to 10^2	10^{-9} to 0.3	1.0	3.5
	0.3 to 10*	$1.5\,t^{0.375}$	3.5
	10 to 3×10^4	3.5	3.5
10^2 to 10^3	10^{-9} to 3×10^4	11.0	11.0
		Limiting Cone Angle, γ (mrad)	
0.400 to 0.600	0.7 to 100	11	
	100 to 10^4	$1.1\,t^{0.5}$	
	10^4 to 3×10^4	110	

* Under normal conditions these exposure durations would not be used for hazard evaluation.

† For guidance on exposure durations less than 10^{-13} seconds, see 8.2.2.

Note: The wavelength region λ_1 to λ_2 means $\lambda_1 \le \lambda < \lambda_2$ μm, e.g., 0.315 to 0.400 μm means $0.315 \le \lambda < 0.400$ μm. Additionally, the exposure duration region t_1 to t_2 means $t_1 \le t < t_2$ s, e.g., 0.3 to 10 s means $0.3 \le t < 10$ s.

Table D3: MPE equation for exposure of 0.25 sec and wavelength 400-700 nm

Maximum Permissible Exposure (MPE) for Intrabeam Ocular Exposure to a Laser Beam

Wavelength (μm)	Exposure Duration, t (s)	MPE ($J \cdot cm^{-2}$)	MPE ($W \cdot cm^{-2}$)	Notes
Ultraviolet				In the Dual Limit Wavelength Region (0.180 to 0.400 μm), the lower MPE considering photochemical and thermal effects must be chosen.
Dual Limits for λ between 0.180 and 0.400 μm				
Thermal				
0.180 to 0.400	10^{-9} to 10	$0.56\ t^{0.25}$		
Photochemical				
0.180 to 0.302	10^{-9} to 3×10^{4}	3×10^{-3}		See Tables 8a and 8b for limiting aperture and Table 9 for measurement aperture.
0.302 to 0.315	10^{-9} to 3×10^{4}	$10^{200(\lambda-0.295)} \times 10^{-4}$		
0.315 to 0.400	10 to 3×10^{4}	1.0		
Visible				
0.400 to 0.700	10^{-13} to 10^{-11}	1.5×10^{-8}		In the Wavelength Region (0.400 to 0.500 μm), T_1 determines whether the photochemical or thermal MPE is lower.
0.400 to 0.700	10^{-11} to 10^{-9}	$2.7\ t^{0.75}$		
0.400 to 0.700	10^{-9} to 18×10^{-6}	5.0×10^{-7}		
0.400 to 0.700	18×10^{-6} to 10	$1.8\ t^{0.75} \times 10^{-3}$		
0.500 to 0.700	10 to 3×10^{4}		1×10^{-3}	
Thermal				
0.450 to 0.500	10 to T_1		1×10^{-3}	For extended sources in the retinal hazard region (0.400 to 1.4 μm), see Table 5b.
Photochemical				
0.400 to 0.450	10 to 100	1×10^{-2}		See Table 6 and Figures 8 and 9 for correction factors C_A, C_B, C_C, C_P, C_E, and times T_1 and T_2.
0.450 to 0.500	T_1 to 100	$C_B \times 10^{-2}$		
0.400 to 0.500	100 to 3×10^{4}		$C_B \times 10^{-4}$	
Near Infrared				
0.700 to 1.050	10^{-13} to 10^{-11}	$1.5\ C_A \times 10^{-8}$		For repeated (pulsed) exposures, see Section 8.2.3. A correction factor, C_P applies to thermal limits, but not to photochemical limits.
0.700 to 1.050	10^{-11} to 10^{-9}	$2.7\ C_A\ t^{0.75}$		
0.700 to 1.050	10^{-9} to 18×10^{-6}	$5.0\ C_A \times 10^{-7}$		
0.700 to 1.050	18×10^{-6} to 10	$1.8\ C_A\ t^{0.75} \times 10^{-3}$		
0.700 to 1.050	10 to 3×10^{4}		$C_A \times 10^{-3}$	
1.050 to 1.400	10^{-13} to 10^{-11}	$1.5\ C_C \times 10^{-7}$		The wavelength region λ_1 to λ_2 means $\lambda_1 \leq \lambda < \lambda_2$, e.g., 0.180 to 0.302 μm means $0.180 \leq \lambda < 0.302$ μm.
1.050 to 1.400	10^{-11} to 10^{-9}	$27.0\ C_C\ t^{0.75}$		
1.050 to 1.400	10^{-9} to 50×10^{-6}	$5.0\ C_C \times 10^{-6}$		
1.050 to 1.400	50×10^{-6} to 10	$9.0\ C_C\ t^{0.75} \times 10^{-3}$		
1.050 to 1.400	10 to 3×10^{4}		$5.0\ C_C \times 10^{-3}$	
Far Infrared				
1.400 to 1.500	10^{-9} to 10^{-3}	0.1		Note: The MPEs must be in the same units.
1.400 to 1.500	10^{-3} to 10	$0.56\ t^{0.25}$		
1.400 to 1.500	10 to 3×10^{4}		0.1	
1.500 to 1.800	10^{-9} to 10	1.0		
1.500 to 1.800	10 to 3×10^{4}		0.1	
1.800 to 2.600	10^{-9} to 10^{-3}	0.1		
1.800 to 2.600	10^{-3} to 10	$0.56\ t^{0.25}$		
1.800 to 2.600	10 to 3×10^{4}		0.1	
2.600 to 1000	10^{-9} to 10^{-7}	1×10^{-2}		
2.600 to 1000	10^{-7} to 10	$0.56\ t^{0.25}$		
2.600 to 1000	10 to 3×10^{4}		0.1	

APPENDIX E: Bill of Materials

Part Description	Qty
11 mm Dia. x 30 mm FL Plano-Convex Optical Lens	2
15 mm Dia. x -15 mm FL Plano-Concave Optical Lens	2
Custom Lens Slider (CAD Structure)	1
Custom Base (CAD Structure)	1
Custom Motor Mount (CAD Structure)	1
150 mW, 532 nm Green Laser Module	1
200 mW, 660 nm Red Laser Module	1
Mercury Stepper Motor, SM-42BYG011-25	1
Sharp Distance Sensor, GP2Y0A710K0F	1
Easy Driver v4.3	1
Parallax Basic Stamp Microcontroller	1
Breadboard	1
5 Volt Power Source	1
¼" x 4" Stainless Steel Drill Bit	1
5 mm to 0.25" Motor Shaft Coupler	1
M3 Screw	4
#6-32 x ¾" Screw	2
#6-32 Nut	2
470 Ohm Resistor	1
2 Position Electrical Switch	1
Transistor	1
Photoresistor	1
Potentiometers	3
Dell Desktop Computer	1
Electrical Wire (ft.)	15

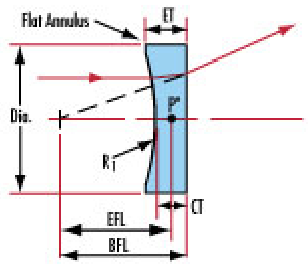
APPENDIX F: Part Specifications

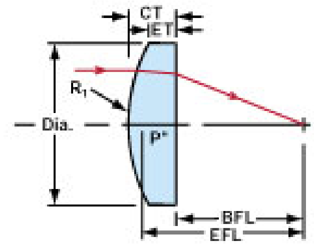
APPENDIX F1. Lasers

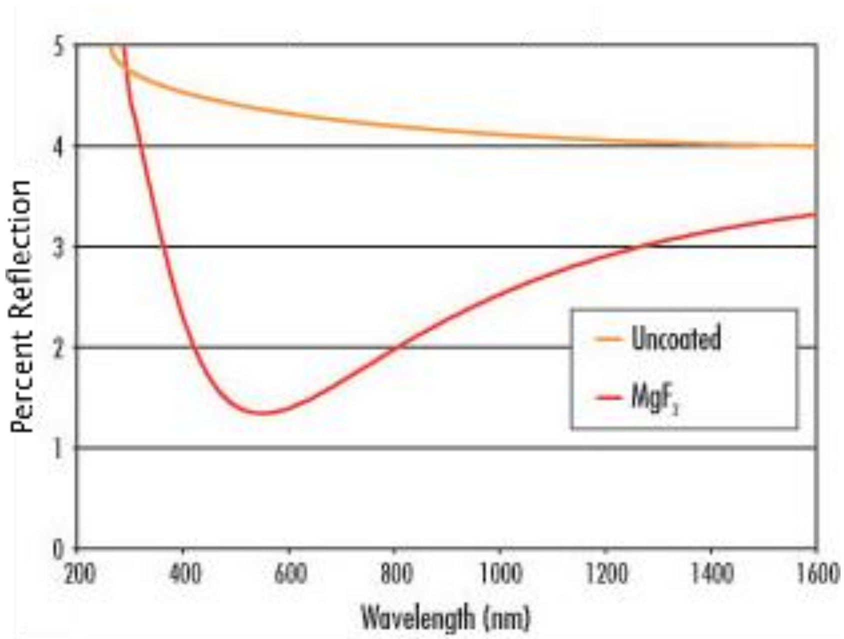
532 nm Laser Module Parameters Specifications	
Name	Green Laser Diode Module
Power	150mw with 5% tolerance
Wavelength	532nm
Supply Voltage	DC 3.7~4.2 V
Working Current	360 mA
Spot Diameter	About 2 ~ 5 mm (<10 m)
Divergence Angle	.01~5 Degrees
Working Temperature	10gC±40dgC
Storage Temperature	10gC±50dgC
Lifespan	>7000hours
Size	25x60mm
Function	Includes adjustable focus
Note: Use laser module <10 minutes time consecutively. If the laser is required to work long hours, need to include a fan or heat sink to reduce the module temperature.	

660 nm Laser module parameters specifications	
Name	Red Laser Diode Module
Power	200mw with 5% tolerance
Wavelength	660nm
Supply Voltage	DC 3.7~4.2 V
Working Current	180~200mA
Spot Diameter	About 2 ~ 5mm (<10 m)
Divergence Angle	.01~5 degrees
Working Temperature	10gC-+40dgC
Storage Temperature	10gC-+50dgC
Lifespan	>7000hours
Size	25x60mm
Function	Includes adjustable focus
Note: Use laser module <10 minutes time consecutively. If the laser is required to work long hours, need to include a fan or heat sink to reduce the module temperature.	

APPENDIX F2. Optical Lenses







Surface Quality:	60-40
Centering Tolerance:	6 arcmin
Diameter Tolerance:	0
Center Thickness Tolerance:	±0.10
Focal Length Tolerance:	±1%
Design Wavelength:	587.6nm
Edge Thickness:	Reference
Coating:	¼λ MgF_2 @ 550nm
Bevel:	12.51-25.41mm Dia: Max Bevel = 0.4mm x 45 5.00-12.50mm Dia: Max Bevel = 0.3mm x 45° 12.51-25.41mm Dia: Max Bevel = 0.4mm x 45°
Clear Aperture:	5.00-12.51mm Dia: CA ≥85% Diameter 12.51-25.41mm Dia: Max Bevel = 0.4mm x 45°

GP2Y0A710K0F

Distance Measuring Sensor Unit
Measuring distance: 100 to 550 cm
Analog output type

■Description

GP2Y0A710K0F is a distance measuring sensor unit, composed of an integrated combination of PSD (position sensitive detector) , IRED (infrared emitting diode) and signal processing circuit.
The variety of the reflectivity of the object, the environmental temperature and the operating duration are not influenced easily to the distance detection because of adopting the triangulation method.
This device outputs the voltage corresponding to the detection distance. So this sensor can also be used as a proximity sensor.

■Features

1. Long distance type
   Distance measuring range : 100 to 550 cm
2. Analog output type
3. Package size : 58×17.6×22.5 mm
4. Consumption current : Typ. 30 mA
5. Supply voltage : 4.5 to 5.5 V

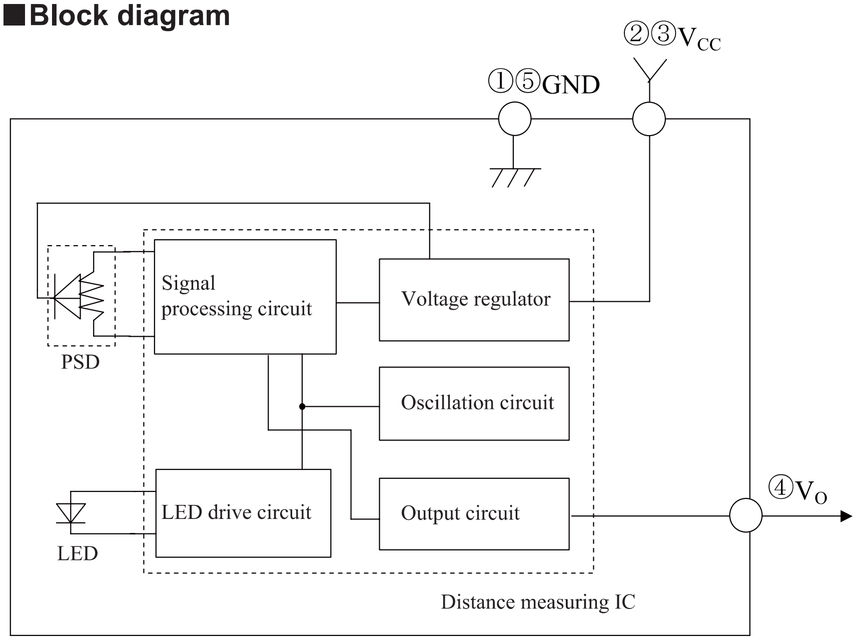
■Agency approvals/Compliance

1. Compliant with RoHS directive(2002/95/EC)

■Applications

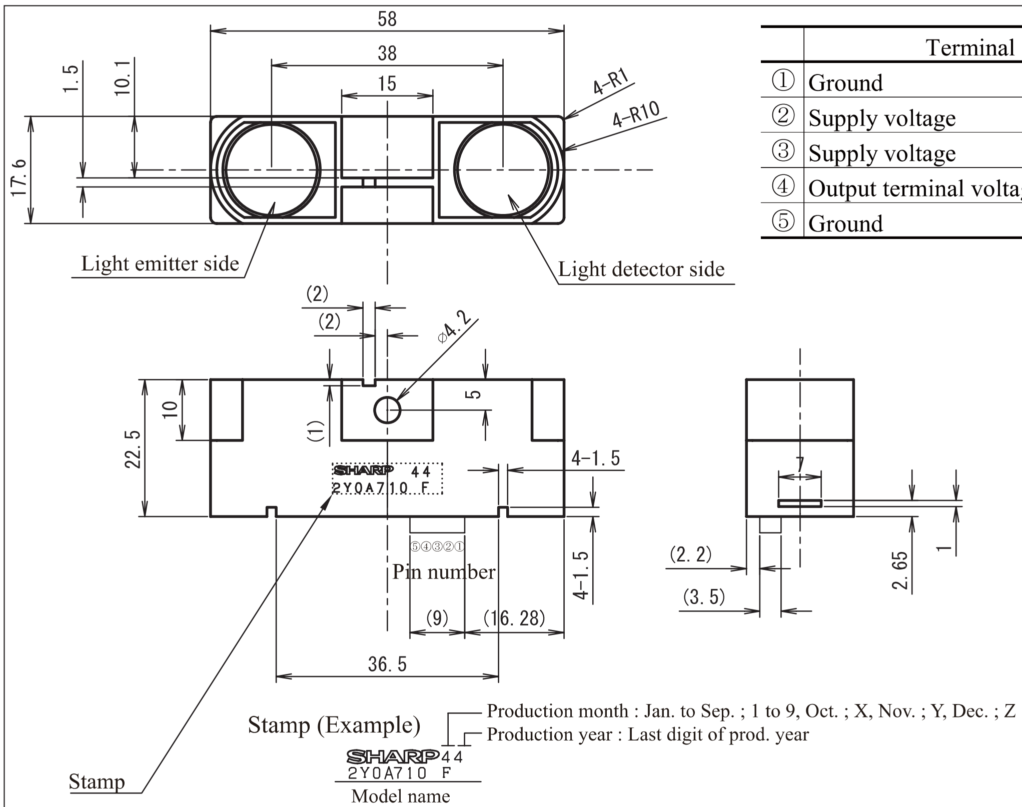
1. Projector (for auto focus)
2. Robot cleaner
3. Auto-switch for illumination, etc.
4. Human body detector
5. Amusement equipment
   (Robot, Arcade game machine)

■Block diagram



■Outline Dimensions

(Unit : mm)



	Terminal	Symbol
①	Ground	GND
②	Supply voltage	V_{CC}
③	Supply voltage	V_{CC}
④	Output terminal voltage	V_O
⑤	Ground	GND

Note 1. Unspecified tolerances shall be ± 0.3mm.
Note 2. The connector is made by J.S.T.TRADING COMPANY,LTD. and its part number is B5B-ZR.
Note 3. The dimensions in parenthesis are shown for reference.

