Design of a Multi-Laser System

Major Qualifying Project

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Abstract

Helium balloon releases have been a mainstay at celebratory events. However, balloons can travel hundreds of miles and have a tendency to end up in lakes, seas and oceans. These bodies of water are vulnerable because balloons pose a danger to aquatic life and have a significant impact on pollution levels. Clean up efforts have found tens of thousands of balloons on beaches yearly in the United States alone (Witmer, 2017). Laser light can be used to damage balloon's membranes and prohibit them from flying into bodies of water. This project explores the usage of a system of links and slides to target and safely remove balloons from the atmosphere using laser light. Theoretically, the linkage-laser system offers ranges of a few miles, but the current system is limited due to Gaussian beam and power limitations. Future work can be extended to auto-detect and target the balloons in the air.

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Table of Contents

List of Figures

1. Introduction

Pollution is at an all-time high and is only increasing in effect on the planet (State Coastal Commission, 2018). The ocean specifically has seen pollution levels that permeate across many facets of human life and environmental wellbeing. Microplastics are found in our food supply, a whale made the news again for washing up on a beach with 48 pounds of plastic in its stomach, and the corals in Australia are bleaching; this is just to name a few of the effects of pollution. One specific type of pollution that has an impact on aquatic life are balloons (Schuyler et al., 2012). Balloons can travel hundreds of miles and look like jelly fish or other prey animals when in aquatic environments. They are being eaten and subsequently killing aquatic life, particularly sea turtles.

This Major Qualifying Project intends to model a solution that will mitigate the effects of balloon pollution in the ocean or other bodies of water. Balloons are able to fly thousands of meters in the air and have a range of hundreds of miles. In addition, balloons appear in the tens of thousands on United States Beaches alone. It is a major problem and the aerial aspect of this problem inhibits collection of the pollutants. If the balloons were not airborne, they would be able to be collected easier. Already, there are organizations that are working to spread awareness of this pollutant, but there are apparently no organizations working to collect airborne balloons.

This project explored building a multi-laser system that can be used to target balloons that are airborne and rupture their membrane. The balloon will then fall onto the land where it can be tracked and collected. The proposed plan is to design a linkage system, a combination of links designed to provide a specific movement that will house diode lasers and will remain safe to humans and wildlife but remain powerful enough to remove balloons from the air.

This paper discusses the background of balloons as a source of pollution, examines the feasibility of using a laser system to remove balloons from the air, and designs a prototype to show the feasibility of the laser system. In addition to a laser system, this project includes a rudimentary model for balloons in free-fall in order to determine where the pollutant will land. Finally, the paper will include a section on future research to improve the current design and implementation of this system.

Plastics and balloons in particular have already shown they are harmful to aquatic environments, those who inhabit aquatic environments, and even the food supply from the oceanic and other waters. The goal of this project is to design and show feasibility of the implementation of a laser system in order to limit the amount of pollution that will end up in the ocean or other bodies of water.

2. Background

2.1 Pollution

As the world becomes more developed, human manufactured waste continues to intrude into different natural habitats. These debris and thrown away goods are often referred to as pollution. According to the Mariam Webster dictionary, Pollution is defined as the action of polluting especially by environmental contamination with man-made waste. Pollution of the ocean is a leading problem for both humans and marine based life.

Pollution of the Earth's oceans takes many forms: agricultural runoff, mining runoff, sewage, littering, commercial debris and toxic chemicals. According to the University of Georgia, 9 million tons of plastic end up in the ocean every single year. Other estimates put this number between 4 and 12 million tons. Plastic pollution in the ocean is such a problem that plastics are the most common debris in the ocean; in some cases, plastic represents 80% of the effects of the pollution (State Coastal Commission, 2018). According to the Californian government, the plastics that are commonly thought of as pollutants are typically broken down and add to the 15-51 trillion pieces of micro plastic. However, many pollutants such as balloons and plastic bags are most dangerous before the marine system breaks them down.

Many animals in the ocean are found with plastic in their system. With the increasing use of plastics throughout the world, animals are coming into contact with these materials at an increasing rate. In the case of sea turtles, they have been consuming plastics at a higher rate.

The University of Queensland performed a study on two different sea turtle species and differentiated between smaller oceanic feeders and larger benthic feeders. The findings of this studied showed that the smaller oceanic feeders were more likely to ingest balloons. 54.5% of those turtles surveyed had ingested plastic. In contrast, 25% of the benthic feeders had plastic in their system (Schuyler et al., 2012). However, the predominant plastic ingested were those that mimicked their natural prey of jelly fish. The preferred type of plastic were rubber and clear plastics. These characteristics fit many of the balloons that end up in the ocean.

In another study on ocean stage loggerhead sea turtles, 83% were shown to have ingested plastic. 25% of the ingested plastic were categorized as microplastics (Pham et al., 2017). Loggerhead sea turtles were used in this study because they can be considered an indicator species for plastic pollution in the ocean. Ingesting plastic can kill or impair sea turtles. The plastics taken from the intestinal tracts of these sea turtles were predominately "user plastics" which means plastics from the general public. Half of the turtles sampled were found dead, possibly due to plastic ingestion.

2.2 Balloons

Many people have first-hand experience with balloons. They are fun to blow up at parties and play with. However, balloons can also have a darker side. During the year of 1986, the city of Chicago had what was known as a Balloonfest (Egnal). They wanted to break the record for the most balloons released at one time. The city ended up releasing 1.5 million balloons at one time. The original goal was to release 2 million, but inclement weather required the release to be early. The same inclement weather made many of those fully inflated balloons float down onto Lake Erie. These balloons ended up polluting the lake and impeding a search and rescue operation.

Balloons pose a risk for search and rescue because they are orb shaped and can look like a head bobbing in the water. They pose a risk to marine animals because of the materials they are made of. The most common materials are Latex and Mylar. The latex (polyisoprene) balloons can look like prey animals of sea turtles and other animals (Pham et al., 2017). Mylar is aluminum foil over polyethylene terephthalate (PET) which makes it look appealing to animals due to the light reflection.

Balloons are able to travel over 800 kilometers (Van Franeker, 2015). Balloons that are released in areas known as inland can result in plastics in the ocean or inland bodies of water. Latex balloons have a larger reach than Mylar because they are able to reach higher altitudes which allows them to travel farther. A latex balloon has the capacity to reach an altitude of ten thousand meters while a Mylar balloon will typically only reach around two thousand meters in the air.

The material of the balloon determines the maximum altitude, but it also determines how the balloon is able to be popped. Balloons pop because there is a hole created in the material that allows the internal pressure to equalize with the external pressure. This pressure difference is what originally gives balloons their shape. Latex balloons are more robust in terms of pressure. The limit in height is determined by the overall pressure on the balloons skin. If the pressure inside minus the pressure outside exceeds the pressure rating, the balloon will pop. This puncturing pressure is lower for Mylar balloons.

However, Mylar has an advantage over latex balloons. Mylar has a higher working temperature range. Working temperature is the maximum temperature for which a plastic will retain most of its tensile strength. Mylar has a working temperature of 150 degrees Celsius. Latex balloons only have a maximum working temperature of 80 degrees Celsius. Additionally, the max height associated with latex balloons is cold enough to cause the latex to become brittle.

2.3 Literature Review

Currently balloons are viewed as a threat to oceanic life. Thus, there have been a few approaches to reducing or curbing the impact of balloons. The most prevalent attempt at reducing the number of balloons that end up in the ocean is through an education campaign. It is considered common knowledge that releasing balloons is dangerous for wildlife and the environment. It is polluting in general. This is taught to children along with practices of recycling. Additionally, websites like "balloonsblow.org" dedicate themselves to educating people about the hazards of balloons.

Beyond education, arguments have been made according to the bio-degradability of latex. According to a study conducted in 1989, latex balloons experience degradation that is similar to that of an oak leaf and the fall incidence of balloons released will not have an impact on wildlife health (Burchette, 1989). This study may have been worded misleadingly. In a study that began in 1934, researcher Felix Gustafson exposed different tree leaves to environmental conditions to test their decomposition rate. The black and white oak decomposed the slowest. By 1942, 8 years after the study began, 53.9% and 40.4% of the black and white oak matter, respectively, were awaiting decomposition (Gustafson, 1934). Prior studies discussed have shown that sea turtles have been known to scavenge enough balloon or plastic pieces for this to be an issue with their health. Additionally, the degradation test was only conducted for 6 weeks. Anecdotal evidence suggests that a longer degradation test needs to be conducted in order for this particular study to be corroborated. Finally, the entity conducting the study was the National Association of Balloon Artists. Without further information, it is difficult to determine if latex is as bio-degradable and inert as suggested.

Finally, there have been attempts to clean up the ocean using automated machinery. Seen in a Forbes news article, Boyan Slat has founded The Ocean Cleanup and is taking aim at diminishing the Great Pacific Garbage Patch (Kart, 2018). The Great Pacific Garbage Patch is a patch of pollutants (primarily microplastics) that have gotten trapped in the currents of the Pacific Ocean. The patch is estimated to be between 700,000 square kilometers to 15 million square kilometers. The NOAA claim that there is no current accurate estimate for the patch. Slat is using a large automatic skimmer that will remove the plastics from the water. The goal of The Ocean Cleanup is to reduce the magnitude of the plastic patch by 90% before the year 2040.

Currently there is no widely used strategy to be implemented in negating pollution between the consumer and the end destination of the balloon.

2.4 Lasers/Light

Light is believed to behave as both an electromagnetic wave and a particle. Light is manifested in quanta. A quantum of light means there is a minimum, discrete amount of energy required to be associated with the light particle. The governing equation for the amount of energy per photon is described in equation 2.1.

$$E = hf \tag{2.1}$$

In terms of this paper, there are a couple properties of light that are important: diffraction due to Snell's Law and Gaussian beam optics. These properties will be discussed below.

