# Maximum Trapping Focal Length in Photophoretic Trap for 3D Imaging Systems

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## Abstract

This product is a photophoretic trapping system which allows varying focal lengths to test which focal lengths are possible for trapping toner particles. This system establishes that there exists a maximum trapping distance limitation and is the first time the effect of focal length is studied in a photophoretic trapping system. Increasing photophoretic trapping focal length is necessary for improving this technology as a 3D display. The 3D imaging technology is realized by dragging a microscopic (micrometer-scale) particles with a laser beam to trace an image. This technology can display fully colored and high-resolution 3D images visible from almost any direction. Currently, 3D images are limited to $1cm^3$ volume using this technology, but with further research the maximum trapping distance limitation can be increased leading to improved 3D displays.


## Introduction

Photophoretic Optical Traps (POT) can develop 3D images that can be seen from almost all angles. While holographs are limited by 'clipping' because they are bound by a 2D space [1]. This clipping causes the holograph to be viewed as a television, rather than a 3D object printed in free space. A POT is best described as a volumetric display for its 360° viewing angle. This kind of display will be attractive as an entertainment device as it depicts technology seen in science fiction. A POT traps particles by heating up the surface of a particle, increasing the air pressure at that region and lifting the particle[2]. An optical trap is formed by using controlled spherical aberration to create a laser cage around a toner particle. Toner particles have a high enough absorptivity and a small enough size to be trapped photophoretically [2]. This cage can then be moved in a 3D with reflective optics to trace a path of an image. An illuminated 3D image is then realized by tracing the particle at a frequency of at least 60Hz [1]. A solution to increasing the maximum trapping distance of POT's will provide an advancement for challenges in photophoretic volumetric displays [7].

The focus of this study is measuring focal length's effect on particle trapping. A two-lens system is used to vary the effective focal length of the system, allowing different trapping distances from the most recent lens in the system. The system used in this study mitigates air currents by encapsulating a two-lens system and trapping region in a transparent enclosure where air currents outside the enclosure cannot affect air inside the enclosure. Longitudinal astigmatism is minimized by aligning the sagittal tilt of the second bi-convex lens to reflect directly back at the laser source. The effects of spherical aberration are accounted for by using 5 different bi-convex lenses at varying diameters and focal lengths.

## Customer Requirements and Engineering Specifications

TABLE I: Customer Requirements

| **Customer Requirements** | **Engineering Specification** | **Justification** |
|---|---|---|
| A | Product must meet FDA laser safety requirements of being less than 5 milliwatts at the trapping site. [7] | High powered lasers can cause severe damage to eyesight and skin. This study must be conducted with eye and skin protection. [7] |
| B | Particle must be trapped consistently and efficiently. Particle is to take at maximum 15 seconds to trap, and remain in the trap for at least 300 seconds as outlined in [7] | To prove the concept that the optical power has been brought to a minimum, the particle must be able to be trapped in the air for a reasonable amount of time. [7] |
| C | The setup must be resistant to air currents in the surrounding environment. Wind velocity must be less than 1 km/h [1]. | Air currents can move the particle out of the optical trap. The setup must block outside air currents for the diffraction patterns to be accurately characterized. [1] |
| D | Optical trap should be realized with one beam on one axis from the source to make the technology competitive with current photophoretic 3D displays. [1] | An interference pattern must be created from one laser stemming from a single axis. Current photophoretic 3D displays use this method to localize particle control at the source side. This contributes to the system's compactness. |
| B, C | Particle trapping must be streamlined to limit data variability, and air current interference. | A clear enclosure must surround the optical system to prevent air currents. Particle trapping can be done manually but must be shielded from outside air current interference. |
| Requirements:<br>A. Safety<br>B. Reliability<br>C. Robustness<br>D. Compactness | | |

TABLE II: Engineering Specifications

| Spec. # | Parameter | Target (units) | Tolerance | Risk (H, M, L) | Compliance (A, T, S, I) | Test Equipment Needed |
|---|---|---|---|---|---|---|
| 1 | Optical Trapping Power | $P_{Trapping}$ > 24mW | +/- 5% | L | T | Optical power meter is needed to verify optical power is greater than the minimum trapping power for toner particles [1][8] |
| 2 | Wind Velocity (Beaufort Force) | v < 1 km/h | max | H | T | A fog machine is used to verify that the air within the enclosure is still such that focal length is an isolated parameter. |
| 3 | Visible Spectrum Laser Diode | LD Wavelength = 380nm-740nm | min/max | L | I | Laser Diode must be within the visible light spectrum. |
| 4 | Time to trap particle | t > 10 min | min | M | A | Enough attempts to trap a particle at a given range to verify trapping cannot exceed maximum trapping distance limitation. |
| 5 | Optical Trapping Duration | t > 300 sec | min | H | A | The particle must be trapped longer than 300 seconds to verify the particle is trapped, and illumination of the trapping region is not caused by smoke from burned toner particles. |