Product mass : approx. 9g

■Absolute Maximum Ratings

(T_a=25℃,V_{CC}=5V)

Parameter	Symbol	Rating	Unit
Supply voltage	V_{CC}	-0.3 to +7	V
Output terminal voltage	V_O	-0.3 to V_{CC}+0.3	V
Operating temperature	T_{opr}	-10 to +60	℃
Storage temperature	T_{stg}	-40 to +70	℃

■Electro-optical Characteristics

(T_a=25℃,V_{CC}=5V)

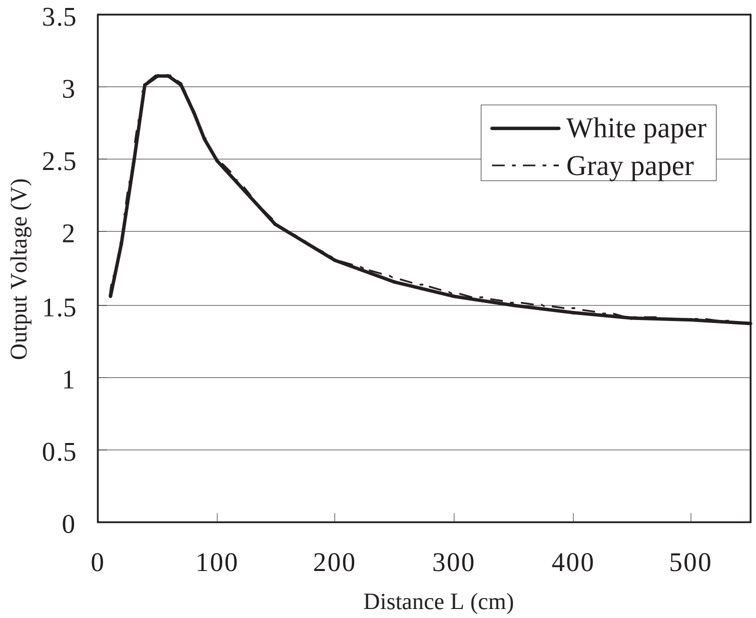
Parameter	Symbol	Conditions	MIN.	TYP.	MAX.	Unit
Average supply current	I_{CC}	L=150cm (Note 1)	—	30	50	mA
Distance measuring	ΔL	(Note 1)	100	—	550	cm
Output voltage	V_O	L=100cm (Note 1)	2.3	2.5	2.7	V
Output voltage differential	ΔV_{O1}	Output voltage difference between L=100cm and L=200cm (Note 1)	0.5	0.7	0.9	V
	ΔV_{O2}	Output voltage difference (L=100cm→200cm)/ Output voltage differentce (L=200cm→550cm)(Note 1,2)	1.25	1.55	1.85	V

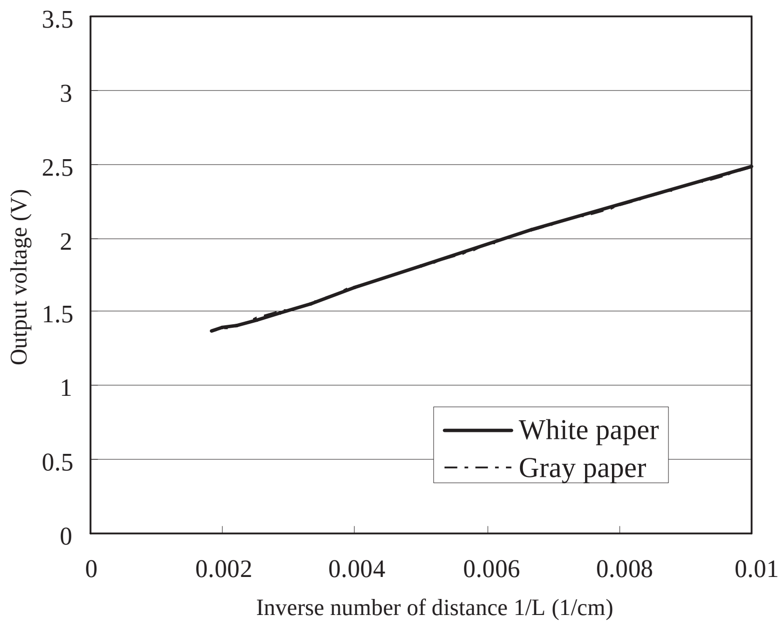
* L : Distance to reflective object
Note 1 : Using reflective object : White paper (Made by Kodak Co., Ltd. gray cards R-27・white face, reflectance; 90%)
Note 2 : The value at 550 cm is the average of 20 times distance measuring.

■Recommended operating conditions

Parameter	Symbol	Conditions	Rating	Unit
Supply voltage	V_{CC}		4.5 to 5.5	V

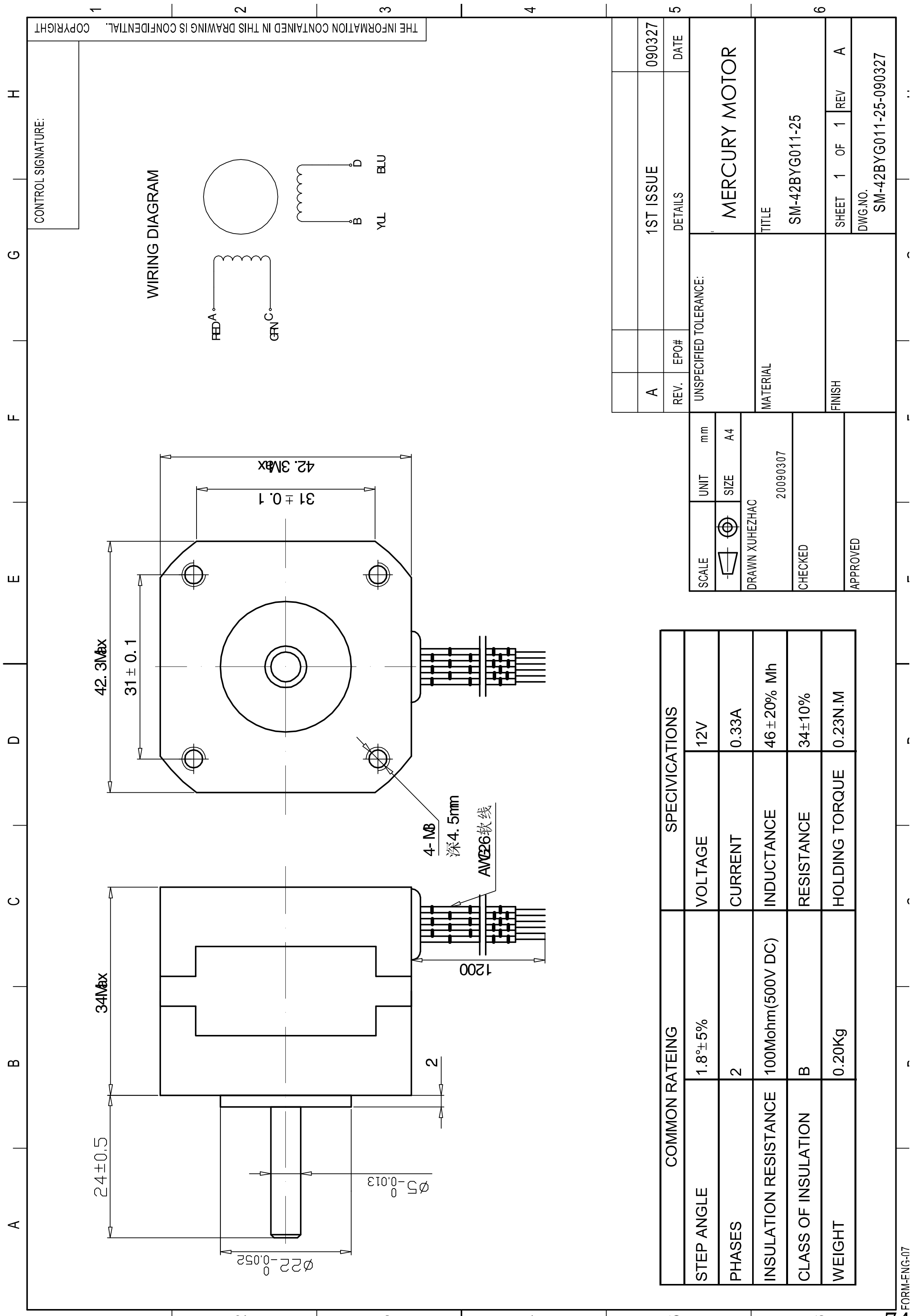
Fig. 2 Example of distance measuring characteristics(output)



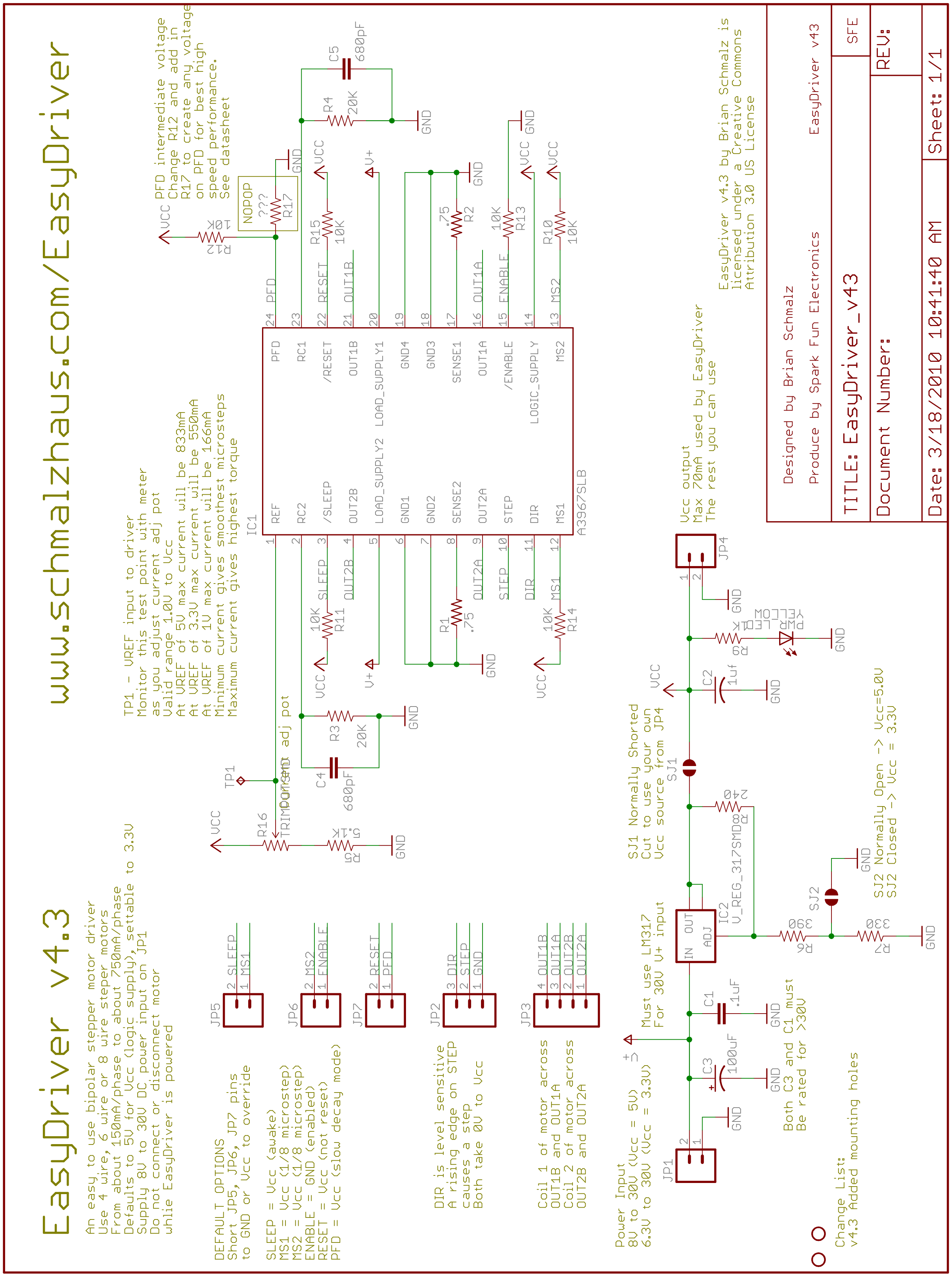


Note. Reflection : White paper (reflectance : 90%)
: Gray paper (reflectance: 18%)