Snell's law states that a light beam will be refracted when it enters into a new material which has a different index of refraction than the material the light is currently propagating in (Quimby, 2015). If the index of diffraction is greater than the current material, then the beam will be refracted towards the normal. If the index of diffraction is lower, then the light will be bent away from the normal. Glass lenses are typically used to refract light in the visible light spectrum. Glass has an index of refraction around 1.5 while air has an index of refraction around 1.

A Gaussian beam is a beam of mono-chromatic electromagnetic radiation whose transverse magnetic and electric fields are governed by the Gaussian function (Quimby, 2015). Gaussians beams have the smallest possible angular spread for a beam of a given initial diameter. The most pertinent parameter for a Gaussian beam is the waist of the beam. The waist of a Gaussian beam is the point in which the beam has the smallest cross-sectional area and has the highest intensity. The cross-sectional area of the beam will increase after the waist. This increase in area and decrease in intensity is affected by the wavelength of the light. The governing equation for a Gaussian beam is shown by equation 2.2 below.

$$E(r,z) = \frac{E_0 w_0}{w(z)} e^{-\frac{-r^2}{w^2(z)}} \tag{2.2}$$

The equation above shows the spatial distribution for the electric field based on the spot size ($w(z)$), the waist size (w_0), the initial electric field magnitude (E_0) and the radial distance from the z axis (r).

Beyond the electric field distribution, Gaussian beams can be shown to have a variable spot size along the z axis. The most important aspect of this variable spot is the Gaussian beam divergence:

$$\theta \approx \frac{\lambda}{\pi w_0} \tag{2.3}$$

In this case, the spot size is determined by the waist size of the beam (w_0) and the wavelength of the Gaussian beam (λ). This divergence can be used to calculate the Rayleigh range of a Gaussian beam. The Rayleigh range is the point where the cross-sectional area of the beam is double the waist. It is described by equation 2.4:

$$z_0 = \frac{\pi w_0^2}{\lambda} \tag{2.4}$$

The Rayleigh range is determined by the properties of the gaussian beam similarly to the divergence of the beam. These equations can be useful in characterizing laser light.

Laser light can be modelled using Gaussian beam optics (Quimby, 2015). Lasers are a light source that use excited atoms to produce light. These light photons released from excited electrons are then reflected multiple times before passing through one end of the laser. The purpose of the multiple passes is to cause stimulated emission from other atoms. Stimulated emission is a product of a specific wavelength of light interacting with an excited atom which will cause another, identical wavelength of light to be emitted. Stimulated emission is a probabilistic phenomenon related to the intensity of light. Therefore, more light will be emitted with more passes because the light that has multiple passes will add to the intensity of light within the waveguide. The energy released via light is from an electron moving to a lower energy level. The difference between energy levels is directly related to the wavelength of light that was emitted. The stimulated emission causes greater number of photons to be released and subsequently will create a laser beam.

There are many different types of laser with many different applications. The laser most commonly associated by the public is produced from a laser diode. A laser diode is a type of semiconductor device which has reflective surfaces in addition to a p-n junction found in light emitting diodes. (Quimby, 2015). The laser light is created by running electric current through the diode. Different wavelengths of light can be created using different sized waveguides and different semiconductor materials. A waveguide is a space that allows wavelengths to propagate. The voltage source supplied to the laser diode creates electrons and holes across the p-n junction. The electrons are supplied by the n side and are excited due to the current run through the system. The p side supplies the holes which the electrons will interact with. Holes are absences of electrons at unfilled, lower energy levels. Holes are apparent in excited atoms. The electrons will combine with the holes and release light as a result of this recombination (Quimby, 2015). The release of light will propagate in the waveguide and will allow for stimulated emission by contributing multiple passes before leaving the diode.

Once the laser light leaves the diode, the light can be affected by the atmosphere. The photons are affected by interacting with the particles in the atmosphere (Penndorf, 1957). If the particle is much smaller than the photon's wavelength, the photon will undergo Rayleigh scattering. If the particle is much larger than the photon's wavelength, then the particle will undergo Mie scattering. The reason the sky is blue is because of Rayleigh scattering. The effect of the scattering is proportional to the inverse fourth power of the wavelength of the photon. Therefore, blue light will scatter more readily than red light. The equations used in Rayleigh scattering (The volume coefficient) can be seen in below in equation 2.5 (Penndorf, 1957):

$$\beta = \frac{32\pi^2(n-1)^2}{3\lambda^4 N}\left(\frac{6+3\rho_n}{6-7\rho_n}\right) \tag{2.5}$$

In this equation β is the Rayleigh scattering coefficient based on the volume of atmosphere that the light travels through. N is the number density which can be looked up in a chart based on atmospheric conditions. ρ_n is the depolarization factor which can also be looked up in tables. Both of these values have dependence on temperature. λ is the wavelength of light and n being the refractive index of the atmosphere.

Gaussian beams are highly directional. As a result, Gaussian beams are able to be collimated. A collimated beam is a beam of light that has all of the beams parallel. However, due to the nature of light, light that is collimated will still diverge slightly. However, it will be at the theoretical smallest amount of divergence. In order to be able to pop balloons at indiscriminate distances, the laser light will need to be collimated. In order to collimate beams, a series of concave and convex lenses must be used. The concave lens is used to create a more prominently diverging wave front of light. The convex lens is then used to create a new waist. The new waist of the laser beam is larger than the prior waist and will result in a beam that does not diverge. The governing equation for this phenomenon is:

$$f = d_1\left(1+\left(\frac{z_{01}}{d_1}\right)^2\right) \tag{2.6}$$

In equation 2.6, f is the focal length of the lens. The variable d_1 is the distance from the first beam waist to the convex lens. Finally, z_{01} is the Rayleigh range before collimation (Quimby, 2005). If the wavelength of the laser light and the focal length of the lens are known, then the placement of the collimating (convex) lens can be calculated. In practice, lasers tend to have their own lenses so there may be a deviation between theory in practice.

2.5 Balloon – Light Interactions

The balloons of interest in this project are latex balloons. These balloons are a polyisoprene polymer (Schaefer, 2018). Polyisoprene consists of many isoprene isomers connected. Polyisoprene, like all materials, has a specific absorption spectrum and that is related to its chemical structure. Isoprene's chemical formula is C5H8 (NCBI, 2019). The structure is as seen: $CH_2{=}C(CH_3)CH{=}CH_2$.

According to quantum mechanics, light interacts with matter by interacting with the electrons of individual atoms. The interactions with these electrons influence whether the light is reflected, absorbed or transmitted through the material. Light is absorbed when the frequency of the light is similar to the vibrational frequency of the electron. Polyisoprene will absorb high energy ultraviolet (UV) lights and some longer infrared (IR) wavelengths. However, between these points of absorption, the absorption of light is around 1% (Wallace, 2018).

Recreational balloons tend to be impure polyisoprene. The balloons have dyes added for color. Although these dyes make up less than 5% of the solution according to industry trends (Worth, 2011). The dyes affect the absorption of the balloon material. If a balloon is green, then it will absorb frequencies associated with other visible light spectrums besides green. Green is the color that is reflected. The effect has not been quantified but was shown during a science fair experiment (Valtakis, 2013). In this test, it was shown that when the laser light was a different color than the balloon, the laser transferred enough energy to pop the balloon.

2.6 Thermodynamics of Balloon Popping

The balloon will be popped using radiative heat transfer from the laser light to the balloon. The absorbed light will transfer its energy to the balloon in the form of heat. The way this will pop the balloon is bringing the temperature of the spot of incidence over the working temperature of polyisoprene. The working range of polyisoprene is -50 degrees Celsius to around 100 degrees Celsius (Cheremisinoff, 2011). Heat will be transferred to the balloon through radiative heat transfer, but the energy will begin to be dispersed throughout the balloon and to the environment of the balloon through heat transfer mechanisms. Heat will be transferred conductively in the balloon, convectively to the surrounding air and the balloon will radiate heat. The conduction through the balloon will be slow because most plastics are thermal insulators. Additionally, the convection to the surrounding air will also be slow because air is known as an effective insulating material.

The balloon will conduct the heat throughout its skin, albeit poorly. The skin of the balloon is thin enough to treat it as a 2D system. The system will evolve with time so is considered transient. The governing equation is (Blomberg, 1996):

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + I(x,y,t) = C\frac{\partial T}{\partial t} \tag{2.7}$$

In this case, I is the rate of internal heat generation. I is included in the generic conduction equation because some systems generate their own heat through chemical reactions. The thermal conductivities are given by λ_x and λ_y. Typically, these two conductivity values are equal. C is the heat capacity of polyisoprene.

The thermal system described does not have internal heat generation. However, the thermal flux from the laser can be treated as a similar component to this setup. In this case, the thermal flux will be different from the laser flux. The thermal flux is only the light that is absorbed by the polyisoprene. Therefore, I can be considered:

$$I(x,y,t) = \frac{A}{A + R + T_l}(L) \tag{2.8}$$

In this case, A is the absorptivity of the polyisoprene and dye to the laser light, R is the reflectivity, T_l is the transmissivity, and L is the laser power. Combining the two prior equations results in:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{A}{A + R + T_l}(L) = C\frac{\partial T}{\partial t} \tag{2.9}$$

In addition to conduction, convection to the surrounding air needs to be taken into account. Although the environment of the balloon can change, the system can be assumed to be a transient natural convective system. However, the time scales that the system will exist for is small enough that the air can be considered another solid in which to conduct heat. This is an approximation but will be comparable to current transient convective models. This will result in an equation of:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) + \frac{A}{A + R + T_l}(L) = C\frac{\partial T}{\partial t} \tag{2.10}$$

In this equation, the z axis is the air that the heat will be conducted into. The λ_z is the equivalent conductive heat transfer coefficient of the air.