# Functional Decomposition

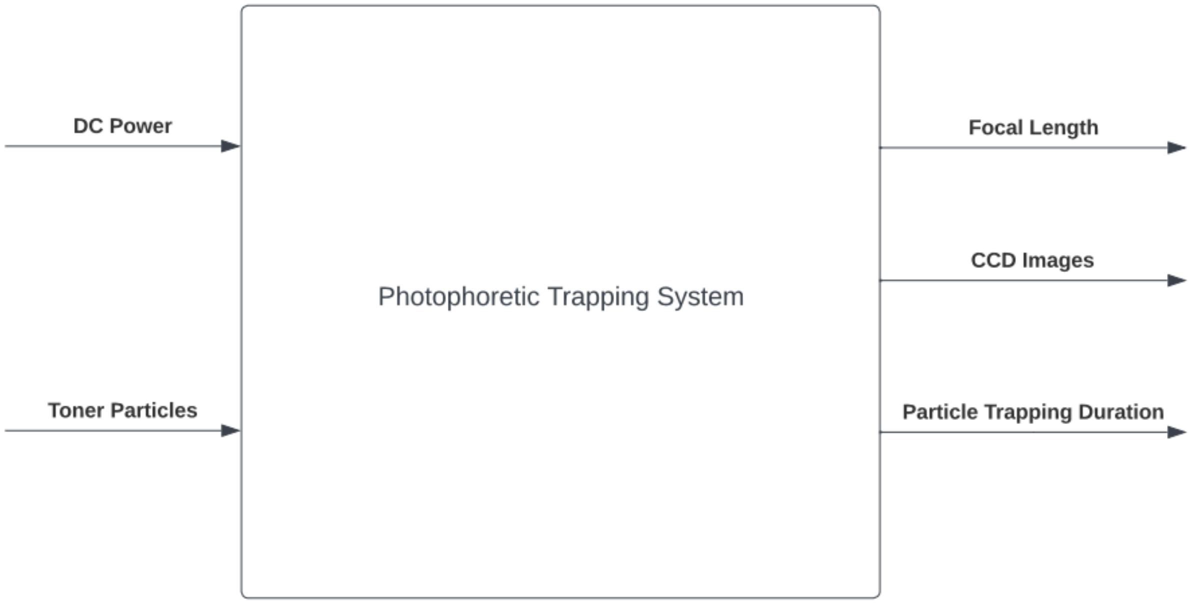


*Figure 1: Level 0 Partial Function Decomposition Diagram*

TABLE IV: Level 0 Partial Function Decomposition Description Table

| Module | Lens System |
|---|---|
| Inputs | Laser Diode which provides the beam for trapping a particle. Power is required at the site of trapping for the photophoretic effect to hold the particle in air. Toner particles are the particles to be trapped. |
| Outputs | Focal Length Is measured from the most recent lens to the beam's focus. CCD images are captured when the particle is trapped. Particle trapping duration is recorded to verify trapping stability at the focal point. |
| Functionality | The photophoretic trapping system provides results of the effect of focal length on trapping toner particles in a photophoretic system. |