APPENDIX F4. Mercury Stepper Motor



APPENDIX F5. Easy Driver v4.3



APPENDIX G: Electronic Schematics

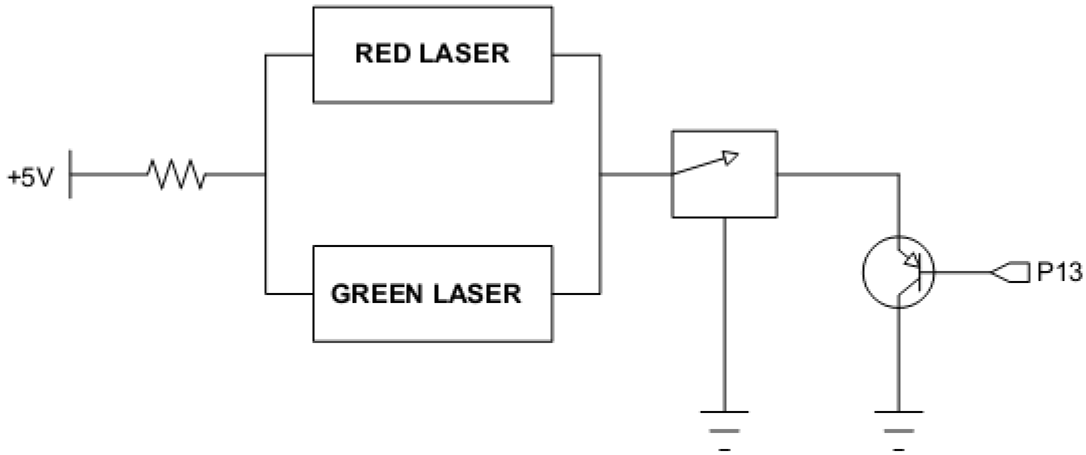


Figure G1: Laser electronic schematic

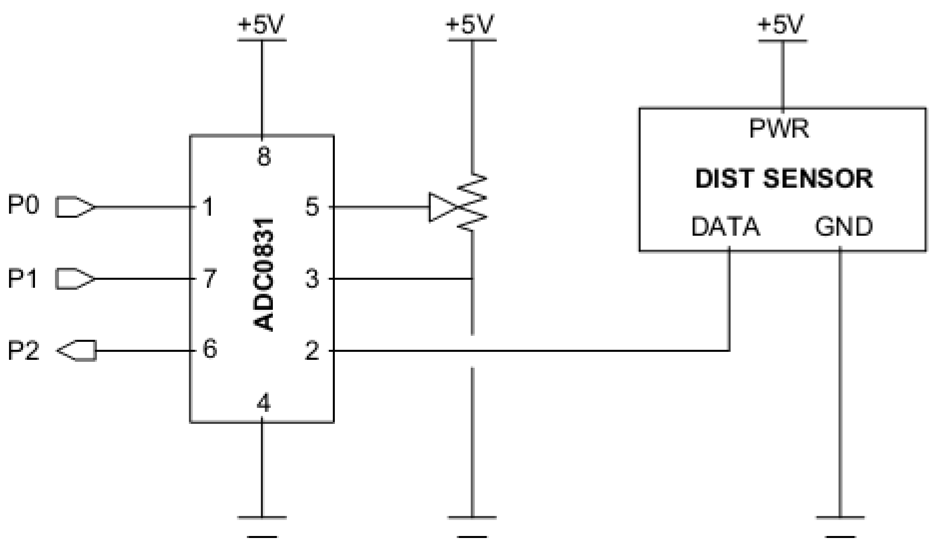


Figure G2: Distance sensor schematic

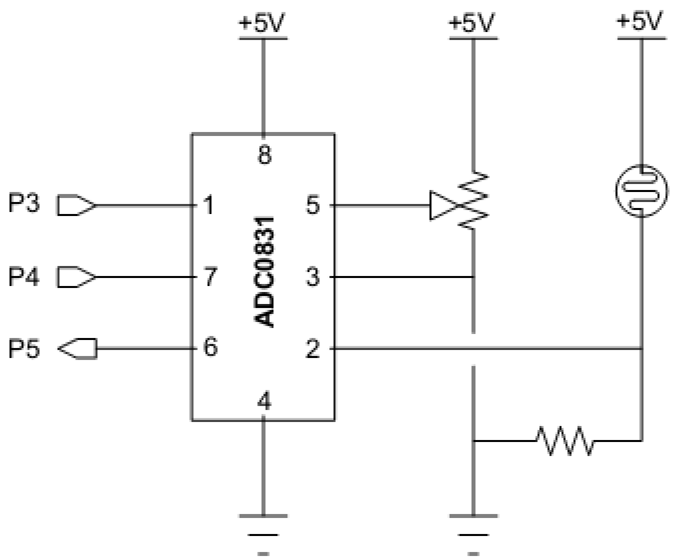


Figure G3: Photoreceptor electronic schematic

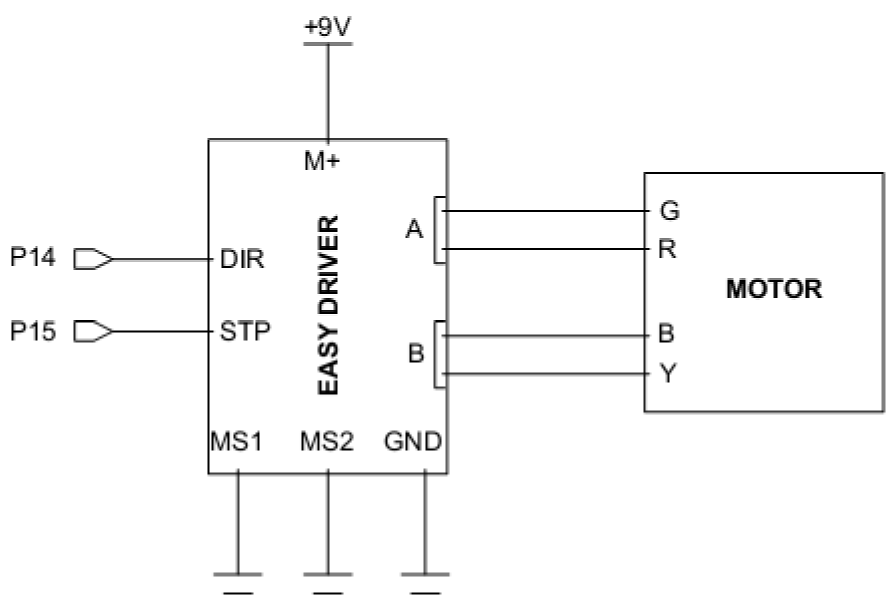


Figure G4: Motor electronic schematic

APPENDIX H: Pictures of System

Figure H1: Front view laser dazzler

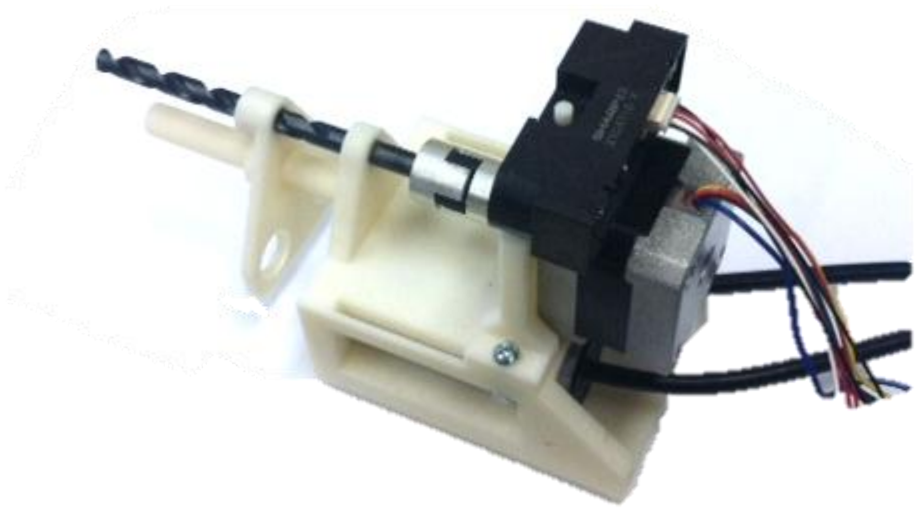


Figure H2: Rear view laser dazzler

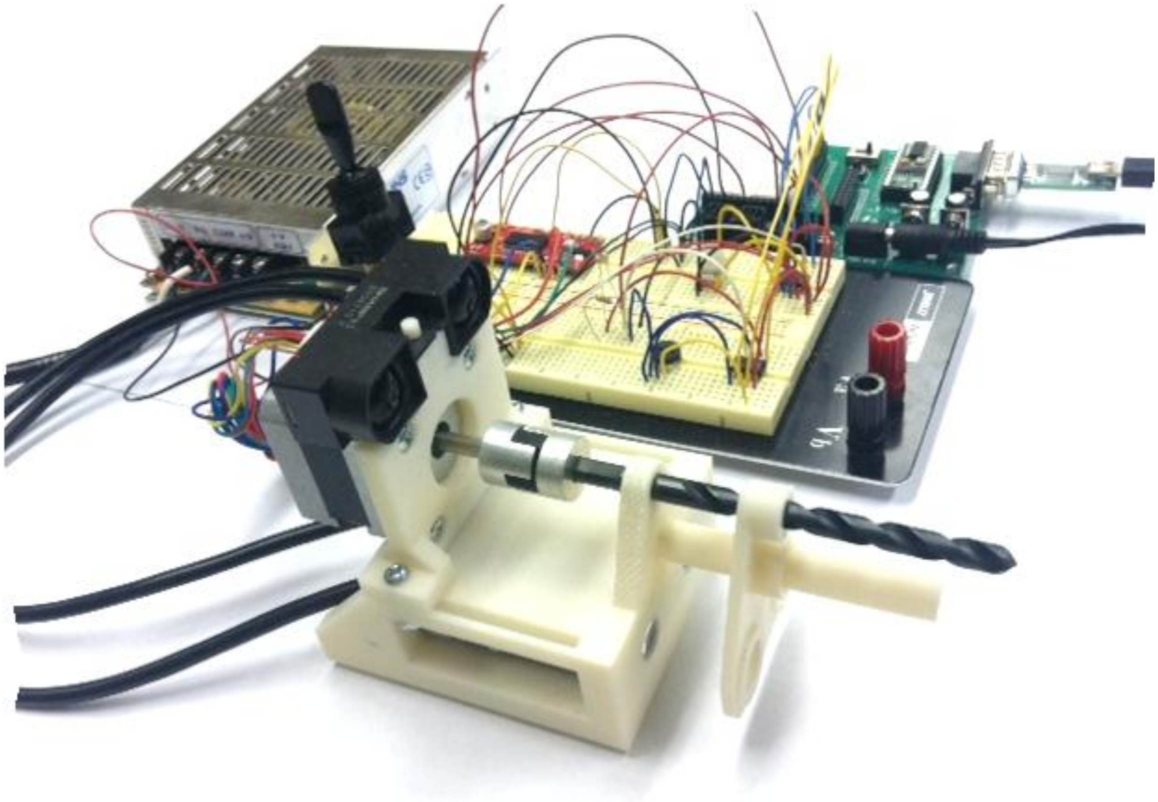


Figure H3: Complete assembled system

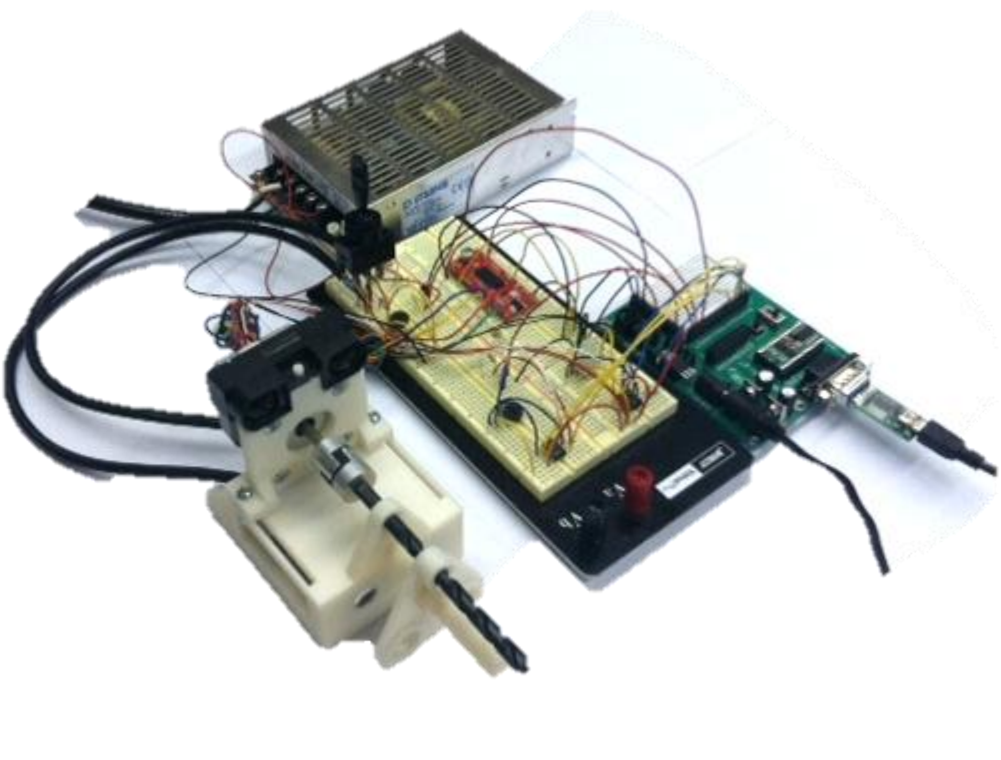


Figure H4: Complete assembled system

APPENDIX I: Program Code

```
' {$STAMP BS2}
' {$PBASIC 2.5}

' Keith Richardson
' Laser Dazzler Microcontroller Program
' This program reads in data from the distance sensor and
' photoreceptor then outputs a motor position.

'-----------------------------------------------------------------


Dist_CS        PIN     0        ' Distance ADC Chip Select (ADC0831.1)
Dist_Clk       PIN     1        ' Distance ADC Clock (ADC0831.7)
Dist_Data      PIN     2        ' Distance ADC Data (ADC0831.6)

Dist_sum       VAR     Word     ' ADC0831 Result
Dist_volts     VAR     Word     ' Volts (0.01 Increments)
Dist_Value     VAR     Word     ' Temp value from Dist_Calc array
Dist_Value_M   VAR     Word     ' Temp previous value from Dist_Calc
array

Photo_CS       PIN     3        ' Photo ADC Chip Select (ADC0831.1)
Photo_Clk      PIN     4        ' Photo ADC Clock (ADC0831.7)
Photo_Data     PIN     5        ' Photo ADC Data (ADC0831.6)

Photo_sum      VAR     Word     ' ADC8031 Result
Photo_volts    VAR     Word     ' Volts (0.01 Increments)

Motor_Pos      VAR     Word     ' Current motor step position
Motor_Value    VAR     Word     ' Temp value from Motor_Calc arrays
Motor_Value_M  VAR     Word     ' Temp previous value from Motor_Calc
arrays
Motor_Int      VAR     Word     ' Interpolated motor position

idx            VAR     Nib      ' Index
Int            VAR     Byte     ' Interpolation percentage
Pulse         VAR     Byte    ' Pulse toggle

'-----------------------------------------------------------------


' These data arrays are calculated values determined through research.
' Dist_Calc correlates the ouput voltage from the distance sensor to a
' distance in increments of 50 cm.
```

```
' Motor_Calc relates to the Dist_Calc to a motor step position for a
' Light (L) and Dark (D) condition

Dist_Calc      DATA    244, 200, 175, 160, 150
               DATA    146, 142, 138, 135, 133

Motor_Calc_L   DATA    198,  81,  49,  31,  18
               DATA     10,   5,   3,   2,   0

Motor_Calc_D   DATA    243, 185, 110,  64,  43
               DATA     31,  17,   9,   3,   1

Motor_Pos = 0                  ' Initial motor position to zero system


'------------------------------------------------------------------


' All of the subfunctions are ran and compiled
' Continuously loops for constant function of laser dazzler

HIGH           Dist_CS         ' Disable Distance ADC0831
HIGH           Photo_CS        ' Disable Photoreceptor ADC0831

DEBUG CR, "Activate pulsing? (1=yes,0=no) ", DEBUGIN pulse

DO
   GOSUB Read_Dist             ' Read distance sensor value
   GOSUB Read_Photo            ' Read photoreceptor sensor value

   GOSUB Motor_Control         ' Outputs motor position
   GOSUB Motor_Control_Pulse

   DEBUG HOME, "Distance Voltage = ", DEC Dist_volts  ' Prints info to
   DEBUG CR,   "Photo Voltage    = ", DEC Photo_volts ' the screen to
   DEBUG CR,   "Motor Position   = ", DEC Motor_Pos   ' ensure
functionality
   PAUSE 10
LOOP
END


'--------------------------------------------------------------------
```