Finally, radiative heat from the balloon to the environment can be taken into account. The laser will heat the balloon at a small point. This point will have a larger temperature than the surrounding environment and will create radiation due to the temperature gradient. However, the attribution of radiative flux from the balloon to the environment should be negligible given the necessity to pop the balloon in a fraction of a second and the limited temperature the latex balloon needs to reach in order to pop. This means that the small time frame and low energy output contribute to negligible attributions from the radiative flux away from the balloon. If the contributions were non-negligible steady state radiative heat loss can be modelled with:

$$\frac{dQ}{dt} = e\sigma A\left(T_{balloon}^4 - T_{atmosphere}^4\right) \tag{2.11}$$

In this equation, e is emissivity, sigma is the Stefan-Boltzmann constant, A is the area of the heated surface and the T's are temperatures. Assuming the most heat transfer is possible from the balloon and laser system, the radiative heat transfer will only emit on the order of microwatts. For the majority of the system's model, the radiative flux from the balloon will be far below that value due to the transient nature of the system.

2.7 Forces During Free-Fall

The most prominent force during free-fall is the force of gravity. Gravity is the attractive force between two bodies. In the case of a free-falling balloon, the force of gravity is felt due to the Earth. The earth attracts the balloon towards its center. This force is given by Newton's law of Universal Gravitation:

$$F_g = G\frac{m_1 m_2}{r^2} \tag{2.12}$$

Where $G = 6.67 \times 10^{-11}\ N \cdot m^2/kg^2, m_1$ and m_2 are the two bodies attracting each other and r is the distance between the center of the two masses.

In addition to the force of gravity the balloon will experience forces related to buoyancy and drag. The buoyancy forces will act according to Archimedes principle which states that the up thrust or buoyant force due to a fluid on an object is equal to the weight of the fluid displaced by the object. For balloons in flight, this force is what suspends the balloon above the earth. The buoyancy of the balloon does not disappear after it is popped, but it will be decreased due to the decreased volume. Archimedes formula is:

$$F_b = \rho g V \tag{2.13}$$

In equation (7), the fundamental aspects affecting the balloon will be the volume (V) of the balloon, the acceleration due to the force of gravity (g), and the density (ρ) of the fluid. During free fall, the density of the surrounding fluid may change over distance. The equation can be modified to account for those differences.

Drag forces will affect the balloon in flight and during free-fall. Drag forces can be modelled using the formula:

$$F_d = \frac{1}{2} C \rho v^2 A \tag{2.14}$$

The factors affecting the drag force are a constant (C) which primarily depends on the shape and size of the object subjected to the drag, the density (ρ) of the fluid, the velocity (v) that the object is falling and the area (A) of the object in the direction of free-fall. The drag force will vary over the time of free-fall for a balloon because the velocity will increase until a terminal velocity is reached.

When any object is pulled towards earth, it will eventually reach a steady state velocity which is known as terminal velocity. Terminal velocity happens when the drag force and the buoyancy become equal to the force of gravity. Then the net force on the object is zero. The net zero force results in no further acceleration. The reason that these forces can add to zero is due to the drag forces dependence on the speed of the falling object.

In addition to the forces always present during free-fall of an object, there are environmental forces that can affect where the balloon will end up. For instances, the winds experienced by a balloon in flight can lead it to travel hundreds of miles. These same winds will exert a force on the balloon during free fall. This wind force can be modelled like the drag force, but the vector of action against the falling balloon will be different. The reasoning for treating the wind force like a drag force is the same reasoning behind using a wind tunnel. The object moving through a fluid can be modelled equally as well as the fluid moving around the object. The forces will come out the same. However, in this case the unit vector associated with the wind force will be different.

3. Methodology

3.1 Project Goals

The goal of this project is to design a mechanical model that sufficiently shows the capacity of a similarly designed prototype's ability to remove balloons from the atmosphere before they are able to travel to bodies of water. With the ability to remove balloons from the atmosphere, the model must prove itself to be mundane towards both humans and wildlife. In addition to a mechanical model, this project will include a mathematical model that can be used as a predictive algorithm for the landing site of the balloons. The goals are listed below:

1. Develop a mechanical prototype
2. Collimate the laser light
3. Prove safety towards humans and animals
4. Design a model for balloons in freefall

The methods employed to accomplish these aforementioned goals will be explored in this section. In addition to designing and building a prototype, this project's aim is to prove the proficiency of the author in both the fields of Physics and Mechanical Engineering for graduation requirements from Worcester Polytechnic Institute.

3.2 Develop a Mechanical Prototype

This section will be dedicated to the methods employed to developing a mechanical prototype. The mechanical prototype is proposed to be based on a linkage system driven by a single input. The linkage system will be used to target multiple lasers in order for the beams to be coherent on a singular point at essentially any distance that is necessary. The lasers will need to be powerful enough to pop the balloons but need to be individually weak enough that they do not pose significant danger to neither humans nor animals. The safety aspect will be addressed in the next section.

The first aspect of this design process will be determining the power that will need to be delivered via the laser system. For this project, the thermal-fluid simulation Comsol will be deployed to model the balloon. Comsol is a physics simulation software that utilizes finite element solvers to model thermal and fluid properties. Comsol will be used to determine the thermal flux that needs to be applied to the outer skin of the balloon in order to bring the balloon's material above its working temperature. For latex rubber, this temperature is 80 degrees Celsius above room temperature.

Once the thermal flux is solved for, the power of the lasers employed can be solved for. In the atmosphere, there is going to be power loss due to scattering. Due to the Gaussian beam mechanics of laser light, the beam of light will not be as concentrated as it is at its waist. That is the beam will expand from the point of production to the point of contact with the balloon. Additionally, the absorptivity of the balloons material to the laser's wavelength will need to be taken into account in order to transmit the needed thermal flux to pop the balloon. These challenges will be addressed using currently accepted mathematical models. The amount of power can be calculated theoretically.

After the simulation and mathematical modeling is complete, commercially available lasers and lenses will be able to be ordered to begin building the prototype. The multi-laser prototype will use a linkage system which can simultaneously aim all of the individual lasers at a singular point at the needed distance. Solidworks will be used to model both this linkage system and the housing of the laser and focusing lenses.

After the linkage system is designed, it will be printed 3D printed for a scale model. This will allow for the model to be tested and reiterated. Reiteration will continue until the model is working as intended. Currently, the entire project is intended to be 3D printed. However, if modelling deems it necessary, the material selection will be changed, and the machining of the parts changed accordingly. The model will only be a model. Further material selection will be theoretically determined based upon the real-world application of this project. The actual material selection is out of the scope of this project.

3.3 Collimating the Laser Light

The linkage system will have an attachment that will collimate and hold the lasers. Collimating the lasers will be done through a series of lenses. The lenses will transmit the laser light and demonstrate the principles of Gaussian beam optics in order to collimate the laser light. This collimation will result in a beam that will less dispersive than typical laser systems.

The lens and laser holder will be modelled in Solidworks as mentioned previously. The model will be tested at different distances and compared to the theoretical expansion determined by a Gaussian beam. A range based upon the degree of collimation and laser light intensity will be determined.

3.4 Prove Safety to Humans and Animals

The second primary objective of this project is to design a system that does not pose any danger to humans or animals. In order for this to be proven, calculations will be performed in order to show that the laser system is not a threat to people or animals. Dangers from lasers can include blindness, possible fire risk, and risk of pollution.

Light moves much faster than the blink reaction in both humans and animals. That means that if a sufficiently powerful laser was shone at someone's eyes then they would be blinded. This basis is the reason there are legalities governing the owning and operations of laser systems. Most of the lasers in the hands of consumers are nothing more than a nuisance even when shone into the eyes of sports athletes. However, this project will be dealing with lasers or an accumulation of lasers that are powerful enough to be blinding. In order to mitigate this danger, the linkage system will allow for the lasers to be separate beams before and after the target point. That means the system will be operating within a very slim distance of danger.

In addition to a mechanical system that predominately has the lasers operating as separate entities, the project will complete with a mathematical model showing the dangers of the system both in reflection off of balloons and through the balloons. Not all of the radiative energy will be absorbed by the balloons. Therefore, the project will include a mathematical look into the laser light and what happens after it reaches its primary objective and what would happen if it did not meet the balloon in the air.

Beyond the danger of blinding radiation, this project may be working with sufficient radiative power to start fires. In order to mitigate any danger, Comsol will be utilized to model worst case situations in regard to the full power of the laser system. By utilizing Comsol, safety features can be built or recommended in order to prevent fires or other hazards due to the radiative flux of the multi-laser system.

Finally, the purpose of this project is to reduce the pollution that is happening in the environment. However, this project could encourage pollution either through decomposition or through the balloons it removes from the atmosphere. Mitigation of balloon pollution can be accomplished by creating a mathematical model that will predict where the balloons will land after popping. The methods used beyond this mathematical model will be discussed in the next subsection.

3.5 Modelling Balloons in Freefall

A mathematical model will be developed that will describe the flight path of the balloon after it has been popped. This mathematical model will be based on physics principles and offer a rough approximation of where the balloon will land. Factors that will be considered are gravity, buoyancy, drag, and other factors expected in this mechanical model.

The mathematical model will not be tested due to time constraints. However, there will be suggestions in order to refine the model in the future. Possible refinements will include up to date weather forecasts and machine learning technologies.

4. Results

4.1 Final Design Linkage

The final design of the linkage system is classified as a 7-bar linkage. The setup includes a four-bar slider with three additional links (ground, rocker and coupler) to host the laser and lens setup. The linkage system will be discussed as a four-bar linkage, slider, and a targeting linkage, the three additional links. The setup can be seen in the images below.

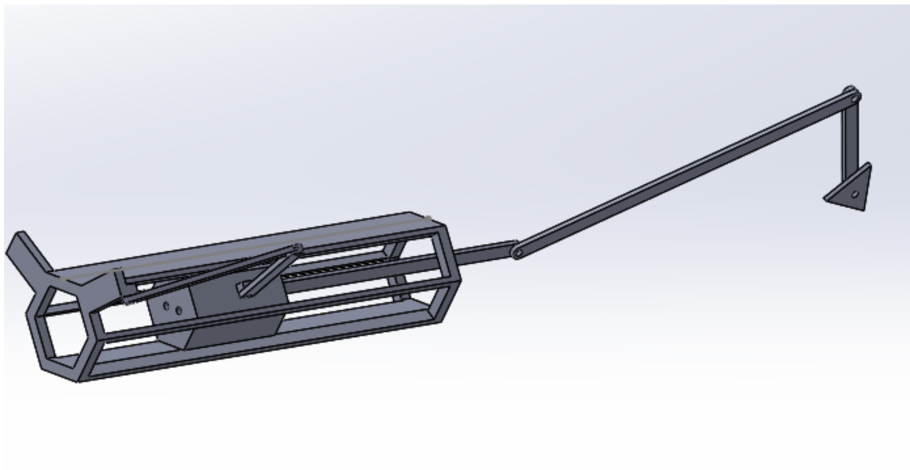


Figure 1. Solidworks Model of 7 Bar Linkage

The Solidworks model shows that the linkage can operate through an entire rotation of the crank. The cranks motion is coupled into a slider through a long coupler link. The linkage system was modelled and 3-D printed. The final small-scale model can be seen in Figure 2.

