THE ADAPTIVE OPTICS DEMONSTRATION DEVICE

MIM 1501-1502

Technical Design Report

The Adaptive Optics Demonstration Device
Project #F00/S01

Final Report

Design Advisor: Prof. Gregory J. Kowalski

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May 31, 2001

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Wednesday June 30, 2001

Prof. Gregory Kowalski
Northeastern University
Dept. of Mechanical Industrial and Manufacturing Engineering
360 Huntington Avenue
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RE: Letter of Transmittal

Dear Professor Kowalski,

The adaptive optics group is pleased to transmit the report for your evaluation. The attached report presents the solution for the making an adaptive optics demonstration device, that will be affordable, easy to set up and easy to operate. The solution is based on cost and availability analysis for making the two-lens system. It has been found that refining the resin casting procedure would produce higher than 20% yield rates. Casting resin allowed producing the lenses at an estimated cost of $45/unit

We would like to express our appreciation to the opportunity given to hand on approach on real life problems. This project is an open-ended solution that allowed us to learn great deal about the adaptive optics technology as well as manufacturing techniques that require casting resin. With that we would like to express our appreciation for your support and advisory. Please feel free to contact us if you have further questions about this project or about future considerations.

Sincerely,

Khalfan Belhoul
Wei Chen
Victor Chung
Mahamed-Zied Driss
Michael Ducharme

Adaptive Optics Demonstration Device Group
Adaptive Optics Demonstration Device

Capstone Design Course
MIM 1502
Technical Design Report

Executive Summary

Design Advisor: Prof. Gregory J. Kowalski

Design Team
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May 23, 2001

Abstract

The project is to improve a simple Adaptive Optics demonstration device by developing a more reliable manufacturing process for the distortion lenses and designing a lens fixture. The final design is easy to set up and operate and cost less than $75/unit for a production run of 100-200 units. The solution is a wooden fixture that provides positive alignment of the distortion and correcting lenses. The lenses are made using a resin casting procedure that overcomes the shrinkage factor. Shrinkage effects have limited the yield of the previous methods.
As you can see the demonstration is quite effective once the lenses are aligned. Aligning the lenses can be quite difficult, since it requires the demonstrator to manual align the lenses.

Another concern is the yield rate of the current manufacturing method, which is approximately 20%. This can be attributed to the shrinkage of the two semi-cured layers of resin, causing spatial voids between the resin and the plastic sheet. These spatial voids are causing an inherent mismatch of the lenses.

**Design Project Objectives and Requirements:**

The sponsor wants the group to develop a manufacturing process for the lenses and design a fixture for aligning the lenses that is easy to use, and setup and affordable. The group analyzed the problems with the current device and determined that the manufacturing of the lenses will be the most difficult part in the project. The cost set by the sponsor was $75/ unit for a production run of 100-200 units. The unit would consist of two lenses and a device, which would be easy to setup and to operate.

**Manufacturing Process Concepts Considered:**

The group considered injection-molding, thermoforming and resin casting as possible processes to create the lenses. Injection molding and thermoforming were too expensive for the project. However a variation on thermoforming initially looked promising.
Resin casting is the method used by the sponsor, and involves manual labor under a fume hood.

**Recommended Manufacturing Processes:**

As previously mentioned, the problem of the current manufacturing method is that there are spatial voids. The two layers of resin are creating the spatial voids as they cure. After some initial testing, it was found that there is a 7% shrinkage in the resin. The volumetric shrinkage only greatly affects the height of the resin. This means that the shrinkage in the other two dimensions is negligible.

The proposed method is to create the first part, allow it to cure to create the distortion lens. Then a plastic sheet is placed on top of the resin and the second layer of resin is poured creating the mating correction lens. This method would allow for the volumetric shrinkage plaguing the current manufacturing process.

**Key Advantages of Recommended Concept:**

The advantages of resin casting are the cost, and no additional or processes are necessary. The resin casting does not require a major initial investment. A matched set of distorting and correcting lenses are created without any secondary processes.

**Experimental Investigation:**

Testing the resin on ceramic and urethane molds showed that the parts were difficult to remove and the surface finish was not acceptable. The wax molds provided easy removal of parts, however the surface finish was also unacceptable. This led the group back to the method.
used by the sponsor.

Further testing showed that mating lenses could be cast from each other with an oven-bag sheet separating them. By placing an oven bag sheet in between the cured part and the layer of resin, the mating lens can be created. After the second layer of resin has cured, the plastic sheet facilitated in the separation of the two lenses. This way once the first part is made the matching lenses can be created from it.