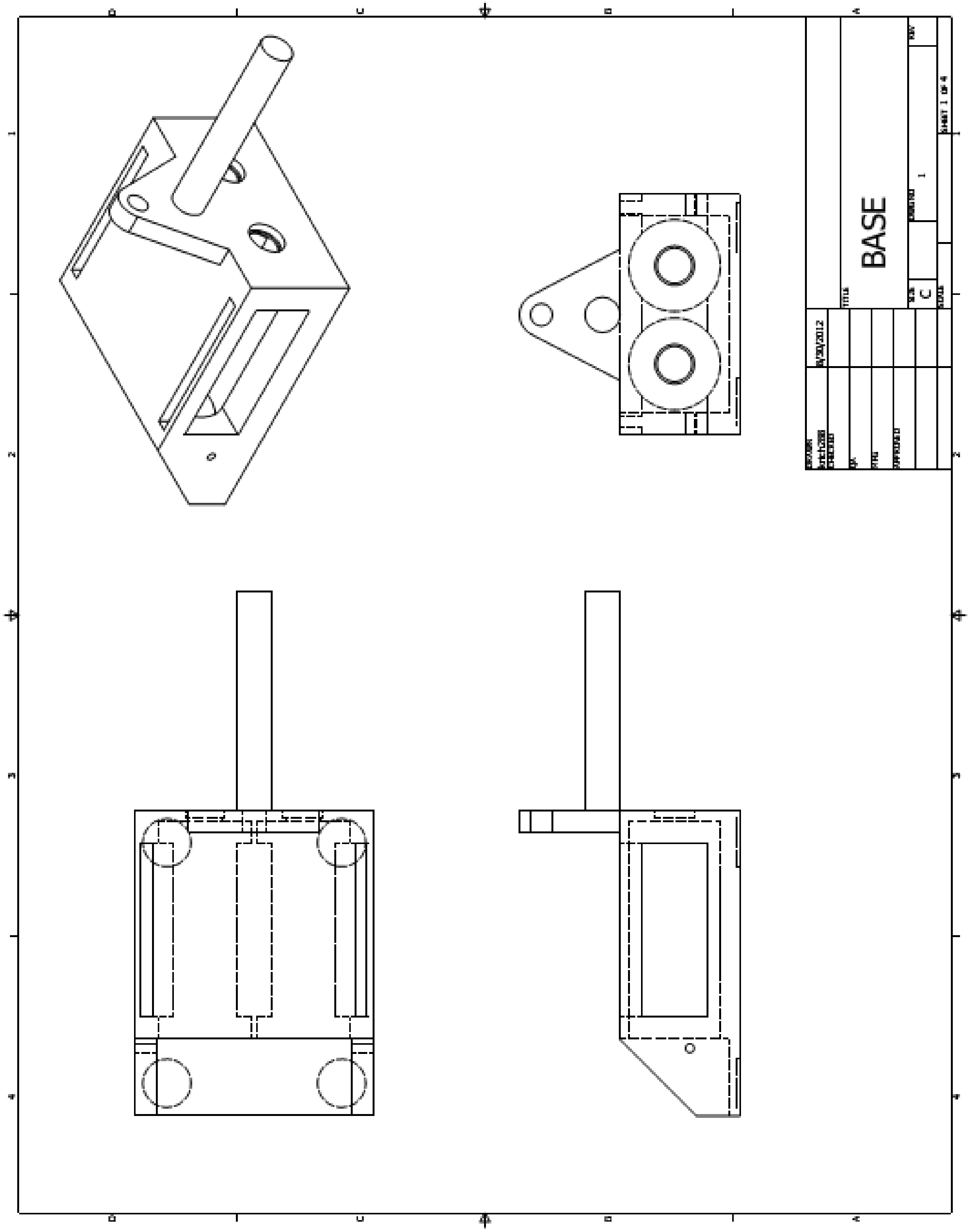
```
' Reads the output of the distance sensor 5 times and averages the
data
' Outputs the voltage of the sensor to be read by subfunction
Motor_Control

Read_Dist:

  Dist_volts = 0               ' Reset sensor value
  FOR idx = 0 TO 4             ' Read 5 times
    LOW Dist_CS                ' Enable ADC0831
    SHIFTIN Dist_Data, Dist_Clk, MSBPOST, [Dist_sum\9] ' Read the
voltage
    HIGH Dist_CS               ' Disable ADC0831
    Dist_volts = Dist_volts + Dist_sum   ' Add the values
    PAUSE 20
  NEXT
  Dist_volts = Dist_volts / 5            ' Average the readings

RETURN


'--------------------------------------------------------------------


' Reads the output of the photoreceptor 5 times and averages the data
' Outputs the voltage of the sensor to be read by subfunction
Motor_Control

Read_Photo:

  Photo_volts = 0              ' Reset sensor value
  FOR idx = 0 TO 4             ' Read 5 times
    LOW Photo_CS               ' Enable ADC0831
    SHIFTIN Photo_Data, Photo_Clk, MSBPOST, [Photo_sum\9] ' Read the
voltage
    HIGH Photo_CS              ' Disable ADC0831
    Photo_volts = Photo_volts + Photo_sum   ' Add the values
    PAUSE 20
  NEXT
  Photo_volts = Photo_volts / 5             ' Average the readings

RETURN


'--------------------------------------------------------------------
```

```
' Evaluates the input distance and photoreceptor values and outputs
' the calculated motor position

Motor_Control:

  FOR idx = 0 TO 9                      ' Searches Dist_Calc DATA for
value
    READ (Dist_Calc + idx), Dist_Value   ' Retrieves value from DATA
table
    IF (Dist_Value <= Dist_volts) THEN EXIT   ' Found value
  NEXT

  READ (Dist_Calc + idx - 1), Dist_Value_M    ' Retrieves previous
DATA value
                                              ' for interpolation
  IF Photo_volts > 80 THEN             ' Determines a light or dark
condition
    READ (Motor_Calc_L + idx), Motor_Value        ' Retrieves relative
value
    READ (Motor_Calc_L + idx - 1), Motor_Value_M  ' and previous value
for
  ELSEIF Photo_volts <=80 THEN                    ' interpolation
    READ (Motor_Calc_D + idx), Motor_Value
    READ (Motor_Calc_D + idx - 1), Motor_Value_M
  ENDIF



' Interpolates the DATA to find the correct motor position on a linear
' scale
  Int= 100*(Dist_volts - Dist_Value) / (Dist_Value_M - Dist_Value)
  Motor_Int = Int * (Motor_Value_M - Motor_Value) / 100
  Motor_Int = Motor_Int + Motor_Value


  DO WHILE Motor_Int > Motor_Pos   ' Checks the desired motor
direction
    LOW 14                         ' Runs motor until it is at the
correct
    PULSOUT 15, 1                  ' position
    Motor_Pos = Motor_Pos + 1
    IF pulse = 0 THEN              ' Checks if user wants to pulse
    PAUSE 6                ' If no then program pauses briefly then
continues
    IF pulse = 1 THEN              ' If yes the laser pulses at 12 Hz
```

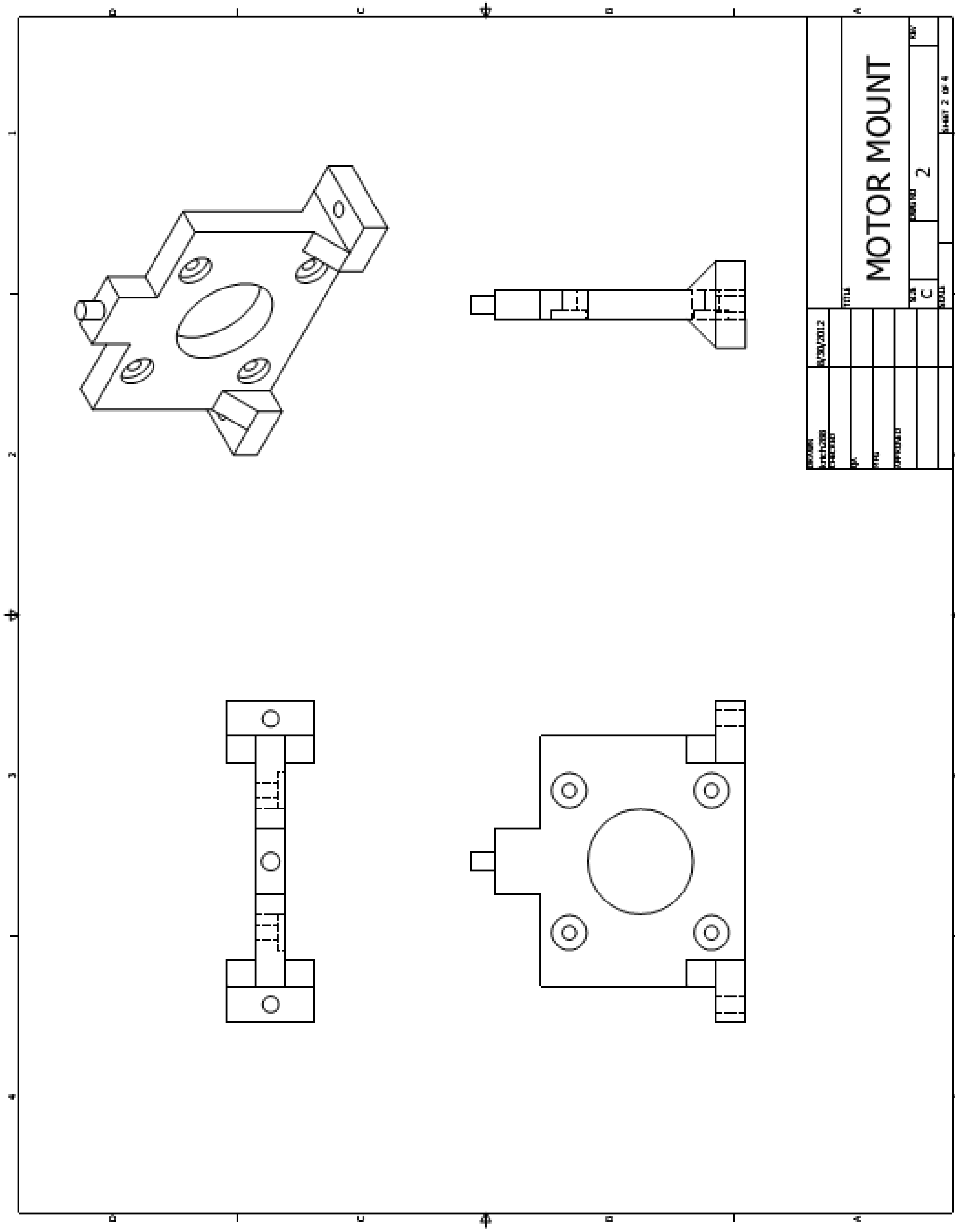
```
    PULSOUT 13, 83
  LOOP


  DO WHILE Motor_Int < Motor_Pos    ' Checks the desired motor
direction
    HIGH 14                         ' Runs motor until it is at the
correct
    PULSOUT 15,1                    ' position
    Motor_Pos = Motor_Pos - 1
    IF pulse = 0 THEN               ' Checks if user wants to pulse
    PAUSE 6                 ' If no then program pauses briefly then
continues
    IF pulse = 1 THEN               ' If yes the laser pulses at 12 Hz
    PULSOUT 13, 83
  LOOP

RETURN
```