Figure 2. 3-D Printed Linkage System

The 3D print only shows one of four possible sets of the targeting 3 bar linkage. Theoretically, three more targeting linkage systems would be added. These targeting links would then allow for multiple lasers to be added onto this design. The lasers would be attached to the rocker of the 3-link system. The lasers are all coupled because the targeting linkages are driven from the same slider and the targeting linkages all have the same lengths.

The most challenging part of the design were the targeting links. There are two important end positions. These positions are the extremes of the system, the farthest point of targeting and the closest point of targeting. The closest point of targeting was considered arbitrarily to be within a few meters of the system. The farthest point was considered to be a target at infinity (all arms would have parallel beams). The two links that make up the moving aspects of the targeting links were then determined based on the geometry of the two extreme positions. Each of the positions could be solved for a minimum or maximum, respectively. Therefore, a length for the rocker in between the two limits was chosen. From this selection, the coupler link could be solved for. The solution was determined to be between the two limits. The lengths were then checked in Solidworks. The two extreme positions can be seen in Figure 3 and Figure 4.

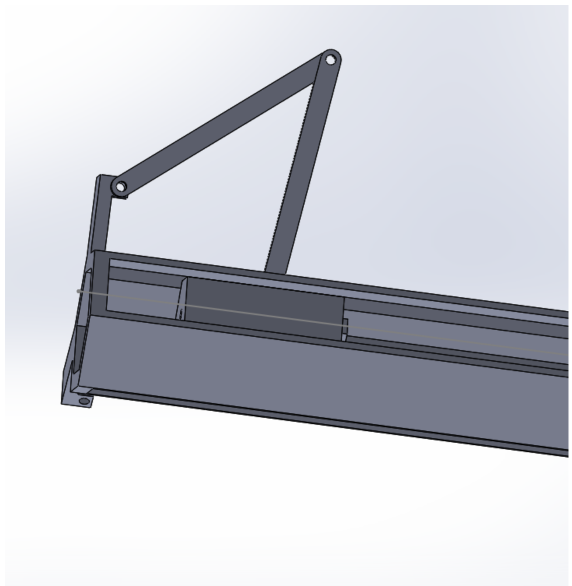


Figure 3. The Linkage System Targeting the Near Position

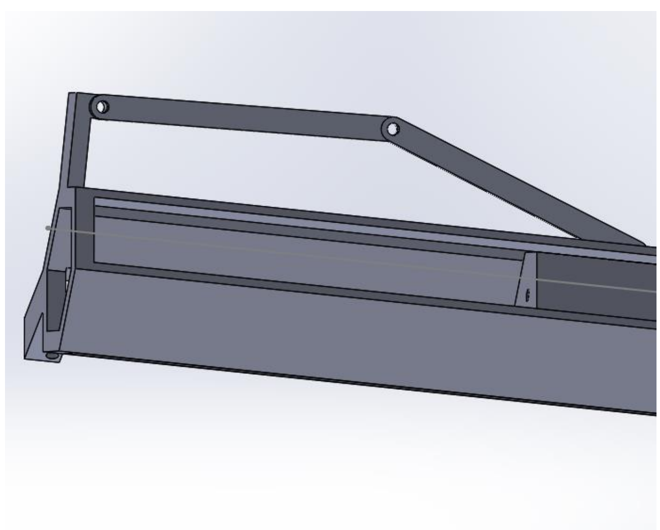


Figure 4. The Linkage System Targeting Infinity

The other lengths were determined in proportion to each other. The crank of the slider linkage system needed to be half the length of the slide’s range. The length of the coupler link compared to the slide was limited by the transmission angle into the slider. If the link was too short, then the rotating link would become stuck. Therefore, the closer the coupler link and slider's angle of attachment was to 180, the better for the system. The link was chosen to be as long as the slide, but the link was not optimized to limit the material used. Finally, the slider had an additional link attached in order to prohibit the connecting link from knocking into the slider's support.

4.2 Final Design Laser barrel

The laser-lens system was designed using solidworks. The original system was based on a scope system similar to a lens system used in binoculars. This system was rigid and just required the lenses to be dropped in. The original design can be seen below.

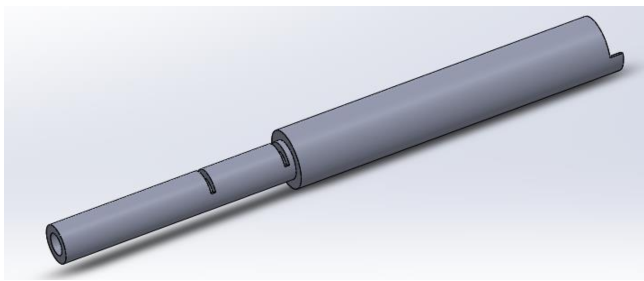


Figure 5. The First Iteration of the Lens-Laser System

The advantage of this design is there are no moving parts. The lenses could be dropped in depending on their focal length and the distance needed to collimate the laser beam. The laser apparatus would then be inserted into the back. The lasers used are laser pointers with a button. Upon insertion, they would remain permanently on unless disabled.

This design was not used. One of the prominent issues resulted from the laser lights different wavelengths. The different wavelengths required different distances for each lens. The design seen in Figure 5 would need separate designs to accommodate the laser light wavelength. Additionally, the laser light was not collimated to begin with. This uncollimated beam would not exactly follow the equation for determining distances in collimating a beam. The lenses need to be adjusted slightly to correctly collimate the light. The theoretical calculation would only give a starting point. Finally, manufacturing lenses is not a perfect process. The previous design would necessitate lenses that were free from imperfections and had exact focal lengths. This design necessitates exactness. It would be a better design to allow for adjustments to be made manually.

A new design was modelled and printed based on the idea of manually adjustable lenses. This design can be seen in Figure 6. The main disadvantage of this lens system was the attachment to the laser. The only attachment method was to glue the lenses onto the laser housing. Additionally, the actual lenses distances involved sliding over a pin. The pin-slide was difficult to adjust finely and was even more difficult to secure into place. This system was redesigned to have a removable laser and to more easily adjust the lenses.

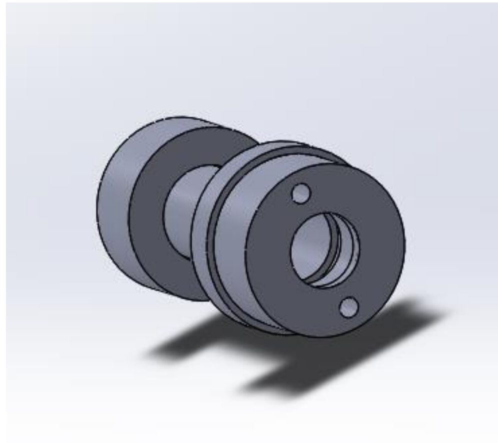


Figure 6. The Second Iteration of the Lens-Laser System

The laser-lens system was redesigned with these concerns in mind. The new system required that the lenses could be moved for each individual laser in order to collimate the beam. Additionally, it needed to support the lenses and the laser. The final design can be seen below.

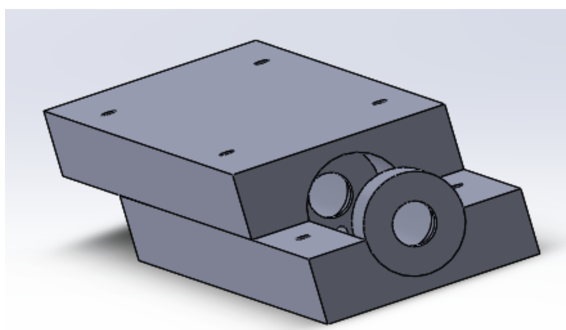


Figure 7. The Final Iteration of the Lens-Laser System

In this design, the lenses are placed in their own support system. The 3D printed laser housing was designed with a cylindrical groove with openings on both ends. The groove has the same diameter as the laser and lens supports (22.5mm). The lens supports are the cylinders with holes seen in Figure 7. The holes are where the lens is inserted. One side of the hole is too small for the lens to fall through. The other side has a 3-D printed insert that is placed behind the lens to secure it into the lens support. The curved groove would securely hold the laser and lens support. The lens supports would be movable (by sliding in the groove) so that the laser would be able to have its beam collimated. However, once the beam was collimated, the lenses could be secured in place by either gluing the lens support to the groove or tightening the outmost housing which stops movement via friction.

4.3 Power Requirements of Laser (Thermal Analysis)

Using Comsol, the laser power requirements were determined. For the simulation, the laser was considered a thermal flux over an area on a silicon rubber orb. The orb's thickness matched that of a balloon at 10 mil or .00025 m. The thermal flux was then considered on the outside of a balloon in open air and filled with helium. The orb had the same diameter of the average balloon with a 12 cm or 0.12m diameter.

According to the simulation, the balloon would require 20,000 watt/m^2 in order to reach the temperature required to destroy the balloon within a couple hundred milliseconds. The couple hundred milliseconds measurement was used because it is a time frame that would be foreseeable once a targeting system is developed for this system. The balloon would not be able to move fast enough to avoid popping except for exceptional conditions. The same experimental setup in Comsol was used on a balloon that had a Mylar skin. This balloon required 40,000 watt/m^2 to induce popping in the required time.