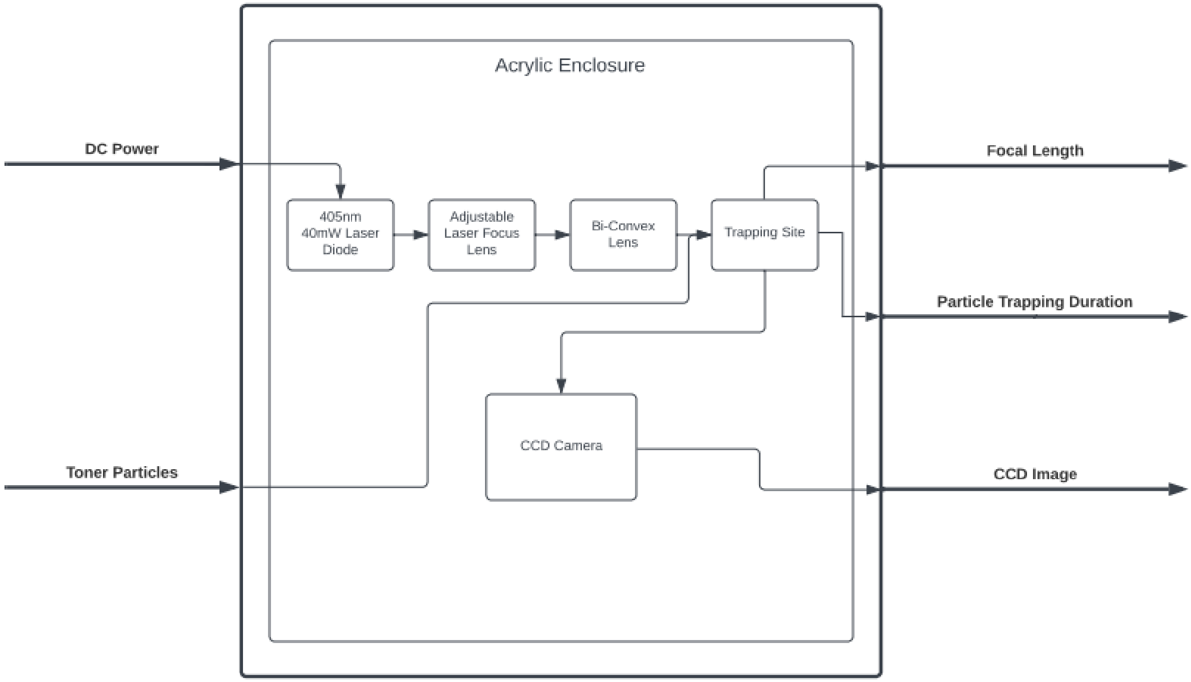


*Figure 2: Level 1 Partial Function Decomposition Diagram*

TABLE V: Level 1 Partial Function Decomposition Description Table

| **Module** | **Laser Diode** |
|---|---|
| Inputs | 40mW Power |
| Outputs | 405nm Laser Beam |
| Function | Produces beam to be altered for particle trapping. |
| **Module** | **Adjustable Laser Focus** |
| Inputs | 405nm Laser Beam |
| Outputs | Diverging Laser Beam |
| Function | The adjustable laser focus allows the effective focal length to be changed to accommodate the fixed Bi-convex focal length. |
| **Module** | **Bi-Convex Lens** |
| Inputs | Diverging Laser Beam |
| Outputs | Converging Laser beam. Laser focal length from Bi-Convex lens to focal point. |

| | |
|---|---|
| Function | The Bi-Convex lens will converge the laser beam and introduce the effects of spherical aberration, elongating the focal point length of the beam. |
| **Module** | **Trapping Site** |
| Inputs | Converging laser beam, Toner particles |
| Outputs | A trapped particle, hovering in free-space, and the trapped particle duration. |
| Function | The trapping site allows for a proof of concept and analysis to be performed on the trapping sites power, beam profile, and effects on the toner particle. |
| **Module** | **CCD Camera** |
| Inputs | Light appearing from the trapped particle. |
| Outputs | A CCD image of the trapping site. |
| Function | The CCD image will allow the proof of concept of the system to be documented. |

## Results

The experimental results show that particles trapped within the range of 80-160mm were stable, achieving trapping durations of 5 minutes or more for all lenses. The maximum trapping duration with respect to focal length is shown in Fig 3. An experimental minimum could not be determined due to our system's effective focal length restrictions. Trapping at 60mm could not be accomplished for a minimum 5 minutes. Maximum trapping durations at 180mm and greater were less than 1 second after extensive attempts. These attempts resulted in particles being accelerated off the collection of toner particles towards the beam's propagation origin, and no fixed trapping would occur. Particle Trapping at 160mm is the experimental maximum with minimum longitudinal astigmatism for all tested lenses. Fig. 4 shows a CCD image of a toner particle trapped at 120mm hovering in free space.