APPENDIX J: AutoCAD of Structure

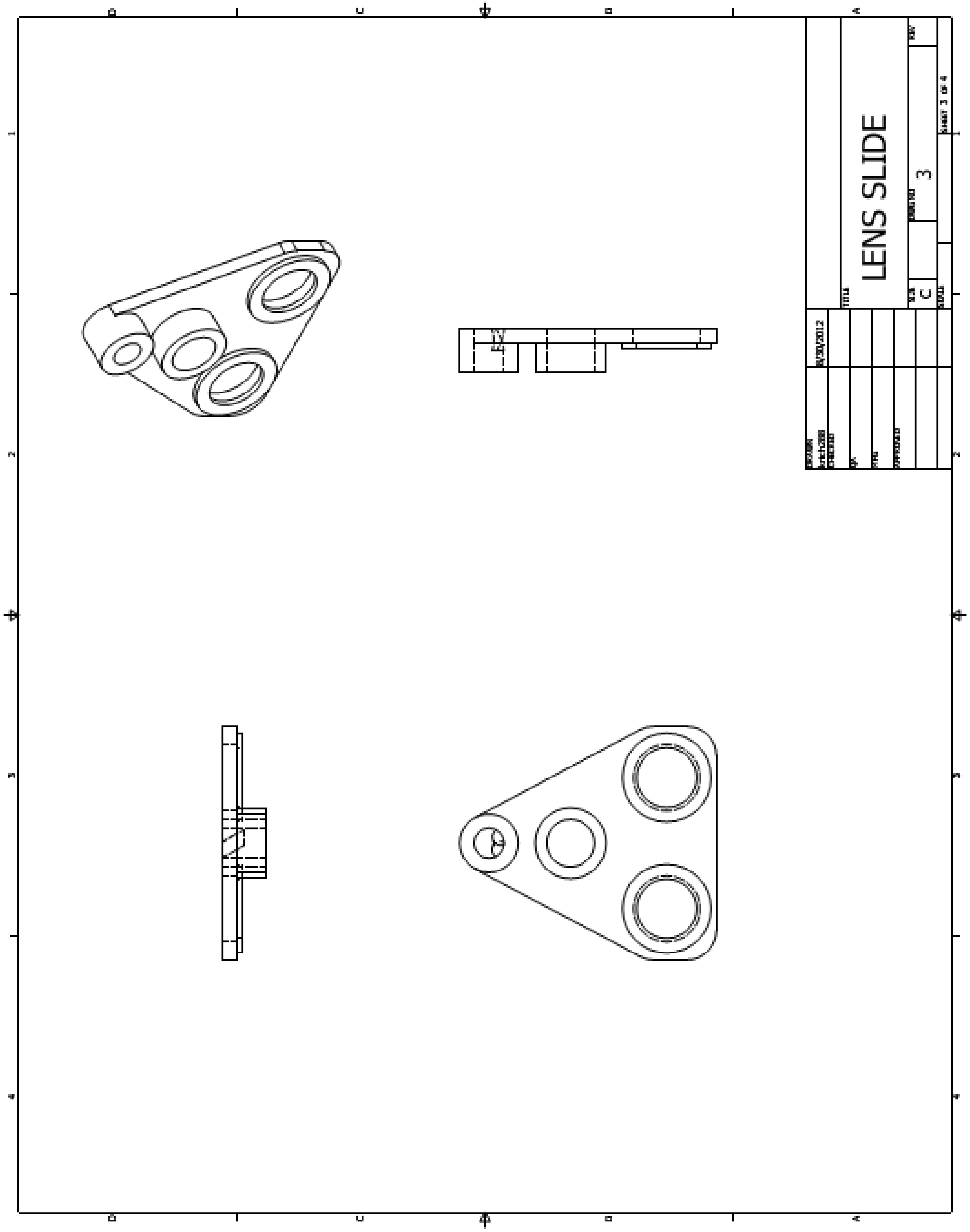
APPENDIX J1. Base



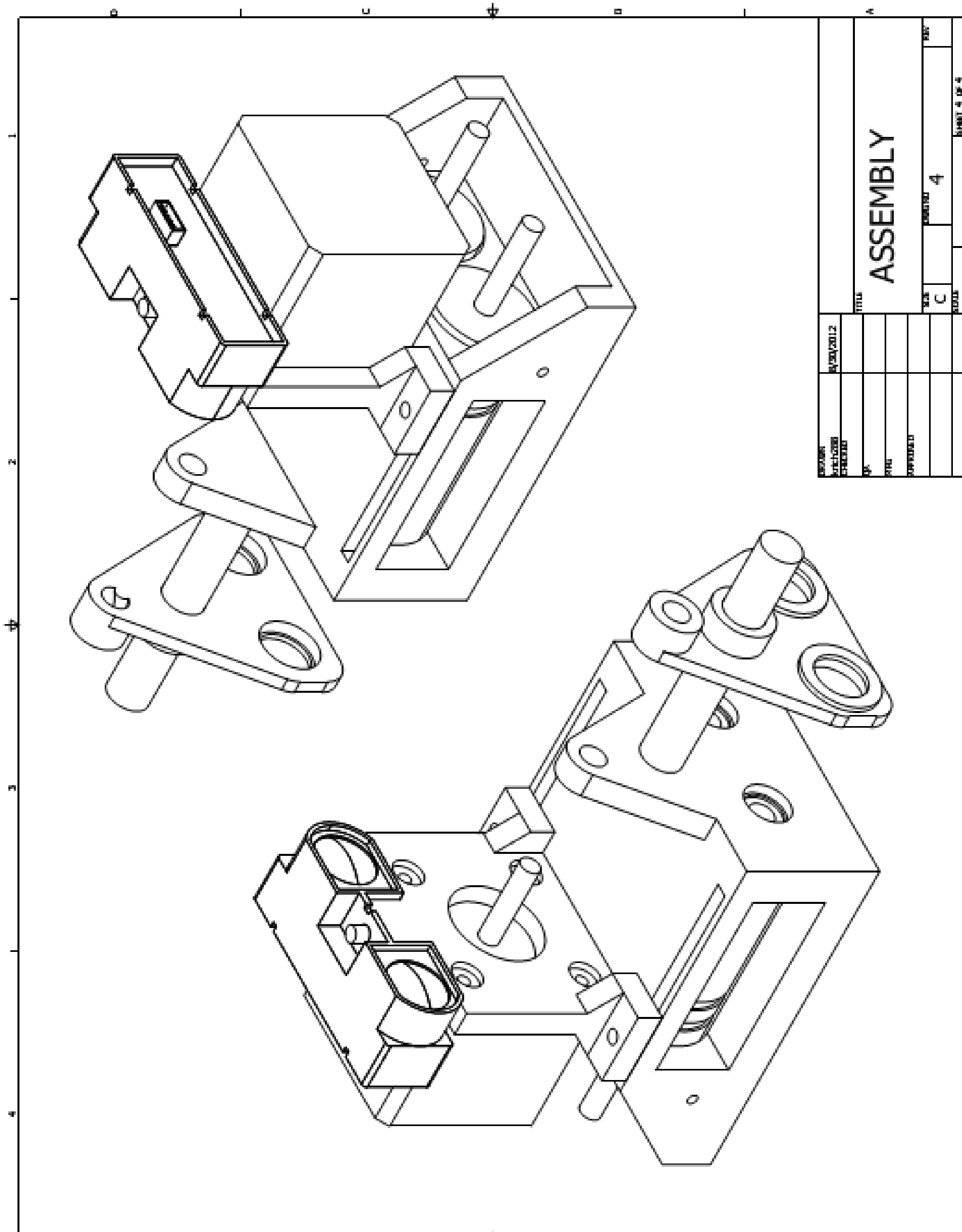
APPENDIX J2. Motor Mount



APPENDIX J3. Lens Slide



APPENDIX J4. Assembly



APPENDIX K: Calculations

APPENDIX K1. Determine maximum permissible exposure (MPE)

$T_{max} = Exposure\ duration = 0.25\ sec$

$F = Pulse\ repition\ frequency = 12\ Hz$

$T = Duration\ of\ pulse\ groups = {}^{1}/_{12}\ sec = 0.08333\ sec$

$n = \#\ of\ pulses\ in\ T_{max} = F\ \times\ T_{max} = 12\ \times\ 0.25 = 3.0\ pulses$

$t = time\ laser\ active\ during\ pulse = 0.05\ sec$

$H = radiant\ exposure = mJ/cm^2$

$E = irradiance = mW/cm^2$

$$Duty\ Factor = \frac{t}{T} = \frac{.05}{.08333} = 60\%\ laser\ active\ during\ single\ pulse$$

Therefore, peak irradiance is 1.677 times greater than average irradiance

Rule 1: Single Pulse Limit

From Table D3

$$MPE_{SP}: H = 1.8t^{0.75} = 1.8(0.05)^{0.75} = 0.1903\ \frac{mJ}{cm^2}$$

$$MPE_{SP}: E = MPE_{SP}: H * F = 0.1903 \times 12 = 2.2839\ \frac{mW}{cm^2}$$

Rule 2: Average Power Limit

$$MPE_{group}: H = 1.8{T_{max}}^{0.75} = 1.8(0.25)^{0.75} = 0.6364\ \frac{mJ}{cm^2}$$

$$MPE_{group}: E = \frac{MPE_{SP}: H_{group}}{T_{max}} = \frac{0.6364}{0.25} = 2.5456\ \frac{mW}{cm^2}$$

Rule 3: Repetitive Pulse Limit

$$MPE_{pulse}: H = c_p \times MPE_{SP}: H = n^{-0.25} MPE_{SP}: H = 3.0^{-0.25} 0.1903 = 0.1446 \ \frac{mJ}{cm^2}$$

$$MPE_{pulse}: E = MPE_{pulse}: H * F = 0.1446 \times 12 = 1.7352 \frac{mW}{cm^2}$$

Rule 3 produces the most conservative value of MPE. The calculations are set for the worst-case scenario when the pupil is fully dilated at 7mm in a dark condition.

$$MPE_{Dark}: H = 0.1446 \frac{mJ}{cm^2}$$

$$MPE_{Dark}: E = 1.7352 \frac{mW}{cm^2}$$

MPE values need to be adjusted for light condition when the pupil is assumed to 4mm diameter. Radiant exposure and irradiance are relative the amount of light entering the eye through the area of the pupil.

$$Area\ of\ pupil = \frac{\pi}{4} d^2$$

$$A_{Dark} = \frac{\pi}{4} 7^2 = 38.4\ mm^2$$

$$A_{Light} = \frac{\pi}{4} 4^2 = 12.6\ mm^2$$

The pupil area in a light condition is only 32.65% of the area in a dark condition significantly limiting the amount of light entering the eye.

$$MPE_{Light}: H = MPE_{Dark}: H \frac{A_{Dark}}{A_{Light}} = 0.1446 \frac{38.4}{12.6} = 0.4428 \frac{mJ}{cm^2}$$

$$MPE_{Light}: E = MPE_{Dark}: E \frac{A_{Dark}}{A_{Light}} = 1.7352 \frac{38.4}{12.6} = 5.3140 \frac{mJ}{cm^2}$$

These values of radiant exposure and irradiance are the amounts the eye can be exposed to for 0.25 seconds without permanent damage.

APPENDIX K2. Determine function of divergence to meet calculate MPE with respect to distance to the target

$\phi = divergence\ of\ laser\ beam = radians$

$\Phi = output\ power\ of\ lasers = 350\ mW$

$a = laser\ beam\ exit\ diameter = 0.2\ cm$

$r_{NOHD} = nominal\ ocular\ hazard\ distance = distance\ to\ target = cm$

Utilizing Equation 8

$$\phi = \frac{1}{r_{NOHD}}\sqrt{\frac{1.27\Phi}{MPE:E} - a^2}$$

$$\phi_{Dark} = \frac{1}{r_{NOHD}}\sqrt{\frac{1.27 * 350}{1.7352} - 0.2^2} = \frac{16.0039}{r_{NOHD}}\ rad$$

$$\phi_{Light} = \frac{1}{r_{NOHD}}\sqrt{\frac{1.27 * 350}{5.3140} - 0.2^2} = \frac{9.1437}{r_{NOHD}}\ rad$$

The projected diameter can be calculated using trigonometry

$D = projected\ diamter = cm$

$$D = 2r_{NOHD}\tan\left(\frac{\phi}{2}\right)$$

Table K1 shows the results. The dark condition requires a projected diameter of approximately 16.00 cm. The light condition requires a projected diameter of approximately 9.14 cm.

Table K1: Nominal ocular hazard function solved for divergence then converted to a projected diameter

NOMINAL OCULAR HAZARD DISTANCE FUNCTION						
	DARK CONDITION			LIGHT CONDITION		
DISTANCE	Radians	Degrees	Projected Diameter (cm)	Radians	Degrees	Projected Diameter (cm)
100	0.160	9.170	16.038	0.091	5.239	9.150
150	0.107	6.113	16.019	0.061	3.493	9.147
200	0.080	4.585	16.012	0.046	2.619	9.145
250	0.064	3.668	16.009	0.037	2.096	9.145
300	0.053	3.057	16.008	0.030	1.746	9.144
350	0.046	2.620	16.007	0.026	1.497	9.144
400	0.040	2.292	16.006	0.023	1.310	9.144
450	0.036	2.038	16.006	0.020	1.164	9.144
500	0.032	1.834	16.005	0.018	1.048	9.144
550	0.029	1.667	16.005	0.017	0.953	9.144

APPENDIX K3. Calculate function to determine distance between the optical lenses to meet the calculated projected area with respect to the distance to the target.

There are two cases that need to be considered for both lighting conditions. The second optical lens moves and will crossover the focal point of the first lens. This changes how the beam is diverged and each case will require its own function. If the projected area can be met and held constant at every distance then the MPE values will met at every distance.

Case 1: Target is close to the laser dazzler in a dark condition. Figure K1 depicts position of the optical lens for this case and describes the variables.

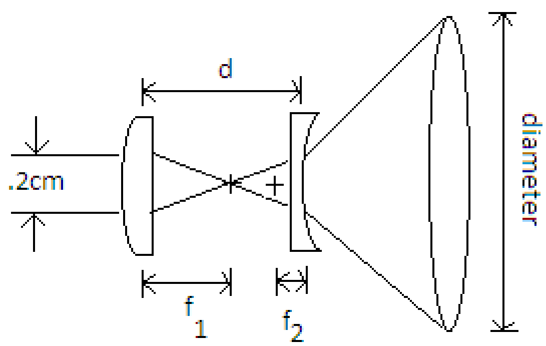


Figure K1: Lens positioning when target is close to laser dazzler

$f = focal\ length\ of\ lens = cm$

$f_{sys} = total\ focal\ length\ of\ the\ system = cm$

$d = distance\ between\ the\ optical\ lenses = cm$

$x = distance\ to\ the\ target = cm$

Determine the distance to the target at which the second lens is on the focal point of the first lens. The second lens can be considered ineffective at this point due to theoretical properties of optical lenses.

$$\frac{0.2}{f_1} = \frac{16}{x}$$

$$x = \frac{16 * 3}{0.2} = 240\ cm$$

At a distance to the target of 240 cm, the second lens is on the focal point of the first lens to produce a projected diameter of 16 cm. Therefore, the function will change at a distance of 240 cm in the dark condition.

For x =100 cm to 240 cm

$$f_{sys} = \frac{0.2x}{16}$$

The focal length of the system is made negative because focal length is behind the lenses creating a diverging lens system. Lens 1 is also treated as a diverging lens in order to utilize the thin lens equation.

$$\frac{1}{-f_{sys}} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

$$\frac{-16}{0.2x} = \frac{1}{-3.0} + \frac{1}{-1.5} - \frac{d}{-3.0(-2.0)}$$

2 times the focal length of lens 1 or 6 cm needs to be added back into the function to convert lens 1 back to a converging lens and provide proper values of distance between lenses.

$$d_{DC} = \frac{360}{x} - 4.5 + 6.0 = \frac{360}{x} + 1.5$$

Case 2: For x =240 cm to 550 cm in a dark condition

Figure K2 shows how the focal length of the system has changed and demonstrates how the thin equation needs to be adjusted.