According to the results from Comsol, a graph was created to show the power required according to the focusing area. The graph can be seen below in Figure 8.

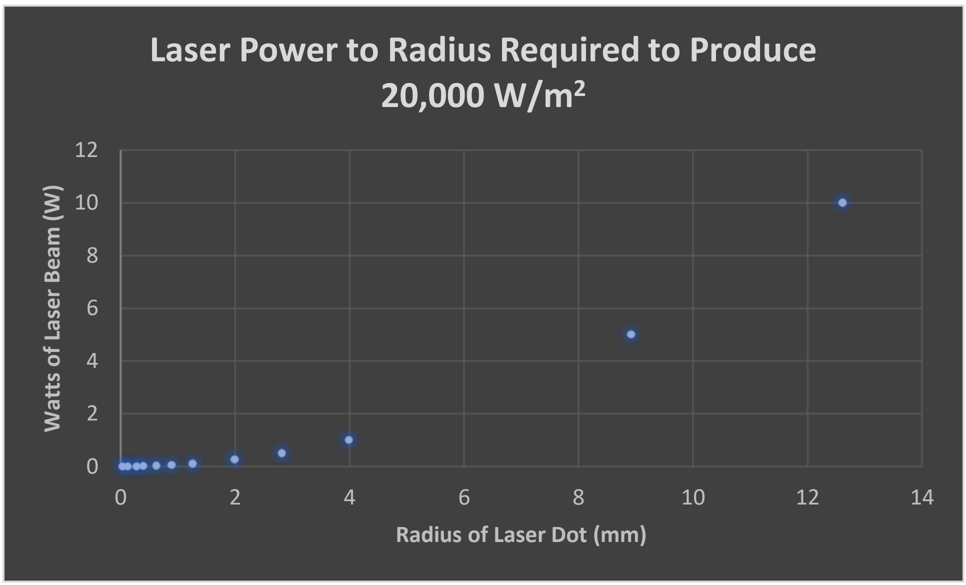


Figure 8. Radius of Laser Dot Required to Rupture Balloon's Membrane

The Y axis of Figure 8 is a span of foreseeable laser's output power. The X axis shows the radius required for the dot created by the laser beam in order to supply the 20,000 W/m^2. However, this is assuming all of the power is converted to the heat flux. The laser used will deliver a heat flux, but the heat flux will be limited by the amount of energy that the laser can deliver to the balloon. Prior research shows that a polyisoprene material will only absorb around 5% of laser light in the visible spectrum. Around 90% of the light will pass through pure polyisoprene. Additionally, the Mylar balloon is similar. It will reflect 90% and will only absorb half of the remaining energy transmitted. Under these conditions, it was determined that the project would focus on only popping the polyisoprene balloons due to power limitations necessitated by budget. Using this information, the updated graph showing the power required by area of absorbed light can be seen below. This graph is updated to account for the amount of energy actually absorbed.

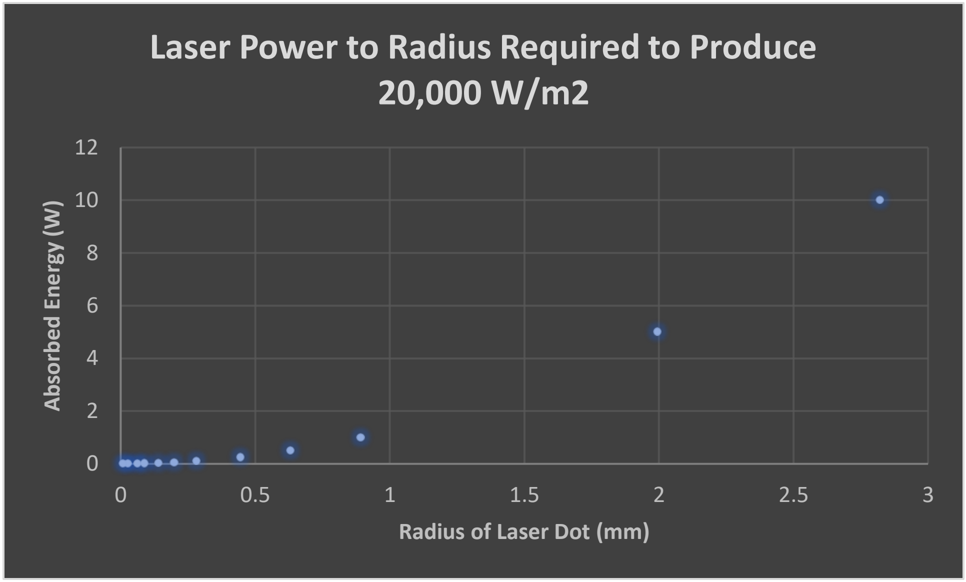
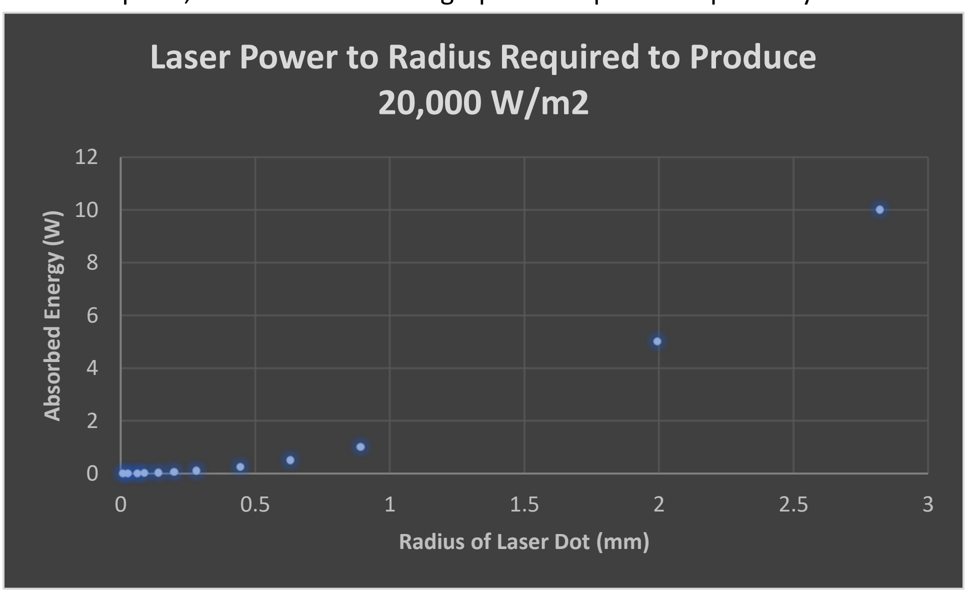


Figure 9. The Updated Power to Radius Needed to Pop a Balloon

Figure 9 shows the updated graph with the laser output power to required dot radius. As shown in the background, the color of balloons greatly affects the absorption of light. In this case, we can assume a larger amount of laser light will be absorbed by the balloon. Assuming that we have an increase to 10% absorption, we can make a final graph of the power required by the area the power is



focused on.

Figure 10. This is the Final Chart Showing Power to Radius of the Laser Beam

From this graph, we can find the required radius for the dot created by the laser beam from the energy absorbed by the balloon. As discussed in the next section, the total power for this MQP is 360 mW. That would result in necessary radius of between 0.6 mm and 0.8 mm. This was found because two of the values plotted are 0.25 W and 0.5 W which have radius around the prior stated values, respectively.

4.4 Laser Light Selection

The laser light selected was based on a number of factors including budget limitations, color of the laser light, and power limitations of commercially available lasers. The budget limitations mandated that the lasers needed to be diode lasers and within the visible light spectrum. The visible light spectrum was tied to the budget limitation because laser pointers facilitated the advancements necessary for the diode lasers used in this project. As such, the diode lasers that fit the bill and were within the power specifications for this project also fell into the visible light spectrum.

Since the lasers were in the visible light spectrum, it was important to select a wavelength that would be absorbed by the color of the balloon. However, balloons come in every color within the visible light spectrum. Due to the design of the linkage system, the multi-laser system would be able to house 4 different laser sources. Since the balloons would vary in color, it was determined that the lasers should also vary in color. Videos online can be found to show laser light with 200 mW of output power were able to pop balloons. It was determined that as long as the lasers collectively had the power to deliver 200 mW regardless of balloon color, then the system would be able to work. As will be discussed, the laser manufacturer used produced different color lasers around 100 mW each. Using this manufacturer, two different wavelengths of light were chosen: 405 nm and 532 nm.

The final consideration for laser light selection were commercially available lasers. After initial market research, Sanswu lasers was determined to offer a laser package that offered both reliable lasers that lased at the quoted wattage and offered lasers of different wavelengths. The two lasers chosen from this manufacturer were a 532 nm laser that offered 80 mW per laser and a 405 nm laser that offered 100 mW per laser. The total capacity of the system would be 360 mW and both individual colors would offer close to the desired 200 mW.

4.5 Laser tests/Beam Dispersion

Gaussian properties of laser beams require that they disperse as they propagate through free space. Due to this property, the lasers used in this project will cover a larger area the farther the target is from the source. Therefore, this property was explored with the collimation of the laser diodes used in this project. Theoretically, the expansion of the laser will follow the formula:

$$\theta = \frac{\lambda}{\pi \omega_0} \tag{4.1}$$

The theoretical expansion of the two laser beams can be calculated. The two lasers have wavelengths of 405 and 532 nm. The waist size of the beams were measured to be 1.13 mm and 2.40 mm respectively. A sample calculation for the 532 nm laser is below.

$$\theta = \frac{532 * 10^{-9}}{\pi * 2.25 * 10^{-3}} \tag{4.2}$$

$$\theta = 7.53 * 10^{-5} \tag{4.3}$$

The theoretical divergence for the 532 nm beam has an angle of $7.53*10^{-5}$ radians. The theoretical divergence of the 405nm beam is $2.69*10^{-5}$ radians. The difference between the divergences of the two wavelengths is due to their wavelength. I would expect the 532 nm beam to diverge more than the 405 nm beam.