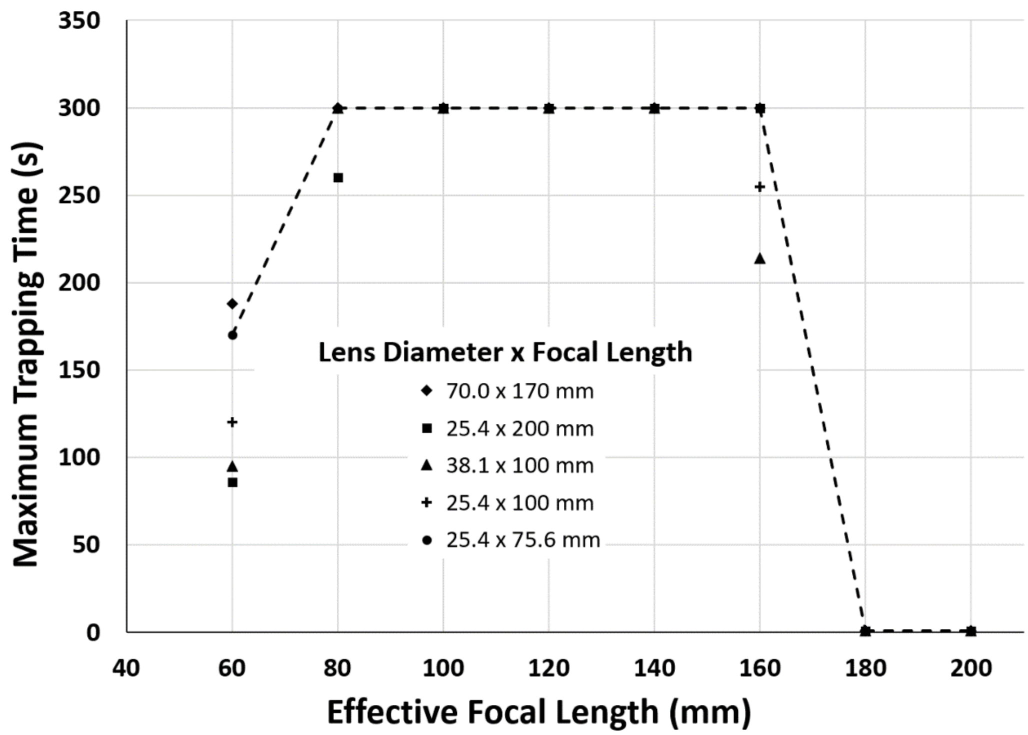


*Figure 3: Maximum trapping time (s) by effective focal length (mm)*

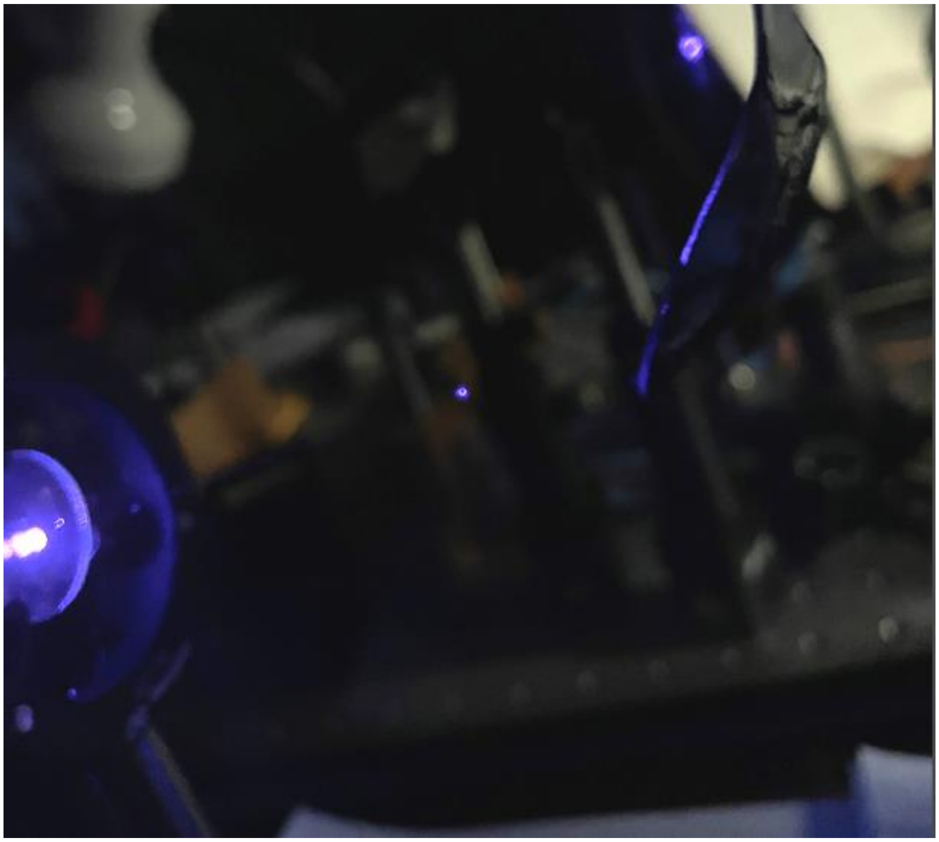

*Figure 4: Trapped particle at 120mm*

## Conclusion

A photophoretic trapping system is designed and built to investigate the effects of focal length by testing toner particles' trapping duration for a given focal length. It was found that focal length and photophoretic trapping duration are correlated. The experimental maximum focal length for the system was found to be 160mm. Particles are unable to be trapped at 1800mm or further. Particles that exceed the maximum focal length limitation are unstable and would accelerate from the toner collection towards the beam's propagation origin. There is a maximum focal length limitation for photophoretic trapping systems.

**Material Cost Breakdown**

TABLE V: Cost Estimates

| Part | Description | Unit Cost | Total Cost | Justification |
|---|---|---|---|---|
| Laser Diode | 405nm 40mW | $30 | $30 | Laser diode is to create the beam for trapping. |
| Toner Particles | Black Printer Toner | $10 | $10 | Toner particles are the particles to be trapped and visualized. |
| Bi-Convex Lens 1 | 70.0 X 170 mm Bi-Convex Lens | $400 | $600 | A Bi-Convex Lens of 70mm diameter is used as the lens with the least spherical aberration, as the diameter is large with the low curvature attributed to a long focal length of 170mm. |
| Bi-Convex Lens 2 | 25.4 x 200 mm Bi-Convex Lens | $230 | $230 | A 25.4mm diameter has much more curvature than the 70mm lens given similar focal lengths. This lens is needed to verify that the change in spherical aberration does not affect trapping distance. |
| Bi-Convex Lens 3 | 38.1 x 100 mm Bi-Convex Lens | $260 | $200 | The 25.4x100mm lens is compared to the 38.1x100mm lens to verify that the inherent focal length of the Bi-Convex lens does not affect trapping distance. |
| Bi-Convex Lens 4 | 25.4 x 100 mm Bi-Convex Lens | $220 | $220 | The 25.4x100mm lens is compared to the 38.1x100mm lens to verify that the inherent focal length of the Bi-Convex lens does not affect trapping distance. |