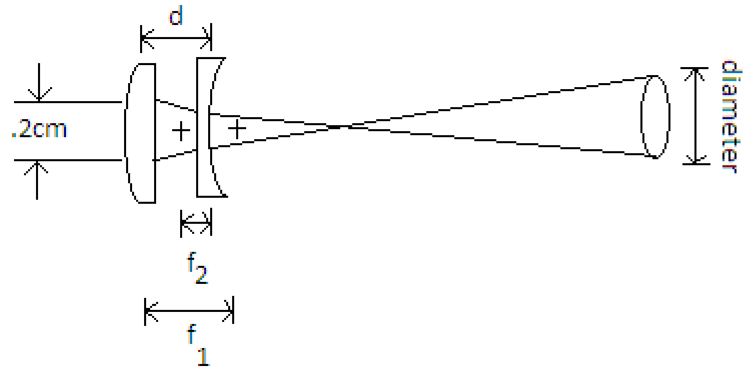


Figure K2: Lens positioning when target is far from laser dazzler

$$\frac{0.2}{f_{sys}} = \frac{16}{x - f_{sys}}$$

$$f_{sys} = \frac{x}{81}$$

$$\frac{1}{f_{sys}} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

$$\frac{81}{x} = \frac{1}{3.0} + \frac{1}{-1.5} - \frac{d}{3.0(-2.0)}$$

$$d_{DF} = \frac{365.5}{x} + 1.5$$

Case 3: The exact same process was followed for the light condition except the projected diameter was evaluated at 9.14 cm. This provided the following functions.

The second lens was determined to cross over the first focal point at a distance to the target of 137.1cm

For a distance of x=100 cm to 137.1 cm in a light condition

$$d_{LC} = \frac{205.65}{x} + 1.5$$

Case 4: For a distance of x=137.1 cm to 550 cm in a light condition

$$d_{LF} = \frac{210.15}{x} + 1.5$$

APPENDIX K4. Convert these functions to the number of motor steps for the control system program.

The camshaft driver for the optical system is a drill bit. It has two starts with a pitch of 0.5465 inches. The lead is 1.093 inches. This means 1 rotation of the cam will move the optical lens 1.093 inches or 2.776 cm. The motor has 200 steps per revolution. This means 1 motor step is equal to .01388 cm. Using this conversion factor, the above functions can be adjusted from centimeters to number of motor steps.

$$d_{DC} = \frac{25937}{x} + 108$$

$$d_{DF} = \frac{26261}{x} + 108$$

$$d_{LC} = \frac{14820}{x} + 108$$

$$d_{LF} = \frac{15144}{x} + 108$$

APPENDIX K5. Nominal hazard zone safety calculation

The nominal hazard zone will indicate the safe distance a subject's eye can be from a reflected diffused beam. This could occur if the subject looks down and the beam is reflected of the shirt and then into the eyes. The reflectivity of white cotton fabric was estimated to be 50% and the angle of viewing was estimated to be 70°.

$\rho = reflectivity\ coefficient = 0.5$

$\theta = viewing\ angle = 70°$

$$r_{NHZ} = \sqrt{\frac{\rho\Phi \cos\theta}{\pi MPE\!:E}}$$

$$r_{NHZ,Dark} = \sqrt{\frac{0.5 * 350 \cos 70}{\pi 1.7352}} = 3.3\ cm$$

$$r_{NHZ,Light} = \sqrt{\frac{0.5 * 350 \cos 70}{\pi 5.3140}} = 1.9\ cm$$

This indicates the subject's eye would need to be closer than 3.3 cm to cause any permanent damage. This is unlikely, but should be considered in other laser dazzler designs and for long-term exposure.

APPENDIX K6. Converting irradiance to Lux

Testing was done with a digital Lux meter providing units of Lux. To convert from Lux to mW/cm^2, the luminosity function needs to be taken into account. The light intensity meter automatically adjusts its values according to the sensitivity of the eye therefore; the integral has already been calculated. This calculation can be done in either direction. This sample calculation will be done with the irradiance equaling the MPE for a dark condition.

$B = lumens$

$J(\lambda) = W/m$

$\bar{y}(\lambda) = luminous\ function$

$\lambda = wavelength\ [m]$

$C = 683.002\ lm/W$

$$B = C\int_0^\infty \bar{y}(\lambda)\ J(\lambda)d\lambda$$

$$\int_0^\infty \bar{y}(\lambda)\ J(\lambda)d\lambda = Power\ [W]$$

$B = C * Power$

$$MPE_{Dark}: E = 1.735\left[\frac{mW}{cm^2}\right] = 17.35[W/m^2]$$

$$\frac{B}{Projected\ Area} = Lux = C * MPE: E$$

$683.002 * 17.35 = 11850\ Lux$

This indicates the MPE value of 1.735 mW/cm^2 is equivalent to a value of 11850 Lux read from the digital Lux meter.

APPENDIX L: Test data

APPENDIX L1. Distance Sensor Calibration

Table L1: Distance sensor calibration

Distance Sensor Calibration Data	
Distance (cm)	Vout (Volts)
100	2.44
150	2.00
200	1.75
250	1.60
300	1.50
350	1.46
400	1.42
450	1.38
500	1.35
550	1.33

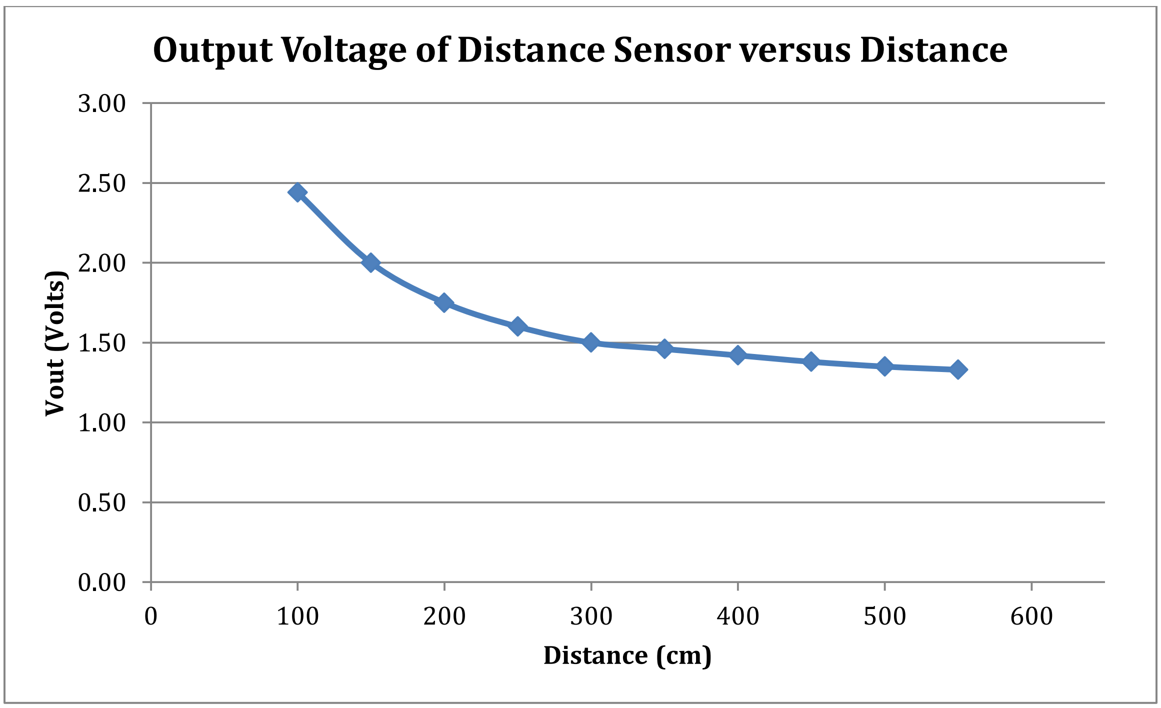


Figure L1: Output voltage versus distance

APPENDIX L2. Gaussian Beam Shape

Table L2: Measurements of the green Gaussian beam

Green Gaussian Beam Set 200 cm, ~15 cm Diameter		
Distance from Center 13 cm	Distance from Center 8 cm	Distance from Center 4 cm
50	171	279
32	112	253
38	125	248
35	142	225
25	123	237
47	162	278
	CENTER	304

Green Gaussian Beam Shape

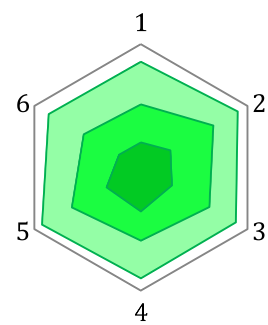


Figure L2: Plot of the green Gaussian beam shape

Table L3: Measurements of the red Gaussian beam

Red Gaussian Beam Set 200 cm, ~15 cm Diameter		
Distance from Center 13 cm	Distance from Center 8 cm	Distance from Center 4 cm
42	80	112
35	69	125
56	94	136
64	117	147
30	65	121
30	68	108
	CENTER	156

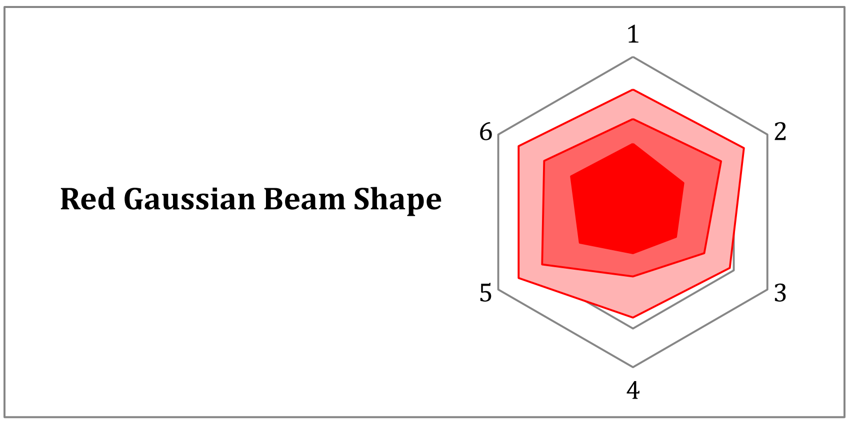


Figure L3: Plot of the red Gaussian beam shape

APPENDIX L3. Constant diameter in light condition

Table L4: Brightness versus distance with lens control, constant diameter, lights on

Brightness vs Distance With Lens Control Constant Laser Diameter / LIGHTS ON						
Distance cm	Motor Pos in	Red Diam cm	Green Diam cm	Red Lux x10	Green Lux x10	Total Illuminance TOTAL Lux x10
100	1.383	15	12	170	363	533
150	1.082	15	13	159	309	468
200	0.908	15	15	175	270	445
250	0.830	15	17	176	223	399
300	0.778	15	18	162	171	333
350	0.755	15	19	150	139	289
400	0.725	15	19	152	106	258
450	0.695	15	19	163	92	255
500	0.685	15	19	153	84	237
550	0.670	15	19	157	80	237

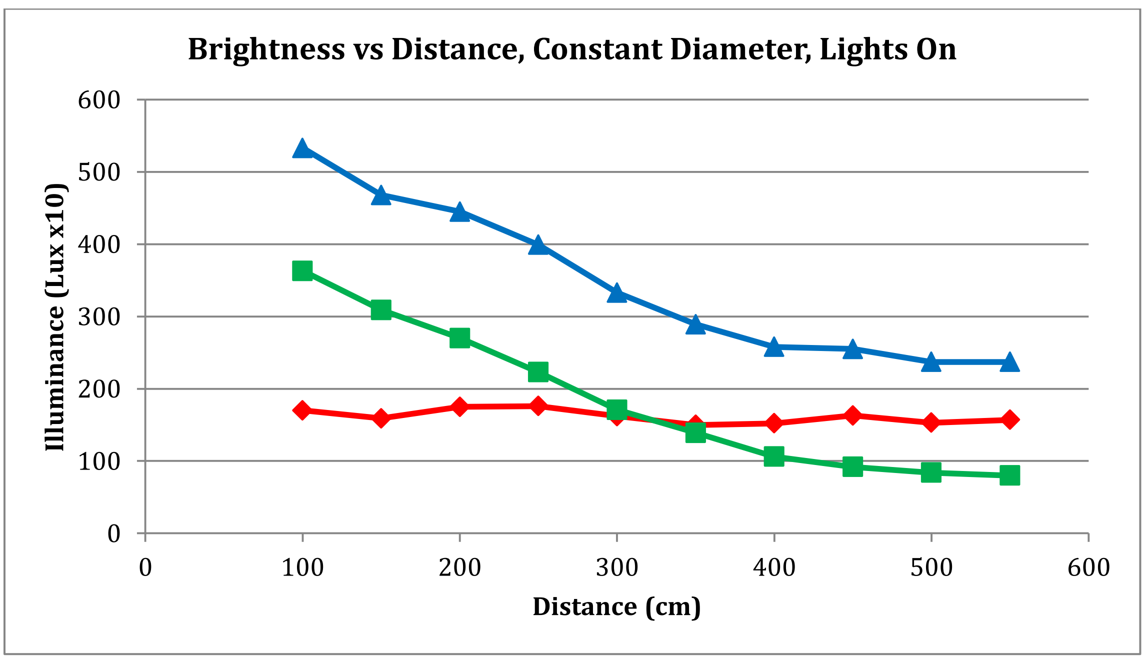


Figure L4: Brightness versus distance with lens control, constant diameter, lights on

APPENDIX L4. Constant illuminance in light condition

Table L5: Brightness versus distance with lens control, constant illuminance, lights on

Brightness vs Distance With Lens Control Constant Illuminance / LIGHTS ON						
Distance cm	Motor Pos in	Red Diam cm	Green Diam cm	Red Lux x10	Green Lux x10	Total Illuminance TOTAL Lux x10
100	1.705	20	12	102	392	494
150	1.065	14	13	176	323	499
200	0.894	14	15	206	291	497
250	0.794	13.5	16	214	266	480
300	0.722	11	17	306	207	513
350	0.679	9	18	357	140	497
400	0.652	8.5	19	373	95	468
450	0.641	8	19	398	91	489
500	0.634	8	20	415	87	502
550	0.625	7.5	20	421	85	506
						TARGET 500

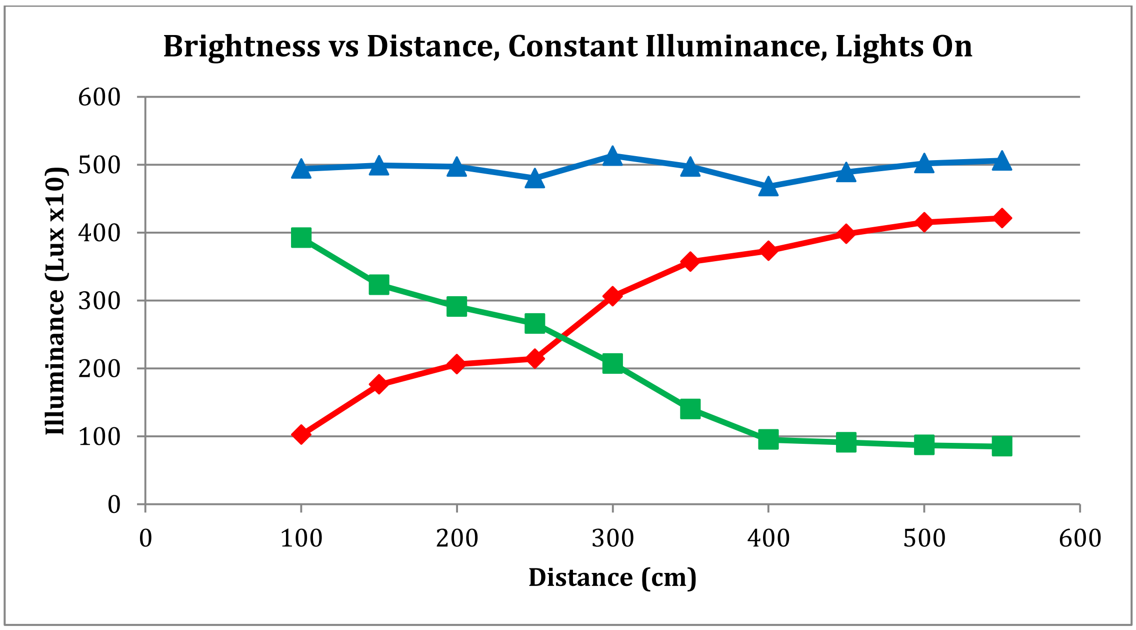


Figure L5: Brightness versus distance with lens control, constant illuminance, lights on