Using the small angle approximation, the predicted divergence can be calculated from the distance the beam dot is away from the source. The initial test for beam divergence was to measure the beam size every 20 cm over the length of a meter. However, the predicted increase in the beam size would only be .02 mm for the 532 nm beam over 20 cm. This would be too fine to measure accurately. The test showed that the measurement could not accurately gauge a difference between the different distances. Instead a new test which measured the divergence over several meters was setup.

The difficulty in the new experiment was due to the dangers of the light beams. This limitation was alleviated by taking measurements in a closed off room from public eye. However, the closed off room only had enough room to allow for one distance to be measured with accuracy. The measurement at a distance of 4.5 m showed the 532 nm beam diverged by 0.57 mm and the 405 beam showed a divergence of 0.29 mm. These compare with the theoretical expansion of 0.34 mm for the 532 nm laser and 0.12 mm for the 405 nm laser light. Additionally, it can be seen that all of the laser light is not fully coupled into the dot produced by the beam. This phenomenon can be seen in Figure 11 below.

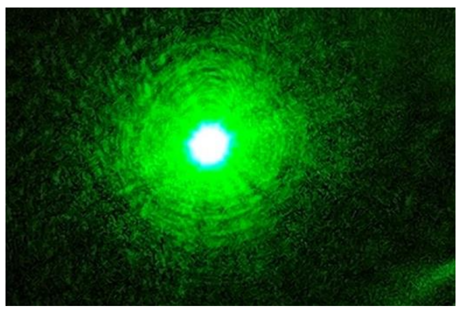


Figure 11. The laser dot after collimation

Both the green and purple show scattering of laser light. It can be seen clearly in Figure 11 that the majority of the beam is focused but the lenses allow for some scattered areas. The collimated portion is the very bright dot in the center of the scattered area. This scattered light will make the total flux of light lower than what is theoretically possible.

Since the actual expansion of the 405 nm laser beam was 0.29 mm at 4.5 m instead of the theoretical 0.12 mm, the actual angle of the expansion will be $6.44*10^{-5}$ radians. This is 2.4 times larger than what is theoretically predicted. The 532 nm laser beam has an actual angular expansion of $12.6*10^{-5}$ radians which is 1.7 times the theoretical expansion. In this scenario, the 532 nm laser diode will have the limiting flux due to its larger expansion and larger initial beam waist. The maximum range of the current system could be estimated using this limiting factor. However, according to the prior chart, the laser light should theoretically not be able to pop a balloon at any distance. Practical tests have shown this to be false. Balloons were popped with a single laser at distances of 4.5 meters. With 4 lasers this distance can be extended.

Since the theoretical tests do not show this system with enough power to pop a balloon, a viable calculation would be to find the Rayleigh range of the current system using the 532 nm light as the limiting factor. In addition to finding the Rayleigh range, the effect of Rayleigh scattering can be found for the range associated with this current project. The Rayleigh range is the range at which the area of the cross-section of the laser beam doubles. Using the equation for Rayleigh range with the multiplying factor to account for the imperfect collimation:

$$z_0 = \frac{\pi w_0^2}{1.68 * \lambda} \tag{4.4}$$

Then the Rayleigh range can be found to be:

$$z_0 = 20.2\ m \tag{4.5}$$

Under these conditions, Rayleigh scattering would not have an affect on the laser beams. The energy of the laser beams is dissipated by a much larger degree from the divergence of area than by the scattering due to the air molecules in the atmosphere. According to the Rayleigh scattering equation, over 99.9% of the light will be transmitted at this distance.

4.6 Safety

Safety is a major consideration for both the beams before and after they make contact with the balloon. There are three main considerations for the safety of the light which are dangers before balloon contact, reflection from off of the balloon, and light transmitted through the balloon's membrane. These three situations were investigated to ensure that the system was not dangerous to humans or the environment.

Before the laser light meets the balloon, they are concentrated beams of energy. The advisory from the FDA is to wear specially designed safety glasses for lasers over 5 mW of power. The reason is that lasers over this threshold approach or surpass the flash blindness limit of 100 µW/cm^2. The lasers currently employed for this project are rated 80-100 mW. This is well above the 5mW power recommendation. This means that the current lasers used would pose harm if shined into the eyes of any observer. However, retinal damage is the only damage that is possible for these lasers. If the laser light were to shine on any part of a person or animal outside of their eyes, there would be no ill effect.

The reflection from the surface of the balloon is of limited concern for humans or animals. Polyisoprene does not reflect visible light well. Depending on the balloon color, the reflection from the surface is only a few percentage points of the incoming laser energy. However, to accommodate a large safety factor and to make the math easier, it can be assumed that up to 10% of the energy is reflected. Additionally, the surface of the balloon is curved which will allow the beam to diverge like a reflection from a convex mirror.

Measurements were taken of reflections off the surface of the balloon over multiple locations. The flux of the beam deflection was then determined over multiple deflection points. The multiple deflection points were considered because of the irregular shape of the balloon. It was found that the strongest flux was 1800 µW/cm^2 at a distance of 0.5 m away from the deflection point. This is dangerous to the eyes of anyone who observes it at this distance. However, the beam expanded from 0.81 cm^2 to 200 cm^2 over a distance of 0.5 m. This means that the limit for flash blindness is at a distance of 4.5 m away from the balloon. The reflections do not pose a danger to humans or animals that are over 4.5 m away.

Finally, the transmission of light through the balloon's membrane could be a cause for concern due to the translucent nature of polyisoprene to visible light. The maximum transmittance of uncolored polyisoprene is 90%. However, the laser light would need to travel through two layers of polyisoprene.

Therefore, the maximum possible transmittance is 81% of the input power. This value appears to be dangerous, but due to the curved nature of the balloon, it is unlikely that the laser beam would remain collimated. Additionally, this is considering an uncolored balloon which would be the worst-case scenario. The transmission only needs to account for a single laser source. In this case, the 100 mW laser was considered because it is the strongest light source in the current setup.

Another test was setup to determine the flux of light that will be transmitted through the balloon. The center of the balloon, midway between the knot and top, was selected because this portion of the balloon would offer the least amount of curve on the surface of the balloon. The least curve will result in the least divergence of the laser light. The worst-case scenario test had a light beam waist of 7.52 mm after passing through the balloon and an area of 10.2 cm^2 at 3.5 meters away. This would result in a light flux of 795 $\mu W/cm^2$ at 3.5 m past the balloon. This is a dangerous amount of light for the eyes of a human or animal. The laser light falls below the blindness limit at 16.2 m past the balloon.

To recap, the laser light that is not absorbed by the balloon poses a danger to animals and humans even after reflecting off of or passing through the balloon. The laser light that is reflected off the surface of the balloon is dangerous out to 4.5 m and the transmitted laser light is dangerous to a point 16.2 m past the balloon. The current setup uses lasers that are dangerous to human or animal eyes before the light makes contact with the balloon. However, a system could be redesigned so the lasers used are all eye safe.

4.7 Balloon in Free-fall

A simple model was created to determine the position of the balloon after it was popped and had hit the ground in respect to the position in which the balloon was popped. Considerations included the effects of gravity, drag and wind. The system includes the use of differential equations which would mandate the use of initial conditions. However, for the example given, it was assumed that the balloon was non-moving. The results would vary for different conditions. Finally, this model is using the balloon's initial position as the origin and bases the free-fall on this reference point.

The beginning of the model needs to determine the distance the balloon is from the ground. This value will then be used to determine the time that it will take for the balloon to hit the ground. Since the balloons popped at high altitudes tend to fragment, each piece will need to be tracked. The general equation for a single piece of the balloon is determined below. It would be beneficial for a computer program or AI system to be used to track balloons before and after they fall. Additionally, this program will need inputs based on the specific conditions present. The simplified model will be presented below.

The model begins with acceleration due to gravity and opposed by the upwards drag force.

$$a(t) = \frac{C_d}{m}v^2 - g \tag{4.6}$$

In this model, C_d is the drag force, m is the mass of the piece of the balloon, v is the velocity and g is the acceleration due to gravity. The equation will be solved in the manner used by Melissa Ng from the Science One Program at the University of British Columbia. In her experiment, she tested the fall time of water droplets compared to the mathematical model. This approach will differentiate the equation in order to solve for the fall time from a set distance above the ground. The distance above the ground will be considered to be along the z axis. This time will then be used in a similar calculation that determines the distance travelled in a horizontal direction (arbitrarily assumed along the x axis).

Integrating this equation with the assumption that the balloon had an initial velocity of v=0:

$$v(t) = \frac{\sqrt{\frac{mg}{C_d}}\left(e^{2t\sqrt{\frac{C_d g}{m}}} - 1\right)}{e^{2t\sqrt{\frac{C_d g}{m}}} + 1} \tag{4.7}$$

The equation above can be solved for the maximum velocity that each piece of the balloon will reach. However, the terminal velocity is now what is important to model for this project. The velocity will need to be integrated further to find the vertical distance the balloon pieces have fallen over a given period of time. Integrating again to find distance with the assumption that the balloon started at x=0:

$$z(t) = \frac{m}{2C_d}\left(\ln\left(e^{2t\sqrt{\frac{C_d g}{m}}} + 1\right) - \ln\left(\frac{e^{2t\sqrt{\frac{C_d g}{m}}}}{e^{2t\sqrt{\frac{C_d g}{m}}} + 1}\right) - \ln(4)\right) \tag{4.8}$$

The above equation can then be solved for the time as long as the drag coefficients for the balloon pieces can be estimated and the location of the balloon above the earth's surface is known. This model assumes that the pieces of balloon will not get stuck in a tree or other scenarios that prohibit the pieces from reaching the ground level. Using the time that was found for each piece of the popped balloon, the distance in the horizontal direction can be found.