Demonstration Device:

The device consists of two wooden rings that encircle the matched lenses and that have a positioning device. A base will encircle the distortion lens with an alignment guide. The second piece will encircle the correction lens and follow the alignment guide to align the lenses.

![Lens Fixture](image)

Financial Issues:

The cost for the production is under $45. The cost of the unit includes labor to manufacture lenses and fixture, expense for research and development materials. The price range is $44.65 for 100 units and $43.50 per 200.

Recommended Improvements:

The use of a different resin and the use of a pair of master molds with mold release may simplify the process further. The material used is a polyester resin with a catalyst added to it to cure. The cure time for the resin is 24 hours. The use of a faster curing resin can increase the production rate. The recommended process creates a pair of lenses which are unique. Using a pair of master molds with the use of a mold release would create interchangable parts.
TABLE OF CONTENT

TABLE OF CONTENT .......................................................................................................................... .0
FIGURES ........................................................................................................................................... i
CHARTS ............................................................................................................................................... i
ABSTRACT ........................................................................................................................................... ii
ACKNOWLEDGMENTS ........................................................................................................................ iii
Copyright........................................................................................................................................... iv
CHAPTER 1 INTRODUCTION ........................................................................................................... 1
PROJECT GOAL ................................................................................................................................ 1
PROJECT OVERVIEW ........................................................................................................................ 1
CHAPTER 2 STATE-OF-THE-ART ................................................................................................... 2
BACKGROUND ................................................................................................................................... 2
END USER .......................................................................................................................................... 2
DESIGN REQUIREMENTS ................................................................................................................... 3
Quick and easy to operate ..................................................................................................................... 3
Quick and easy to set up ..................................................................................................................... 3
Portable ............................................................................................................................................. 4
Costs .................................................................................................................................................. 4
Quantity .............................................................................................................................................. 4
AVAILBLE DEVICES .......................................................................................................................... 4
Chanan’s Two-lens System .................................................................................................................. 4
Seven Segment Demonstrator ............................................................................................................ 5
Project Approach ................................................................................................................................ 5
CHAPTER 3: MANUFACTURING PROCESSES CONSIDERED ....................................................... 7
RESIN CASTING ................................................................................................................................ 7
Chanan’s Casting Process .................................................................................................................... 7
Problems with Chanan’s Casting Process ............................................................................................ 7
INJECTION MOLDING ...................................................................................................................... 8
THERMOFORMING ............................................................................................................................ 8
Initial success ....................................................................................................................................... 9
Failure .................................................................................................................................................. 9
RECOMMENDED PROCESS .......................................................................................................... 10
Key advantages ................................................................................................................................... 10
CHAPTER 4 DESIGN DETAILS AND ANALYSIS ............................................................................ 11
OPTICAL ANALYSIS ......................................................................................................................... 11
Assumptions ...................................................................................................................................... 11
FIGURES

Figure 1: Neptune without AO.................................................................2
Figure 2: Neptune with AO.................................................................2
Figure 3: 1st lens distorts image .........................................................3
Figure 4: 2nd lens corrects image........................................................3
Figure 5: Seven-Segment Demonstrator courtesy of Blue Line Engineering .......5
Figure 6: Lens profile.................................................................6
Figure 7: Shrinkage effects on curing lenses ........................................8
Figure 8: Trace of the bolt edge ...........................................................9
Figure 9: Follow up experiment ..........................................................10
Figure 10: Plano-Convex lens ............................................................12
Figure 11: Plano-Concave lens ...........................................................12
Figure 12: Shrinkage effect on the lens diameter...............................13
Figure 13: Lenses combined .............................................................13
Figure 14: Ray tracing.................................................................14
Figure 15: Support lens ...............................................................17
Figure 16: Flush lenses ...............................................................17
Figure 17: Vertically moved lenses by 3/32 in. ....................................17
Figure 18: Ideal case .................................................................18
Figure 19: Real case ........................................................................18
Figure 20: Alignment Fixture ...........................................................20

CHARTS

Chart 1: Distortion effects with Gap increase ........................................16
Chart 2 Cost Analysis .................................................................21
ABSTRACT