| | | | | |
|---|---|---|---|---|
| Bi-Convex Lens 5 | 25.4 x 75.6 mm Bi-Convex Lens | $220 | $220 | A 25.4x75.6 Bi-Convex lens has the most spherical aberration out of the set, this further verifies that spherical aberration does not increase or decrease trapping distance. |

## Labor Cost Estimate

| EE 460 | | | Optimistic | Most Likely | Pessimistic | | |
|---|---|---|---|---|---|---|---|
| | HW 1.1 | | | | | | |
| | | Resume | 2 | 3 | 4 | | |
| | | Cover Letter | 1 | 2 | 3 | | |
| | Project 2.1 | | | | | | |
| | | Abstract | 1 | 1 | 2 | | |
| | | Intro | 2 | 2 | 3 | | |
| | | Customer Reqs. | 1 | 1 | 2 | | |
| | | Engineering Specs | 1 | 1 | 2 | | |
| | | References | 3 | 4 | 5 | | |
| | HW 1.2 | | | | | | |
| | | Monte Carlo | 2 | 3 | 4 | | |
| | Project 2.2 | | | | | | |
| | | Abstract | 0 | 0 | 0 | | |
| | | Specs and Reqs. V2 | 0 | 0 | 0 | | |
| | | Functional Decomposition | 1 | 2 | 3 | | |
| | | Cost Estimates | 1 | 1 | 2 | | |
| | | Gantt Chart | 2 | 3 | 4 | | |
| | Project 2.3 | | | | | | |
| | | ABET Analysis | 3 | 4 | 5 | | |
| | Project 2.4 | | | | | | |
| | | Powerpoint | 2 | 3 | 4 | | |
| | HW 1.3 | | | | | | |
| | | Reverse Engineering | 3 | 4 | 5 | | |
| | | | 25 | 34 | 48 | Total | 34.83 |

*Figure 5: Labor for EE460 in Days*

| EE 461 | | | Optimistic | Most Likely | Pessimistic | | |
|---|---|---|---|---|---|---|---|
| | Design V1 | | | | | | |
| | | Laser Diode Supply Design | 4 | 5 | 6 | | |
| | | Lens System Design | 2 | 2 | 3 | | |
| | | Trapping Site Design | 3 | 4 | 4 | | |
| | | Enclosure Design | 1 | 1 | 2 | | |
| | | Order Parts | 1 | 1 | 2 | | |
| | Build V1 | | | | | | |
| | | Assemble Parts | 3 | 4 | 5 | | |
| | | Verify System Integrity | 3 | 4 | 5 | | |
| | Design V2 | | | | | | |
| | | Laser Diode Supply Modification | 2 | 3 | 4 | | |
| | | Lens System Modification | 2 | 2 | 3 | | |
| | | Trapping Site Modification | 1 | 1 | 2 | | |
| | | Enclosure Modification | 1 | 1 | 2 | | |
| | | Order Modified Parts | 1 | 1 | 2 | | |
| | Report | | 24 | 29 | 40 | Total: | 30 |
| | | Report Review | | | | | |
| | | Documentation | | | | | |

*Figure 6: Labor for EE461 in Days*

| EE 462 | | | Optimistic | Most Likely | Pessimistic | | |
|---|---|---|---|---|---|---|---|
| | Build V2 | | | | | | |
| | | Assemble Parts | 3 | 4 | 5 | | |
| | | Verify System Integrity | 4 | 5 | 6 | | |
| | | Build Enclosure | 3 | 4 | 5 | | |
| | Test | | | | | | |
| | | Test Design Specifications | 3 | 4 | 5 | | |
| | | Verify System Parameters | 3 | 4 | 5 | | |
| | | Fine Tune Lens System | 3 | 3 | 4 | | |
| | | Test at Cal Poly | | | | | |
| | Report | | | | | | |
| | | Finalize Report | 12 | 13 | 14 | | |
| | | Documentation | 33 | 39 | 47 | Total | 39.33 |

*Figure 7: Labor for EE462 in Days*

**Total Labor Days for Product Estimate using 3-Point System:** 104

**Labor Cost Summary:**

A competitive Electrical Engineering Salary in the Bay Area is $82,000 [11], $39/hour. One workday would equate to 3 hours per day. For one engineer to build, test, and produce this product, the total labor cost will be $12,000.