Forces are vectors and can be added or subtracted. Using this information, the model for horizontal direction can look essentially identical to the model above used to determine the time the balloon is in flight with a few assumptions and math tricks. A similar drag force is going to be acting on the pieces of the balloon:

$$Drag = \frac{C_d}{m}v_x^2 \tag{4.9}$$

In this case the drag is going to be in the x direction. It was discussed in the background, but the wind exerting a force on the balloon or its pieces can be considered similar to the drag force. However, the velocity would be of the wind. The equation would be the same besides the velocity to the equation above. However, the force can be denoted by a singular symbol for wind force (W_F). Additionally, there could be other forces that are acting on the balloon. These forces for this simplified model will be ignored. They could be easily incorporated under an "All Force (A_F)" type notation because they would be additive to the wind force:

$$A_F = W_F + All\ other\ forces \tag{4.10}$$

This is true for all forces that do not depend on the location or velocity of the balloon. If these forces are apparent, they would need to be included into the full acceleration formula and not within a constant acceleration value. Again, to simplify this model, it will be assumed that the x axis is in the direction of the cumulative forces. The initial acceleration in the x direction is:

$$a_x(t) = \frac{C_d}{m}v^2 - A_F \tag{4.11}$$

Under the same assumptions of the balloon not initially moving and the balloon existing at the origin, the final solution of this equation becomes something very similar to before:

$$x(t) = \frac{m}{2C_d}\left(\ln\left(e^{2t\sqrt{\frac{C_d A_F}{m}}} + 1\right) - \ln\left(\frac{e^{2t\sqrt{\frac{C_d A_F}{m}}}}{e^{2t\sqrt{\frac{C_d A_F}{m}}} + 1}\right) - \ln(4)\right) \tag{4.12}$$

The final horizontal position of the balloon pieces can then be determined from the time it took the balloon to reach the ground.

5. Discussion

5.1 The Final Linkage Design

The final linkage design can be seen in the results section in Figure 1. This design accomplishes the required criteria because it was designed with the two extreme points necessary. It can target a balloon that is a few meters in front of the system or one that is at infinity. Since the system is continuous, all points between those two endpoints can be targeted.

Despite the ability to target any point in between the two extreme positions, the linkage system does not have a linear movement between the two positions. Assuming that the position of the balloon is directly in front of the linkage system and this position is defined as along the x axis, the targeted position will not move with the same velocity along this x axis at all times. The targeted point will actually reverse before reaching its closest point to the system. The movement of the targeted point is not a practical issue but an ascetic one. The linkage system will be able to target any point as long as the system controlling the link moves with enough precision.

Additionally, the current system is only meant to have 4 targeting linkages attached. However, the system can be modified to include as many targeting linkages as are necessary. The number of targeting linkages will be limited by the power of the lasers and the safety required for the system. At the moment, the linkage system is not optimized for safety.

The current linkage model is small scale and 3-D printed. If this design were to be used in a more practical setting, there would need to be further research into the material selection of the linkage system. The current system uses PLA plastic, but a system that would be practical needs to withstand outdoor conditions found near fresh and saltwater. The current PLA would deteriorate when exposed to the UV light from the sun. The conditions around bodies of water require a material that is corrosion resistant, are strong enough to support themselves and are not hazardous to the surrounding environment.

Finally, there is no targeting system except for along a single axis. In the future, work will need to be done in order for the system to be able to move in two more directions to be most functional. This system could be setup on a tripod that is similar to the ones used for cameras that allow for multi-directional movement. This would allow for the system to be able to be moved in any direction but still allow for it to target along the third plane of existence.

5.2 Final Design Laser Barrel

The laser light used for this project needed to be in a collimated beam in order for the beams to reach the farthest possible distance with the highest flux of light. The design went through a few different designs before the final design (Figure 7) was chosen. This design was ultimately chosen because it allowed for the lenses to be adjusted manually. The manual adjustment of the lenses was necessary because of the two different wavelengths of the lasers and because the laser light was not a coherent beam incident on the lens system.

The lenses themselves are made of the same glass that is found in a standard magnifying glass. The lenses under the current design do not need to be any special material. The important aspect of the lenses is their shape. However, if the laser used in this system was not of the visible spectrum, then the lenses may need to be a different material. The material used for a lens needs to be as transparent as possible to the wavelength of light that it is refracting.

The formula (2.3) that could be used to determine the distance between the two lenses was only used for a ballpark estimate. After the laser light was close to collimation, the lenses were moved slowly in order for the light to be fully collimated by eye. The collimated light was not perfect as will be discussed. However, after the laser light was as close to collimated as possible, the lenses were then glued into position. The lens system could then have the laser inserted into the back of the housing in order for the light to be focused into the lenses.

This system has a flat bottom which will allow it to be readily secured on to the linkage system. Since PLA was used for the prototype, a larger prototype could just have the entire lens system glued to the link. If this system were to be brought to full scale, the lens system could be incorporated into the link itself. Currently they were designed independently, but it would be trivial to turn this lens system into a link to be used directly in a full-scale linkage system.

The full-scale model would have the same requirements of the linkage system in terms of material selection. The outer housing would need to be able to withstand the environment that the laser system is facing. However, the actual lenses and laser within the full-scale model would not need to change size just because the system is sizing up. The lenses size is only determined by the size of the laser beam from the laser. The size of the laser beam from a diode laser is determined by the focusing lens that comes from the manufacturer. In this manner, the full-scale model would not need the electrical components to increase in size but would only need the linkage or lens housing to increase proportionally to the total linkage system increase.

5.3 Power Requirement of Laser (Thermal Analysis)

The power requirements for the laser light to pop the balloon were calculated based upon a simulation. The power is limited by the total thermal flux the laser is able to imbue on the surface of the balloon. The results of the thermal analysis can be seen on the graph of Figure 10. This plot shows the curve of the laser's output energy to the radius of the laser dot which would result in the mandated 20,000 W/m^2 of thermal flux absorbed by the balloon.

Future work concerning the power of lasers that should be used for this application should include real-world tests of different balloons of different color with differently powered lasers. The test performed for this project was very narrow in scope. It assumed the laser light as a given flux and found the necessary flux to heat the balloon to a given temperature within a reasonable time span. Instead, future work should use a thermal sensor in order to record the heating effects of the laser on a balloon and under different scenarios. These scenarios could include different laser light areas, different inflation levels of the balloon and with different colors of balloons. These future tests would be able to create a more accurate model of the absorption characteristics of the light and balloon membrane.

In addition to altering the conditions that may influence the heating of the balloon, the environmental factors of the balloon should be deviated and the actual temperature that the balloon reaches before popping should be empirically found. The balloons that are at the height of their flight experience temperatures that are quite a bit colder than on the surface of the earth. The cold temperature is what influences how the balloons pop at those atmospheres. This cold temperature may impact how the balloon absorbs or dissipates heat. The simulation for Comsol assumed that the balloon was experiencing environmental conditions similar to those on the surface of the earth. Additionally, the temperature that the thermal simulation assumed would pop the balloon was the working temperature of the material. For polyisoprene, that temperature is around 80 centigrade. However, the balloon may pop below this value. If the balloon's membrane is popped below the working temperature of the balloon's material, then the power necessary has been overestimated in this project.

5.4 Laser Light Selection

The laser light was primarily chosen based upon cost. The cost of this project was limited which made this the primary concern. This budget restriction limited the laser power, the wavelength and the type of laser that could be used. If budget were not a concern, the primary factor for choosing the laser would have been wavelength and power.

The wavelength of light is important for the light's interaction with matter. Light in the visible spectrum does not interact with the most common materials that balloons are made out of. Instead, UV light and Infrared light could have been better candidates because they are more likely to interact with the balloon's material. If there were no budgetary concerns, the laser light could be tailored to the wavelength of light that polyisoprene has the highest absorption coefficient for.

The power of the laser would be the second priority if there were no budget. The power of the laser or lasers would be based on the divergence of the beam and the safety that is needed for the particular application. Applications without the need for safety could then optimize the power needs with the cost of the lasers. This would then allow for the system to have multiple lasers that offer the highest wattage per dollar spent. If safety were an issue, then the system could utilize many low powered lasers to the same effect. The many small lasers would be additive at the target and nearly benign at any other distance.

5.5 Laser Beam Dispersion

It was shown that the laser beams were not fully collimated. The 532 nm laser beam had a divergence that was 1.7 times greater than the theoretical and the 405 nm laser beam had a divergence that was 2.4 greater than the expected value. In addition to imperfect collimation of the laser beams, it was determined qualitatively that all of the light was not adequately transmitted through the center of the lenses. There was light that was no longer part of the beam.

The final design for the lens system was chosen so that the lenses could be adjusted, and the individual lasers could be collimated by hand. However, this adjustment was not exact. The collimation was based on the sharpness of an image that was 4.5 m from the laser source. The image that was viewed was a reflection off of the point of the laser. The image was expanding from the source on the wall. This increase in the size of the image made it difficult to fully collimate the laser beam. If a remote camera was used to give instant feedback to the entity collimating the laser beam, the collimation may have been more precise.

Another aspect affecting the collimating of the laser beam would be the precision of the setup. The lens system was 3-D printed. However, 3-D prints are known to be imperfect. In addition, the adjustments were done by sliding the lenses along a track without fine adjustment. This lack of fine adjustments and imperfect machining could allow for imperfect collimation. Every slight deviation would allow for the beam to diverge to a greater degree. Using a gear system that adjusts the lenses by microns would allow for a finer collimation of the laser beam. However, a setup with micron adjustments could not be 3-D printed and would be more expensive.

The beam may not have been centered on the lenses. The deviation of the lens could be caused by the limits of 3-D printed precision and the manufacturing of the laser diodes. The lens holders were designed to be the same diameter as the stated diameter of the laser diode casing. However, the 3-D printer may have printed these holders a little smaller or larger than designed. In addition, it is possible that the laser diode's casing was larger or smaller than stated. The casing was assumed to be accurate. These could have resulted in the scattering of the light seen in Figure 11. This scattering is presumed to be from imperfect coupling between the two lenses.

Another possible explanation for the light that was no longer focused into the laser beam would be the use of lenses and not a mirror system. Lenses refract light and there are differences in the refraction based upon the wavelength of light. This principle is how a crystal can create a rainbow. The wavelength of light for a laser should be all the same wavelength based on the theory of operation. However, practical applications do not always follow theory. The different wavelengths of light would make up the minority of the beam, but these could be visible when they are no longer focused within the beam. This scenario is unlikely but not impossible. If the similar but different wavelengths are the culprit behind the scattering of light, then using a lens-mirror system to collimate the laser beam would mitigate this problem.