The project is to improve a simple Adaptive Optics demonstration device by developing a more reliable manufacturing process for the distortion lenses and designing a lens fixture. The final design is easy to set up and operate and cost less than $75/unit for a production run of 100-200 units. The solution is a wooden fixture that provides positive alignment of the distortion and correcting lenses. The lenses are made using a resin casting procedure that overcomes the shrinkage factor. Shrinkage effects have limited the yield of the previous methods.
ACKNOWLEDGMENTS

The adaptive optics demonstration device group of the year 2001 would like to take the opportunity to express their appreciation to everyone that helped in the project design. The group is very grateful to Dr. Gary Chanan the sponsor of the project. Special thanks to thank Prof. Gregory J. Kowalski for assigning this project and his outstanding advisory to make this project successful. We would like also to thank Northeastern University and in particular the Department of Mechanical, Industrial, and Manufacturing Engineering, for providing human support and necessary resources for the successful completion of the project. Our families and friends deserve also special thanks for their support.
Copyright

“We the team members,

Khalfan Belhoul  Wei Chen  Victor Chung  Mohamed Zied Driss  Michael Ducharme

Hereby assign our copyright of this report and of the corresponding Executive Summary to the Mechanical, Industrial and Manufacturing Engineering (MIME) Department of Northeastern University.” We also hereby agree that the video of our Oral Presentations it’s the full property of the MIME Department.

Publication of this report does not constitute approval by Northeastern University, the MIME Department or its faculty members of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.
CHAPTER 1 INTRODUCTION

PROJECT GOAL
The project goal is to improve a simple adaptive optics demonstration device by developing a more reliable manufacturing process for the distortion lenses and designing a lens fixture.

PROJECT OVERVIEW
Researchers in the field of adaptive optics need a simple device to demonstrate the benefits of their work. The sponsor has developed a method of demonstrating those benefits. The demonstration device, though effective has a low production yield rate and requires manual alignment of the lenses. These problems will be addressed by the group in this project. By looking into the current manufacturing process, the group will develop a more reliable manufacturing process for the lenses and design a lens fixture to align the lenses.
CHAPTER 2 STATE-OF-THE-ART

BACKGROUND
Adaptive Optics (AO) is a technique used to compensate for distortion in images through changes within optical systems. Turbulence in the earth's atmosphere causes distortion in astronomical images (Fig. 1). This is similar to internal imperfections and fluid in the eye that blurs images when they reach the retina, or the visible distortion caused by imaging through water. Adaptive optics techniques allowed earth-based telescopes to obtain images as clear as than space-based telescopes (Hubble Space telescope) or better. With the advances in computers, optics, and laser technology, astronomers are developing the next generation of terrestrial telescopes equipped with the adaptive optics technology, which will eliminate the distortion effect of the turbulent, non-isothermal atmosphere (Fig. 2). In order to develop the technology, it is necessary to bring researchers and funding agencies closer to a fundamental and unified understanding of the adaptive optics technology. Astronomers need an easy to use demonstration device to educate the public about the benefit of adaptive optics.

Figure 1: Neptune without AO
Figure 2: Neptune with AO

END USER
The sponsor, Dr. Gary Chanan of the Center for Adaptive Optics (CfAO) has developed a method to demonstrate the benefits of adaptive optics. His method uses a two-lens system, in conjunction with an overhead projector. A transparency is placed on the overhead projector providing a basis for comparison. The first lens, simulates the Earth's turbulent, non-isothermal atmosphere, distorts an image when placed on top of a spacer above the transparency (Fig, 3). While the second lens, which represents the adaptive optics technology corrects the distorted image (Fig, 4).
The demonstration is very effective, however, the yield rate for the lens manufacturing process is low (approximately 20%) due to shrinkage effects, and the demonstration requires manual alignment of the lenses. The sponsor has requested the group to develop a manufacturing process for the lenses and design a fixture for aligning the lenses.

**DESIGN REQUIREMENTS**

A teleconference with Dr. Chanan, laid out the following requirements for the device:

- Quick and easy to operate.
- Quick and easy to set up.
- Portable.
- Cost: $75/unit.
- Quantity: 100-200 units.

It is by meeting these requirements a device would be considered to be suitable for the sponsor’s needs.

**Quick and easy to operate**

For the device to have a dramatic effect, the change from distorted to correct image should be close to instantaneous. The sponsor’s current method requires manual alignment by the presenter, which can take valuable time from the presentation. The device must be quick and easy to operate. Here Dr. Chanan suggested a maximum operating time of 5 seconds.