APPENDIX L5. Constant diameter in dark condition

Table L6: Brightness versus distance with lens control, constant diameter, lights off

Brightness vs Distance With Lens Control Constant Laser Diameter / LIGHTS OFF						
Distance cm	Motor Pos in	Red Diam cm	Green Diam cm	Red Lux x10	Green Lux x10	Total Illuminance TOTAL Lux x10
100	1.554	20	14	111	274	385
150	1.292	20	15	109	238	347
200	1.094	20	16	110	220	330
250	1.001	20	17	110	172	282
300	0.876	20	18	122	160	282
350	0.817	20	18	110	135	245
400	0.802	20	19	109	112	221
450	0.76	20	19	112	101	213
500	0.742	20	19	108	93	201
550	0.721	20	20	110	87	197

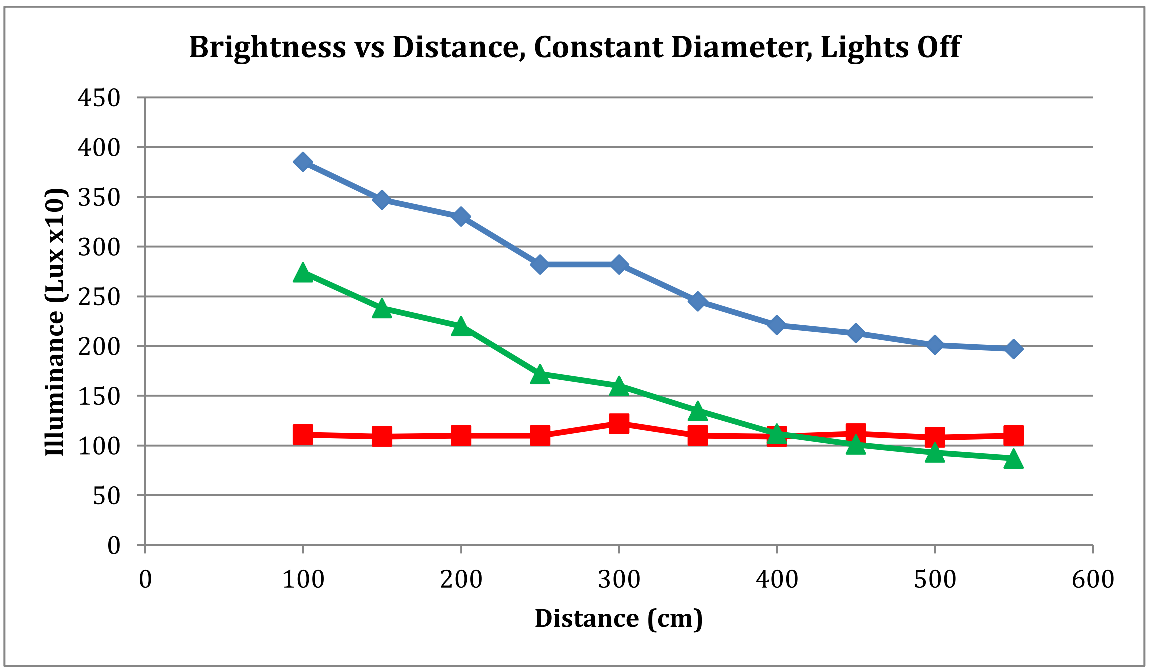


Figure L6: Brightness versus distance with lens control, constant diameter, lights off

APPENDIX L6. Constant Illuminance in dark condition

Table L7: Brightness versus distance with lens control, constant illuminance, lights off

Brightness vs Distance With Lens Control Constant Illuminance / LIGHTS OFF						
Distance cm	Motor Pos in	Red Diam cm	Green Diam cm	Red Lux x10	Green Lux x10	Total Illuminance Lux x10
100	2.135	30	16	50	265	315
150	1.638	30	17	61	253	314
200	1.224	26	18	97	201	298
250	0.977	24	18	98	204	302
300	0.861	18	18	133	185	318
350	0.795	18	19	130	172	302
400	0.716	16	19	154	143	297
450	0.673	16	19	172	124	296
500	0.636	14	19	185	105	290
550	0.627	13	19	205	101	306
						TARGET 300

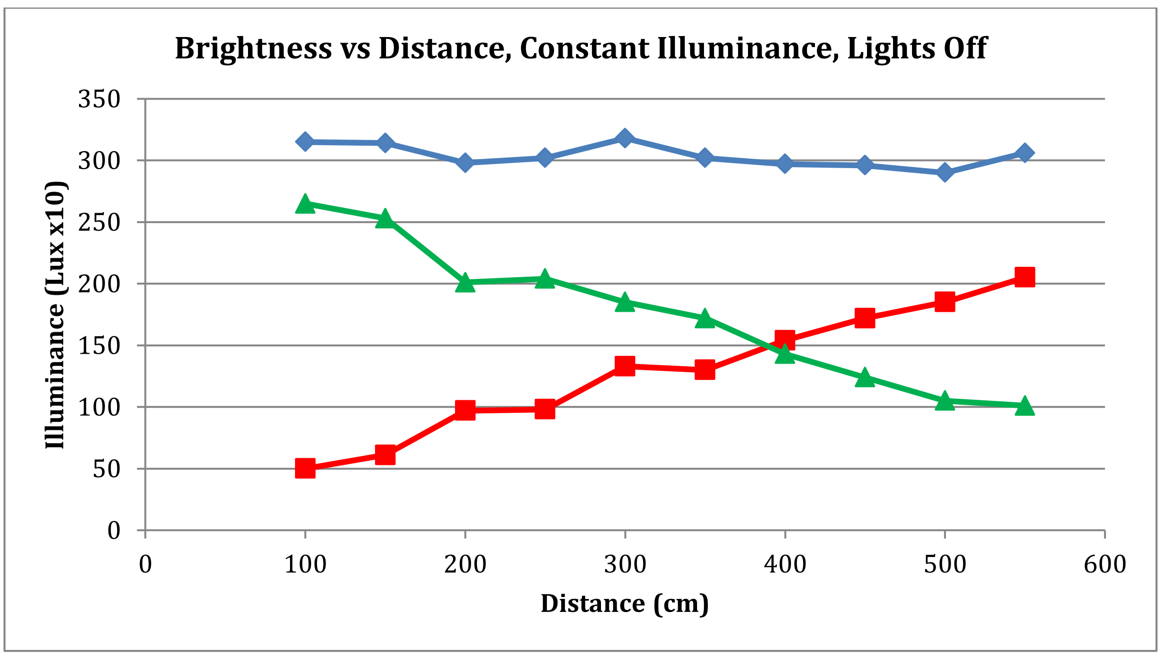


Figure L7: Brightness versus distance with lens control, constant illuminance, lights off

APPENDIX L7. Control system standalone

Table L8: Optical system and motor positioning, constant diameter, lights on

LIGHT CONSTANT DIAMETER				CALCULATED STEPS	
Distance cm	Motor Position in	Lens Distance in (CF=+0.2)	Rotation Position Rotations	Total Steps Steps	Normalized Steps Steps
100	1.383	1.583	1.265	253	130
150	1.082	1.282	0.990	198	75
200	0.908	1.108	0.831	166	44
250	0.830	1.030	0.759	152	29
300	0.778	0.978	0.712	142	20
350	0.755	0.955	0.691	138	16
400	0.725	0.925	0.663	133	10
450	0.695	0.895	0.636	127	5
500	0.685	0.885	0.627	125	3
550	0.670	0.870	0.613	123	0

Table L9: Optical system and motor positioning, constant illuminance, lights on

LIGHT CONSTANT ILLUMINANCE				CALCULATED STEPS	
Distance cm	Motor Position in	Lens Distance in (CF=+0.2)	Rotation Position Rotations	Total Steps Steps	Normalized Steps Steps
100	1.705	1.905	1.560	312	198
150	1.065	1.265	0.974	195	81
200	0.894	1.094	0.818	164	49
250	0.794	0.994	0.726	145	31
300	0.722	0.922	0.661	132	18
350	0.679	0.879	0.621	124	10
400	0.652	0.852	0.597	119	5
450	0.641	0.841	0.586	117	3
500	0.634	0.834	0.580	116	2
550	0.625	0.825	0.572	114	0

Table L10: Optical system and motor position calibration, constant diameter, lights off

DARK CONSTANT DIAMETER			CALCULATED STEPS		
Distance cm	Motor Position in	Lens Distance in (CF=+0.2)	Rotation Position Rotations	Total Steps Steps	Normalized Steps Steps
100	1.554	1.754	1.422	284	152
150	1.292	1.492	1.182	236	104
200	1.094	1.294	1.001	200	68
250	1.001	1.201	0.916	183	51
300	0.876	1.076	0.801	160	28
350	0.817	1.017	0.747	149	18
400	0.802	1.002	0.734	147	15
450	0.76	0.960	0.695	139	7
500	0.742	0.942	0.679	136	4
550	0.721	0.921	0.660	132	0

Table L11: Optical system and motor position calibration, constant illuminance, lights off

DARK CONSTANT ILLUMINANCE			CALCULATED STEPS		
Distance cm	Motor Position in	Lens Distance in (CF=+0.2)	Rotation Position Rotations	Total Steps Steps	Normalized Steps Steps
100	1.951	2.151	1.785	357	242
150	1.638	1.838	1.499	300	185
200	1.224	1.424	1.120	224	109
250	0.977	1.177	0.894	179	64
300	0.861	1.061	0.788	158	43
350	0.795	0.995	0.727	145	31
400	0.716	0.916	0.655	131	16
450	0.673	0.873	0.616	123	8
500	0.639	0.839	0.585	117	2
550	0.628	0.828	0.575	115	0

Table L12: Control system programming motor steps, constant diameter

CONSTANT DIAMETER		
Distance cm	LIGHT STEPS	DARK STEPS
100	130	162
150	75	114
200	44	78
250	29	61
300	20	38
350	16	27
400	10	24
450	5	16
500	3	13
550	0	9

Table L13: Control system programming motor steps, constant illuminance

CONSTANT LUMINANCE		
Distance cm	LIGHT STEPS	DARK STEPS
100	198	276
150	81	185
200	49	110
250	31	64
300	18	43
350	10	31
400	5	17
450	3	9
500	2	2
550	0	0

Table L14: Red laser brightness vs. distance, standalone system, constant diameter

RED Brightness vs Distance, Standalone System, Constant Diameter				
	Lights ON		Lights OFF	
Distance cm	Red Diam cm	Illuminance Lux x10	Red Diam cm	Illuminance Lux x10
100	15	165	20	103
150	15	170	20	100
200	15	162	20	109
250	15	172	20	111
300	15	178	20	120
350	15	168	20	115
400	15	151	20	115
450	15	150	20	105
500	15	154	20	101
550	15	152	20	115

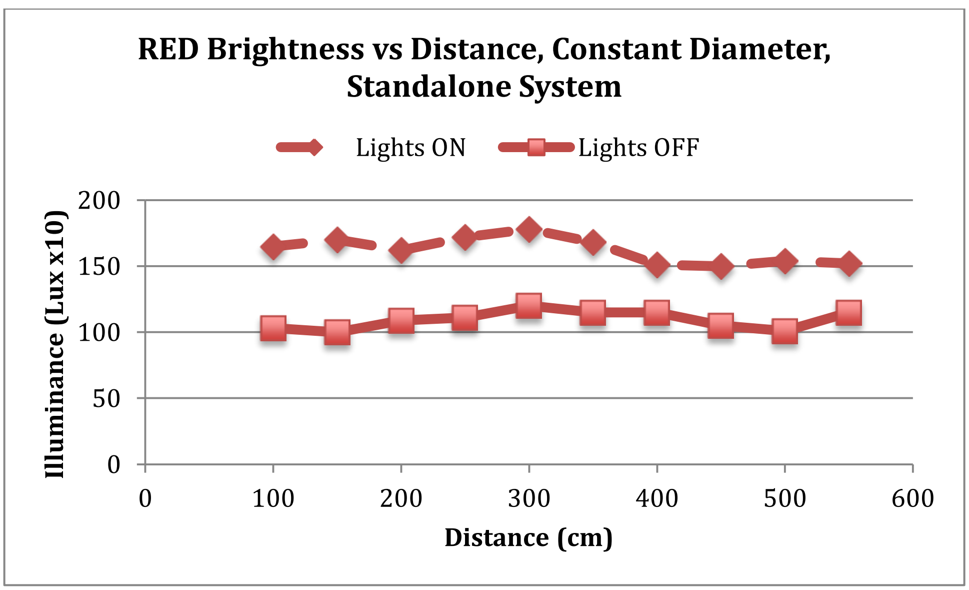


Figure L8: Red laser brightness vs. distance, standalone system, constant diameter

Table L15: Standalone system, brightness vs. distance, constant illuminance, lights on

Brightness vs Distance, Standalone System Constant Illuminance / LIGHTS ON					
Distance cm	Red Diam cm	Green Diam cm	Red Lux x10	Green Lux x10	Peak Brightness TOTAL Lux x10
100	20	12.5	95	380	475
150	15	13	172	340	512
200	14.5	15	212	299	511
250	13.5	15.5	230	254	484
300	11	16.5	310	200	510
350	8	17.5	370	142	512
400	8.5	19	385	105	490
450	8	19.5	389	95	484
500	8	20	425	85	510
550	7.5	20	437	79	516
				TARGET	500