The current system has a Rayleigh range of around 20.2 m. The range for popping a balloon is theoretically non-existent. The conditions for popping the balloon have been discussed above. However, this system is currently limited by the power that was within the purchasing capacity of this project. Additionally, if the laser light were coupled to a small enough diameter to pop balloons, then the range would be limited due to the beam expansion. If the laser light had a smaller diameter, the Gaussian properties of the light propagation would result in a larger rate of divergence. If this project were to be implemented, then the laser power would need to be increased. Currently, there are lasers on the market that would be powerful enough to extend the range to kilometers but are prohibitively expensive for this particular project.

5.6 Safety

Safety was important for this project. The laser system would not have real world applicability if it was dangerous to humans or animals. The current system is dangerous within certain limitations. The system is comprised of laser beams that are well past the FDA recommendation for laser safety. They should not be used in a situation that would result in possible eye exposure. However, the only danger is that of the eyes of any person. The system could be redesigned akin to the current system and be made to be harmless to a person or animal if directly eye contact was made by one of the beams.

The current system is dangerous after contact is made with a latex balloon that does not have any coloring. Coloring will affect the safety analysis discussed in the results section, but to create a safety factor, the worst-case scenario was considered. In this scenario, the reflections off of the balloon were found to be dangerous up to 4.5 m away. The light that made it through the balloon was shown to be dangerous up to 16.2 m away from the balloon. However, when color is introduced into the balloon, the effects of reflection and transmittance are reduced. In a black balloon for instance, there was no transmittance that could be detected with the human eye. Additionally, transmittance and reflection were greatly reduced when the balloon had a color that was not associated with the wavelength of the laser light used.

Mylar balloons were not considered for this project because the power that was needed to pop these balloons was beyond the budget limit. However, these balloons are of specific interest because they can have a flatter surface and the Mylar has an aluminum layer. The flat surface would result in less dispersion of light. The aluminum would result in a reflectance value that is similar for the transmittance of the latex balloons. Reflection in this case would be a greater concern because of the angle from which the majority of the light flux is directed. In the latex balloons, the majority of light not absorbed by the balloon would be transmitted outwards away from the earth and the majority of people and animals. However, the Mylar balloons would reflect the majority of power back towards the people and animals that it could harm. This would make the Mylar balloons more dangerous for blinding. Additionally, since the Mylar requires more power, there would be more powerful laser light reflected back towards the earth.

The current laser system from a safety perspective is only capable of being implemented if the system is able to determine where the balloon is and what is surrounding the balloon. This could be accomplished with a human. However, this would be economically unviable. The other option would include using an AI based system that could sense balloons and surrounding objects and categorize them. The sensing system would need to range find every object in view and determine how close they were to the balloon. From there the system could calculate if the reflections or transmittance would pose harm to anything in the laser's path. A particularly adept system should be able to target specific areas of the balloon and calculate the reflection and transmittance angles in order for the unabsorbed energy to be dispersed in safe directions.

5.7 Balloon in Free-Fall

The simplified model that was created to predict where the balloon would land is mathematically sound but untested. The actual model would need to be tested, but in real world applications it is expected to be only a ballpark estimate. The model assumes that the balloon is not moving to begin with and that the forces acting on the balloon are all constant. If the laser system were to be used, then the model would not be able to accurately determine where the balloon would land except for a rough estimate. However, this current project only required an estimate.

In order to improve the model, there would need to be an in-depth analysis of the current weather conditions of the specific area that the system is deployed. The largest considerations would be the wind that the balloon would be subjected to before and after the membrane is ruptured. However, the density of the wind or any precipitation in the atmosphere would also affect how the balloon would fall. Tracking the weather conditions at a particular place for a short period of time would present a difficult problem to solve. There is not enough available data in order to look up these conditions.

Instead of looking up particular conditions, it would be more effective if a computer program was implemented that would be able to track weather conditions. This data from the site of deployment could be extrapolated to the placement of the balloon. Additionally, a sensing system that detects where the balloon is, and the movement of the balloon could be incorporated in order to gain a more accurate image of what the conditions the balloon is undergoing. Combining the sensing and weather collection into a mathematical model of the balloon's freefall would result in a more accurate free-fall model.

5.8 Future Work

Future work predominately entails incorporating an appropriate computer system into the laser system. An AI based machine learning system that is able to auto-target balloons would allow this system to be implemented. The computer system needs to be developed to differentiate between balloons and non-balloons. The targeting would then need to predict where the reflections and transmittance of laser light would be an issue. Finally, the system should be able to track where the balloon is headed and extrapolate weather related data that can be used in predicting where the destroyed balloon will fall. Preferentially, this computer system would track each of the individual pieces of the popped balloon and update its predicted landing site as needed. If the prediction model is accurate enough, the system could begin optimizing where specific balloons should fall for easiest retrieval.

In addition to an AI based system for targeting, a sensing array would need to be incorporated into the laser system so that the AI system can gather data. Different sensors would need to be looked at in order to determine which would be adequate. AI systems are beyond the scope of this project, but if image recognition is able to continue improving, a simple video camera may be all that is needed in order to train the AI system for balloon recognition. Otherwise, other sensors would need to be incorporated. The biggest issue with sensing the balloons is the spherical shape. This shape makes it difficult to sense balloons based on rebounding signals. This and other unforeseen challenges will need to be surmounted before this system is able to be implemented.

In addition to an AI system, the materials that the laser system is made out of needs to be investigated further. Corrosion tests would need to be incorporated based on the location of the laser system. Since this system's primary objective is to stop balloons from falling into aquatic environments, the system should be able to withstand conditions found near bodies of water. Saltwater locations in particular will need to be looked into as the salt in the air may have an effect on metal components of the laser system.

Currently, there are limited plans when the balloon has been popped. The location of the balloon will be recorded, but someone or something needs to retrieve the fallen balloon. A plan that could be beneficial would be partnering with local Boy Scout and Girl Scout groups. The scouts could earn a badge for finding balloons that have fallen to the earth. This is dually beneficial because it could foster an interest in the sciences whilst also helping the environment.

Yet, the collection may not be an issue. A study conducted by the National Association of Balloon Artists showed that latex balloons decompose at the same rate of oak leaves (Burchette,1989). If this is true, then latex balloons may not need to be collected. However, this is a biased source of information and there was not another reputable study on balloon degradation that was found. Future research should look into the impacts of balloon decomposition and incidence of accidental wildlife ingestion. Mylar balloons do not have the decomposition of an oak leaf and would still need to be collected.

Finally, due to the limited budget of this project, only lights in the visible spectrum were investigated. Future research should look into the feasibility of non-visible wavelength lasers for the use of rupturing balloon membranes. Additionally, the threshold for deployment should be researched. These two ideas need to be researched dually because they will impact each other. Ultra Violet lasers would be the best candidates for limited Dispersion from Gaussian beam optics but may be the most expensive. Infrared Lasers may be the least scattered wavelength available but the optimization of scattering to price would need to be looked at.

Beyond a laser system, other methods of balloon destruction should be considered. Drones may be able to be used to destroy balloons. A similar targeting and recognition system could be developed but the drone may be able to fly up to the balloon. If the balloons are too high for the range of a drone, then a laser system may even be attached to the drone. The benefit of the drone is the ability to change proximity to the target. The benefit of the laser is the system does not need to make physical contact with the target. The drone could move itself to an optimal position and a laser could be focused upon the balloon in order to pop it. The benefit lies in the proximity. The laser system could be setup to disperse the laser rapidly so is only dangerous to whatever target the drone gets close too. This would be one example of another method that may be deployed in order to remove balloons from the atmosphere.

6. Conclusion

Pollution is a very real problem that is facing the entire world. Everyday there are more and more news articles of aquatic wildlife washing up with plastics and pollutants in their digestive tracts. Whether the plastics are littering the ocean or the lakes, aquatic life is affected by humans. It is therefore our responsibility to find a solution that will mitigate the harm that is coming to the animals inhabiting our shared earth.

The current, widely used methods of pollution prevention is to educate the public. Despite this education, balloon releases are still mainstays at celebratory events and there are tens of thousands of balloons picked up off United States beaches every year. Pollution from balloons is a problem. They look like prey animals to many aquatic animals like sea turtles. This Project proposed a solution to mitigate the problem after the pollution has been released but before it can be collected from it is floating in the water. There is a potential to save a life for every balloon that is caught before it lands in a body of water.

The intent of this Major Qualifying Project was to design a multi-laser system that would be able to remove balloons from the air without posing a significant safety threat to humans or animals. The current system satisfies that goal to an extent. The system as designed would have the capacity to rupture the membranes of balloons at a theoretical distance of 20.2 m but would be dangerous if the laser light were to shine directly into the eyes of any person or animal. The simplified model for the free-fall of the balloon would give a proximity of where the balloons were to land but needs to be refined in order to increase the accuracy of its predictions.

Future work has this system operating with an auto-targeting system that will be able to track balloons with a higher degree of accuracy than the current simplified mathematical model. Additionally, the environments that this system would experience are damaging too many materials. Materials used in the linkage system will need to be explored further. In addition to a more robust material selection, the use of an AI system could revolutionize the implementation of this system. The current laser light selection was selected based on budget constraints, but future models have the potential to have ranges of kilometers and could safely remove balloons from the environment. With a partnership with boy and girl scouts, who can collect the fallen and tracked balloons, the deployment of a multi-laser system could be used in order to stop balloons from reaching aquatic life. The design right now is the beginning to cutting down on pollution by knocking down rogue balloons.

Pollution is a phenomenon that is affecting humans and animals. The current, widely used methods of education fall short of eradicating pollutants entering the environment. Balloons are still readily found on beaches and in waters across the United States. With the future development of the Multi-Laser System, pollution that harms aquatic environments could be mitigated.

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