**Quick and easy to set up**

Set up of the demonstration should not detract from the presentation. The demonstrator does not have time to waste in setting up a complicated device. Therefore, the device must meet this requirement to prevent important information lost to the audience due to the distraction of setting up the device.
**Portable**
Due to the various locations that adaptive optics is researched, the device design must be easily shipped or carried. The presenter should be able to conveniently pack the device. The design must fit into standard school bag and a briefcase.

**Costs**
Researchers require funding for their work, often have a limited budget. A demonstration device, which uses AO, is often too expensive to be an option. The sponsor set a price limit of $75/unit.

**Quantity**
The sponsor needs a 100 to 200 units to send to various research locations. These locations will then be able to educate the public and funding agencies to the benefits of adaptive optics. The quantity needed is a low quantity production run that may limit production methods.

**Available Devices**
Extensive searches were conducted in both the US patent database and the Internet for available AO demonstration devices. In the US patent database, searches for keywords such as “adaptive”, “optics”, “demonstrations”, or any relevant combinations thereof provided some adaptive optics patents. However, found various adaptive optics technologies, all found patents have been examined, but no one could be used for educational purpose. While nothing was found in the US patent database, only one instrument called the Seven-Segment Demonstrator (SSD) was found in the Internet. Both SSD and the device developed by Dr. Chanan are listed and analyzed in the following sections.

**Chanan’s Two-lens System**
As shown in figure 4, the apparatus components are a transparency sheet, a spacer, and the two lenses with irregular mating surfaces. Setting up the demonstration requires an overhead projector, which is in general available in most schools and conference rooms. Placing a transparency on the overhead projector and focus the image on a screen. The next step in preparing the demonstration is placing the spacer on top of the transparency. The operation to run the demonstration is placing the first lens on the spacer to distort the image, and mating it with the second lens to compensate for the distortion effect and obtain a corrected image. The two-lens system appears very simple since no complex mechanics or electronics is associated with it. The demonstration device is low technology, transportable, quick to set up, and easy to operate.
Seven Segment Demonstrator

The Seven-Segment Demonstrator made by Blue Line Engineering is the only commercially available AO demonstration device. As shown in figure 5, the device is composed of sensors, a notebook computer, and seven individual mirrors (segments) array and a camera to focus images. Set up for this high technology device, requires set up the individual components and connecting the notebook computer to the device. Operations require all the following steps: the sensors detect the wave front and sends inputs to the computer. The computer then actuates the controllers for each mirror to alter its orientation. This change in orientation reflects the light source in such a way that the image is no longer distorted. This device is highly mobile since it is possible to fit all components within one specially designed case. However, because of its many components and high technology, this system is expensive. Also when compared to Chanan’s two-lens system, it is relatively heavy to carry and requires more time to set up. Both reasons make such a device not comply with the specifications set by Dr. Chanan.

Figure 5: Seven-Segment Demonstrator courtesy of Blue Line Engineering

Project Approach

A teleconference with Dr. Chanan confirmed that he appreciated the simplicity of the design of his current device. It is important for the demonstration device to effectively deliver the adaptive optics concept. Dr. Chanan’s two-lens system with its simple design left a very good impression about the concept of adaptive optics. On the other hand, the SSD is a miniature of a telescope equipped with an adaptive optics technology; while this is what’s happening in reality, the cost benefit ratio is high. The failure of the SSD to meet the requirement stated earlier, means the acceptance of Dr. Chanan current method with improvements.

The two proposed improvements are to develop a more reliable manufacturing process for the lenses and designing a fixture to align the lenses. Since the success of the demonstration depends on both the distortion of the image by the first lens and the correction of the image by the second lens, manufacturing of the lenses is critical to
the demonstration. The random surface profile of the lenses (Fig. 6) makes the lens manufacturing process more difficult of the two improvements. This will be the main focus of the project.

**Lens Description**

Each lens is a plate with random irregular surface in one side and flat on the other side. The diameter of each lens is 7 in. and the thickness is approximately 0.5 in. and the weight is about 0.75lb.

![Figure 6: Lens profile](image)
CHAPTER 3: MANUFACTURING PROCESSES CONSIDERED

Resin casting, injection molding, and thermoforming, were considered as possible lens manufacturing processes. These were thought to be able to produce the desired complex surface profile. The final selection is based on the costs, availability of material and success in creating lenses.