# Gantt Charts

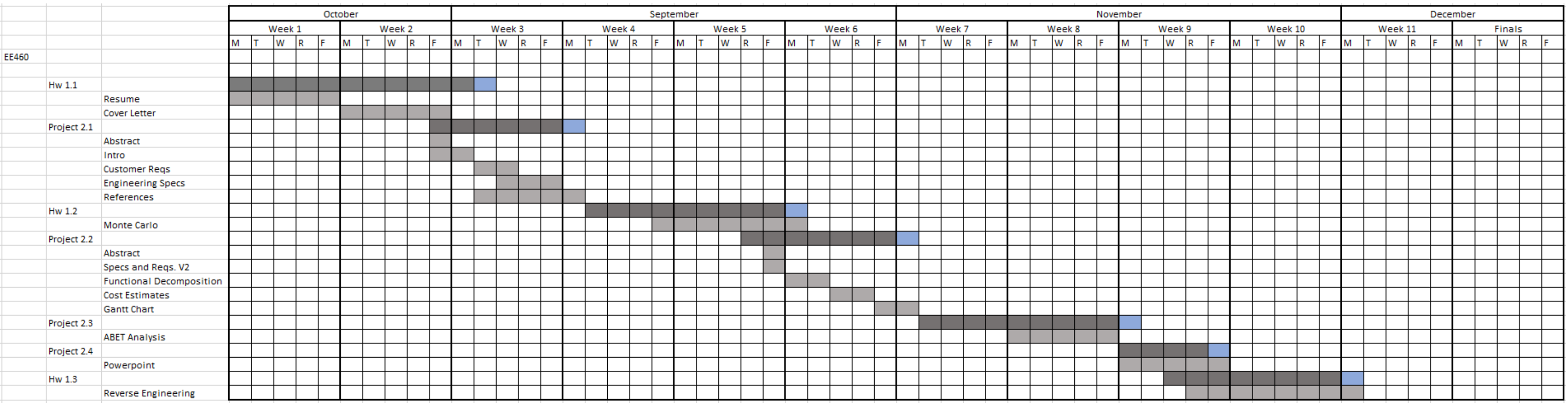


*Figure 8: EE460 Gantt Chart*

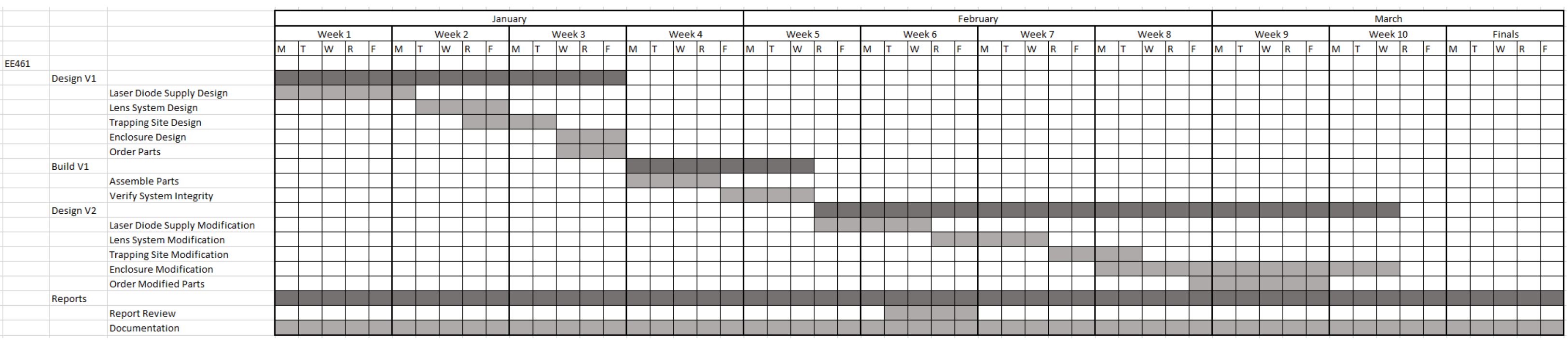


*Figure 9: EE461 Gantt Chart*

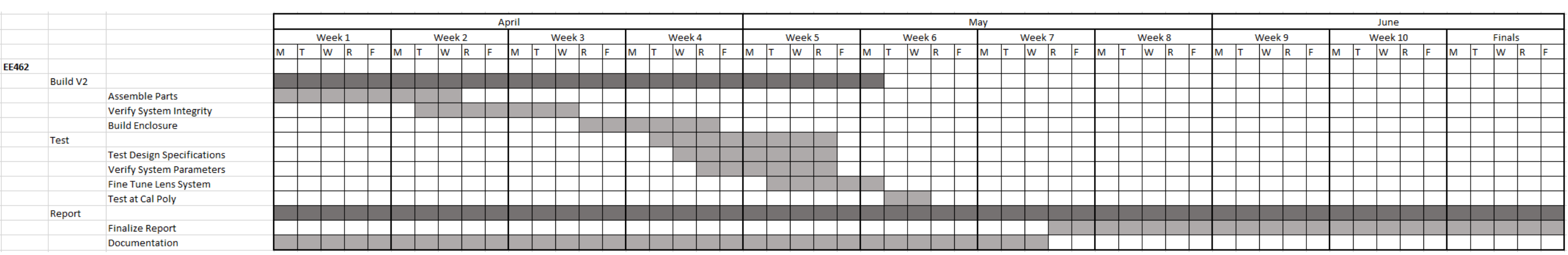


*Figure 8: EE462 Gantt Chart*

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# Appendix A

## 1. SUMMARY OF FUNCTION REQUIREMENTS

This product is an optical trap test setup designed to test the capabilities of photophoretic trapping. The trap works by focusing a laser to hold a particle in free space using heat and air. With optical traps on the micrometer scale being used for 3-Dimensional displays, multiple parameters such as air current, wavelength, longitudinal astigmatism, spherical aberration, and particle diameter must be accounted for to isolate focal length. The test setup minimizes adverse effects of each parameter. Longitudinal astigmatism and spherical aberration can be adjusted by selecting different bi-convex lenses. The wavelength of the laser can be varied at a low cost by switching the laser used on the laser diode mount. Particle absorptivity can be studied by using different types of particles, each having its own absorptivity relative to the laser wavelength. Air current can be controlled with the glass enclosure surrounding the lens system.

## 2. PRIMARY CONSTRAINTS

The two primary constraints associated with the test-setup are the interference from external air current, and the cost-effectiveness of optical components. Air current is the strongest limiting factor when it comes to photophoretic trapping. The air must be close to still so the gradient forces on the mico-meter scaled particle can be distributed properly across the particle. Thus, a proper enclosure must be constructed around the trapping site to prevent interference. Optical equipment is very specialized and therefore it can get extremely expensive. Adjusting the air current parameter, for example, requires a very specialized enclosure. Thorlabs sells well suited enclosures for thousands of dollars, but this is not economically feasible. Instead, cheaper enclosures must be built and found at a cheaper price. Another price constraint is varying laser wavelength. There are instruments that change the output wavelength of laser, but they cost about $50,000. Instead, it’s more economically feasible to manually switch out laser diodes that cost $300 a piece. Since high quality equipment is traded for cost, the system quality diminishes as a constraint.

## 3. ECONOMIC

The product requires specialized optical equipment, and an in-depth understanding of the optical theory involved with photophoretic trapping. Expensive optical equipment reduces the difficulty it takes to photophoretically trap a particle, however better understandings of the optical phenomena can reduce the cost as one understands the minimum requirements needed for the test setup.