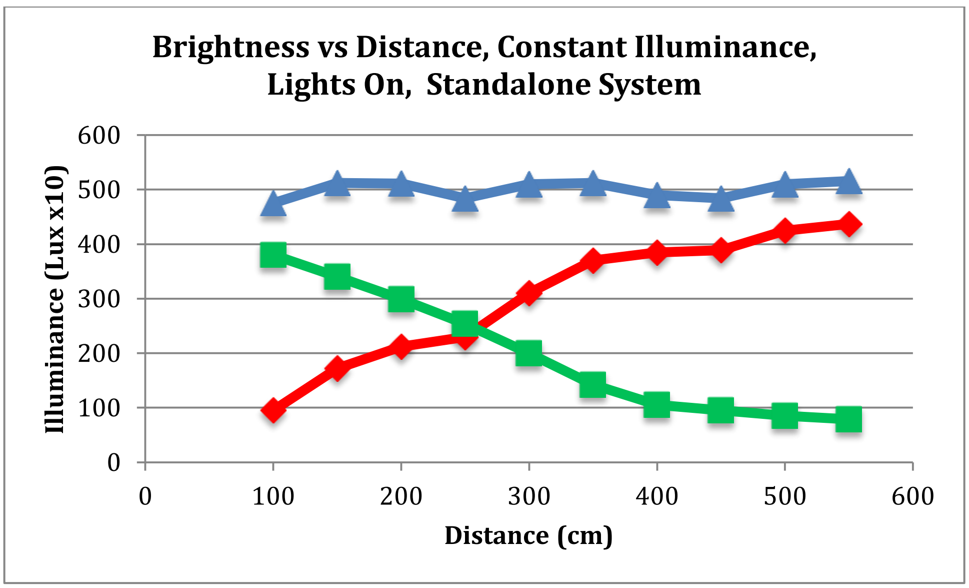


Figure L9: Standalone system, brightness vs. distance, constant illuminance, lights on

Table L16: Standalone system, brightness vs. distance, constant illuminance, lights off

Brightness vs Distance, Standalone System Constant Illuminance / LIGHTS OFF					
Distance cm	Red Diam cm	Green Diam cm	Red Lux x10	Green Lux x10	Peak Brightness Lux x10
100	30	15	60	278	338
150	29	16	76	262	338
200	27	17	101	214	315
250	23	17.5	120	197	317
300	19	18	142	185	327
350	18.5	18	140	165	305
400	16.5	18.5	158	140	298
450	16	18.5	186	132	318
500	14.5	19	190	108	298
550	12.5	19	202	100	302
				TARGET	300

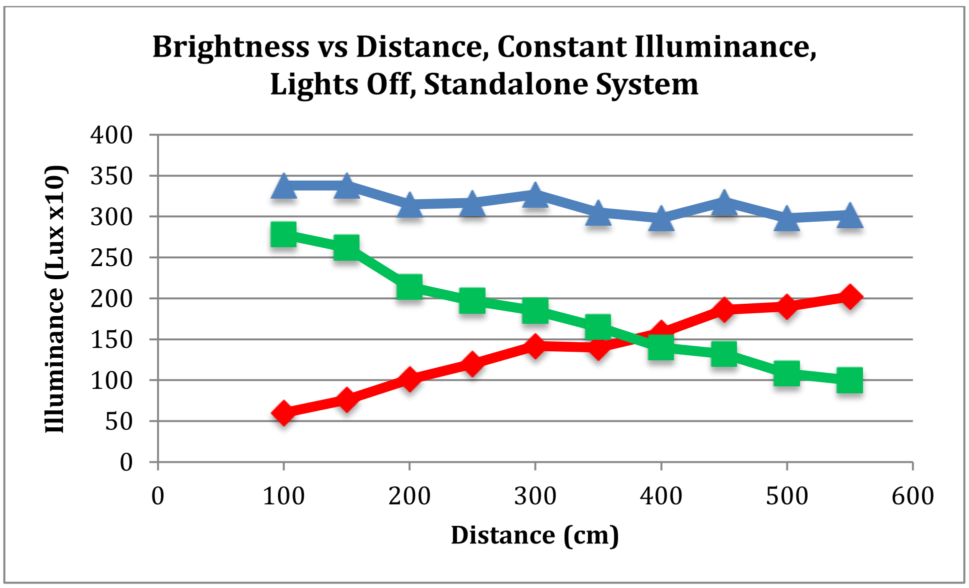


Figure L10: Standalone system, brightness vs. distance, constant illuminance, lights off

APPENDIX L8. Constant divergence

Table L17: Brightness vs. distance, system optimized for 50 cm target

Brightness vs Distance No Lens Control (set 50 cm for 15 cm Diam, MP=2.200 in)			
Distance cm	Peak Brightness RED Lux x10	Peak Brightness Green Lux x10	Peak Brightness TOTAL Lux x10
50	164	475	639
100	82	124	206
150	38	64	102
200	38	43	81
250	34	38	72
300	35	36	71
350	32	34	66
400	30	32	62
450	31	30	61
500	32	30	62
550	30	30	60

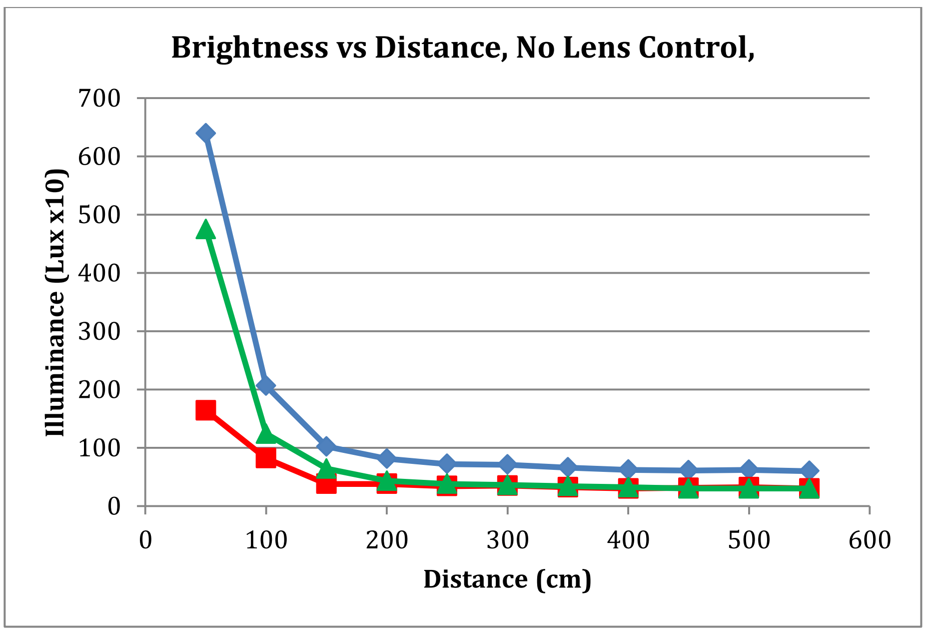


Figure L11: Brightness vs. distance, system optimized for 50 cm target

Table L18: Brightness vs. distance, system optimized for 550 cm target

Brightness vs Distance No Lens Control (set 550 cm for 15 cm Diam, MP=0.670 in)			
Distance cm	Peak Brightness RED Lux x10	Peak Brightness Green Lux x10	Peak Brightness TOTAL Lux x10
50	6550	5980	12530
100	3120	3210	6330
150	1651	1580	3231
200	1120	1036	2156
250	740	665	1405
300	640	444	1084
350	501	345	846
400	413	326	739
450	395	286	681
500	237	232	469
550	302	199	501

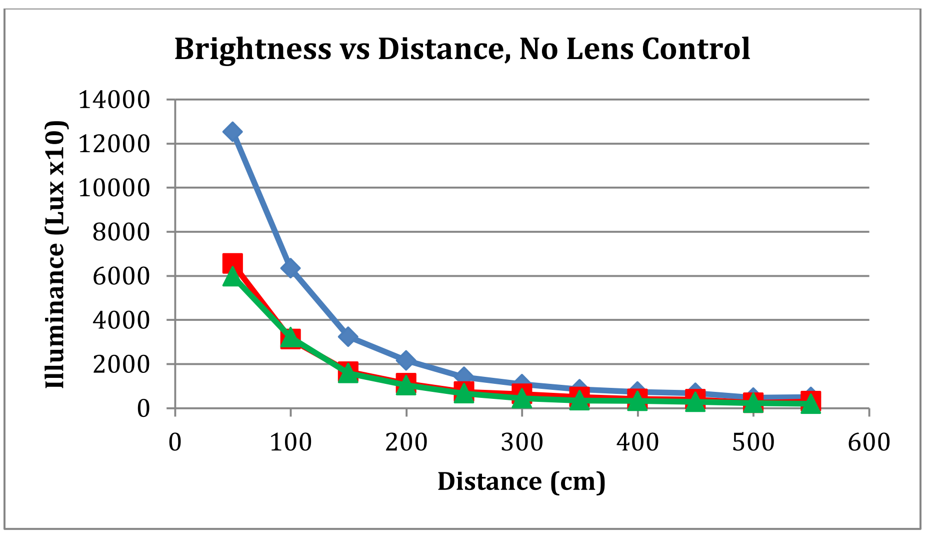


Figure L12: Brightness vs. distance, system optimized for 550 cm target

APPENDIX L9. Theoretical versus measured distance between optical lenses

Table L19: Thin lens equation producing projected diameter of 15 cm

DARK THEORETICAL CONDITION OF DIAM 15cm		
Distance cm	Gap b/w Lenses cm	Gap b/w Lenses in
100	4.88	1.92
125	4.20	1.65
150	3.75	1.48
175	3.43	1.35
200	3.19	1.25
225	3.00	1.18
250	2.87	1.13
275	2.74	1.08
300	2.64	1.04
325	2.55	1.00
350	2.48	0.98
375	2.41	0.95
400	2.36	0.93
425	2.30	0.91
450	2.26	0.89
475	2.22	0.87
500	2.18	0.86
525	2.15	0.85
550	2.12	0.84

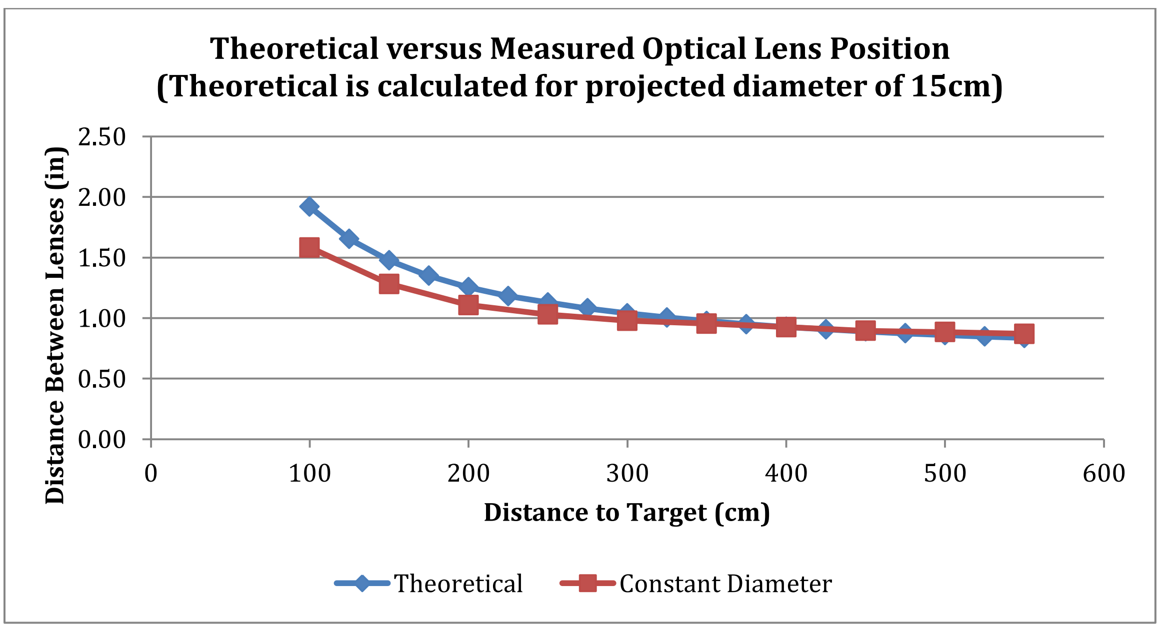


Figure L13: Comparison of theoretical calculation and measured distance between lenses

APPENDIX L10. Compilation of all tests, projected diameter versus illuminance

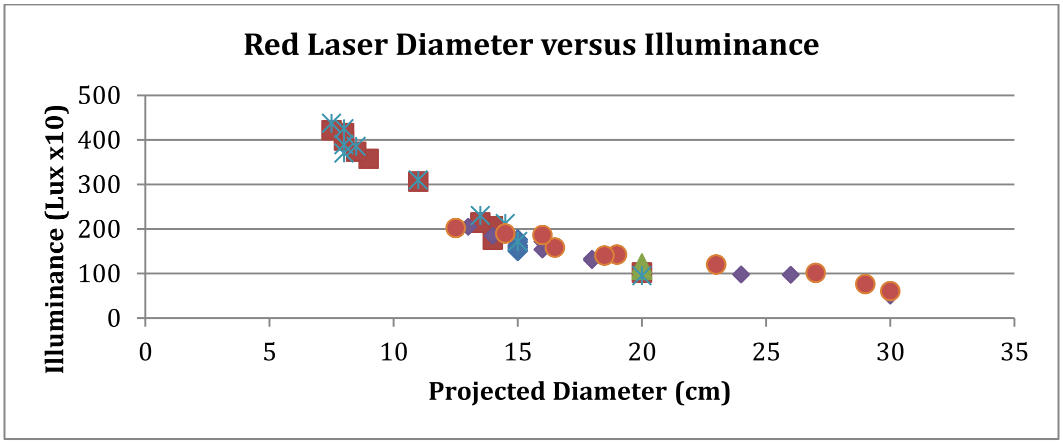


Figure L14: Red laser diameter versus illuminance

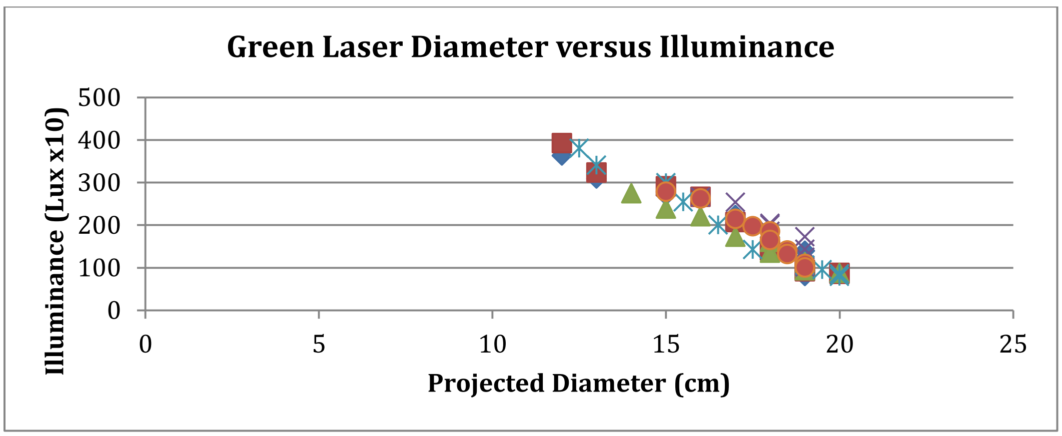


Figure L15: Green laser diameter versus illuminance