Consulting several different experts in material science, electro-holography, fourier optics, ray tracing optics, and photophoretic trapping itself contributes to the human capital needed to make this product possible at a cheaper price. This experience allows one to strip down the optical trapping phenomena to the minimum components required to make a low-cost photophoretic trap test setup, capable of characterizing the effects of varying parameters.

The financial capital required for an optical test setup is large, however large-scale manufacturing can dramatically reduce this price as optical equipment's specialization increases the price. For example, as the use of CD players decreased, the price of laser diodes dramatically increased. As the demand for photophoretic trap displays as a consumer electronic device increase, the equipment used in this product would return to its original, low-cost, price.

The resources required for the device are remarkably low. As the device requires one laser-diode, a lens system, and a single printer toner particle. The limiting reagent for earth's natural capacity regarding this device is the glass needed for the lens system.

Product trade-off's come into play with ease of use and cost. As previously stated, laser diodes of different wavelengths must be switched in and out of place to test the laser diode wavelength's effect on photophoretic trapping. A higher budget could replace this method by using a single laser diode supply with variable power and wavelength varying from 405nm to 650nm. The main cost of the test setup is the laser diodes, as many different wavelengths are needed, and laser diodes come at about $300 each.

## 4. IF MANUFACTURED ON A COMMERCIAL BASIS

If the photophoretic trapping test setup were to be manufactured on a commercial basis, the price would dramatically decrease, as the necessity for a variable wavelength laser supply would increase. This increase in demand for a variable wavelength laser supply would decrease the specificity and manufacturing cost of the instrument. A reduction in the price of this instrument would dramatically reduce the cost of the test setup, as the many laser diodes needed could be reduced to the price of the supply. The supply currently costs $50,000, but prices like this have seen reductions down to $100. The technology known as a liquid crystal on silicon spatial light modulator (LCOS SLM) costed about $80,000 until the increase in touch screen displays. The consumer electronic market provided a high enough demand for touch screen phones that these LCOS SLMs were put into the iPhone, allowing for variable brightness and color in the display. A retail markup could even be put into place as a result of this price reduction. The same concept could be applied to this consumer electronic device as a 3-Dimensional display. As the need for a variable wavelength supply will increase, reduce the cost of the photophoretic trap, and make room for a retail markup.

## 5. ENVIRONMENTAL

The environmental impact from this device would rely on the glass used in a lens system, the circuitry needed for a laser diode supply, and the glass needed for a lens system.

The major environmental impact of glass comes from atmospheric emissions in their production process. As the glass production results in the release of CO2, Sulphur Dioxide, and Nitrogen oxide which all contribute to acidification and formation of smog. Another impact of the glass is the amount of time it takes for it to break down, as glass takes millions of years to break down.

Printer toner is also required in this product, which has its own impacts on the environment. A single laser cartridge requires a gallon of oil to manufacture. Even though the product uses a single particle out of the cartridge, a single cartridge would be needed for each device. Therefore, a gallon of oil is added to the production cost for each product developed.

While the glass in the product can be melted down to be reused, the printer toner and circuitry required to power the laser are non-reusable. The build up of non-reusable circuit boards contribute to landfills with toxic matter. PCB factories alone contribute to wastewater contaminated with copper and iron. As the products lifetime degrades, the only component left to recycle is the glass. Thousands of photophoretic volumetric displays would not have a significant effect on the environment, however if this technology becomes the technology behind the newest displays, millions of these devices will end up in landfills.

## 6. MANUFACTURABLILITY

Manufacturing the product will rely on the same technology used to manufacture digital cameras. The laser diode source only needs to be focused by a lens system, in which the trapping site must be injected with printer toner particles. The use of glass requires high melting temperatures for the lenses to be manufactured, however the entire product can be assembled with plastic and a lens system as the operating temperatures are 20 degrees Celsius above room temperature. The power supply required to manufacture the product is the limiting factor, as the current price to manufacture the variable wavelength supply is high because of its scarce demand.

## 7. SUSTAINABILITY

The product provides the framework for the 3-Dimensional display to be used in consumer electronic devices. As people would benefit from an entertainment system that draws images in 3D free space, the environmental impact and economic requirements compare to an iPhone. As the cost to manufacture the product decreases, the economic feasibility becomes trivial because the technology is heavily sought after. As the manufacturing technology behind this device becomes more adept, the product will require the use of more recyclable materials. The glass is already recyclable, and the printer toner storage can be standardized. Incorporation of this product into a consumer electronic device would replace the environmental impact of a 2D touchscreen display.

## 8. ETHICAL

This product seeks to reduce the optical trapping power of 3D photophoretic volumetric displays to comply with the health, safety and welfare requirements set by IEEE. The safety hazards that come with high powered lasers are of concern. Tampering with the product by extracting the high-power laser diode can be a safety hazard.

Lasers with a power of higher than 5mW can cause severe damage to the eyes and skin. This product will not be safe for consumer use if this requirement is not met at the trapping site of the product. Misuse of the product can come with extracting the laser diode which could be at a higher power than 5mW. For the product to become safe for use as well as tampering, the power must be reduced to lower than 5mW at the source side as well. This would then comply with

IEEE code of ethics, as well as Laser Product regulations set by the FDA. Currently, the trapping power is at a minimum of 25mW, however this product provides an instrument to investigate reducing the trapping power to comply with regulation. Complying with these regulations prevents the misuse of this product to physically harm other individuals.

## 9. HEALTH AND SAFETY

This uses a 40mW laser diode which does not comply with health and safety regulation set by IEEE. The safety hazards that come with high powered lasers are of concern so safety precautions must be put in place when operating this specific product.

Lasers with a power of higher than 5mW can cause severe damage to the eyes and skin. This product will not be safe for consumer use if this requirement is not met at the trapping site of the product. This product uses high powered lasers (Above 5mW) but seeks to reduce the optical power required for this technology to make it a consumer electronic device. Lasers above 5mW can damage the skin, and eyes, therefore safety glasses must be always worn.

## 10. SOCIAL AND POLITICAL

The technology behind this product could benefit consumer electronic companies such as Apple, Google, and Amazon as this technology brings the current 2D displays to a higher 3D display. These displays could impact educational presentation, electronic communication, and entertainment.

The harm from this device would take the same shape as the social harm from social media, as this device will change the way people communicate. The change in technology could, however, reduce these harms. To develop a 3D display would produce a more life like image of another person, giving a greater sense of interpersonal connection. This type of communication could heighten political globalization as reality from other parts of the world may be brought to the user directly.

## 11. DEVELOPMENT

In developing this product, I learned how to build optical test setups and safely handle laser diodes. This allowed me to gain enough experience to work as an optical engineering intern at Amazon Prime Air. I learned to manage lenses on an optical bench, measure power and incorporate measurements into python and labview based program. Additionally, I learned ray tracing and Fourier optics associated with the trapping region of the optical trap.