RESIN CASTING
Resin casting process uses a resin to create a part. The resin can be a two part mixture a single component material or UV activated material. The resin is poured into a mold and cured. Problems with resin casting include part removal, air bubbles, and working in a fume-hood.

Chanan’s Casting Process
The current lens production method begins with mixing resin with catalyst carefully to prevent air bubbles in the mixture, and pour approximately 300-400ml into a pan (8inch non-stick circular baking pan). Place a plastic (part of Ziploc) over the resin and make sure there are no air bubbles trapped underneath the sheet. Create a random texture on the surface by pressing in various places. Do this until resin begins to harden. Then pour about 300-400 ml of the remaining mixed resin on the top of the plastic sheet. To insure that the top surface of the second lens is flat and smooth, place an acetate sheet on the top of the resin.

Problems with Chanan’s Casting Process.
There is only 20% yield rate for this process. This can be attributed to the shrinkage effect of the two layer resin curing shown in (Fig. 7). As the layers of resin cure, the shrinkage is causing the plastic sheet to separate from one of the surfaces creating gaps between the two surfaces. These gaps cause an inherent mismatch of the two lenses. Developing a process that eliminates the gaps would provide a greater lens yield.
INJECTION MOLDING
Injection molding is used for creating repeated number of parts at desired tolerance. The re-usage of a common mold and the ability of the machine to conform the plastic to this mold repeatedly make it an ideal solution for making large production runs.

There are many major advantages to injection molding. Initially, the injection molding process can repeatedly produce large quantities of parts at desired tolerance. Secondly, operator cost is low since the process is automated. The only real manual operations are the introduction of raw material and removal of finished parts from the machine. Wide range of thermoplastic can be used in injection molding. Finally, the amount of wasted material is negligible.

There are, however, disadvantages to injection molding. The processing itself is fairly expensive. An injection-molding machine has a heating element, a conveying element, molds, and in some cases a removal element, all of which require initial investment. This high initial cost makes injection molding makes it non-viable solution to our project as the costs for the molds only is estimated at $20,000 to $30,000.

THERMOFORMING
Thermoforming is a process in which a plastic is placed on a heated mold cavity. A press pushes the partially molten plastic into the bottom half of the mold giving the desired shape. The part is held within the mold as it cools down, and then ejected from the mold.
Thermoforming has few advantages. In general, thermoform molds are usually easier and cheaper to make as estimated at $8,000/mold. The process can use a wide range of plastics such as transparent acrylic. Thermoforming shares a disadvantage with injection molding in the processing operation, which requires the use of heating elements, a press, and a process to remove the part. This process can create a noticeable amount of flash, and may require secondary processes to create a finished part.

Despite the disadvantages of thermoforming, the group initially considered a variant form of this process for the manufacturing of the lenses.

**Initial success**
As a proof of concept, a basic experiment was performed to validate the thermoforming process as a viable lensmaking option. This test involved heating a sample of material, in this case a general acrylic, to a temperature high enough that it begins to soften, about 150°C. When softened, a pair of pliers was used to forcibly press the edge of a bolt into the material, to show the material’s shape holding abilities. While this bolt edge was not perfectly representative of the necessary geometry, it gave a good idea as to whether the material could hold shapes and if the material shrunk significantly (Fig. 8). It did not shrink a significant amount, and this sample is shown in the picture below. The next experiment was to attempt to press a smooth shaped object into the plastic to mimic the profile of the mold.

![Figure 8: Trace of the bolt edge](image)

**Failure**
With the encouraging results from the first experiment, the next experiment was to attempt to press a smooth and curved object into the heated acrylic. At 150°C, it was impossible to press the shape into the plastic. Gradual rises in temperature did not produce any significant reduction in the force required to make the necessary shape in the plastic. At about 305°C, the material began to decompose by forming small bubbles within the sample, which both
weakens the material, and reduces its optical quality. The material was still not workable at this point, and when attempts were made to press the shape into the bubbled material, it broke in half (Fig. 9).

With this setback, the group found it is necessary to further investigate the sponsor’s method. Experimenting with the method, it was found that the shrinkage of the resin was volumetric as opposed to linear as was earlier believed. Taking into account this new fact, the group developed its final recommendation.

**RECOMMENDED PROCESS**
The previous method attempted to create the two mating parts simultaneously. The initial belief that shrinkage was linear would require that the two resin lenses be poured simultaneously to control shrinkage differences. However, with the volumetric shrinkage, it is possible to pour the first lens, let it cure, and then pour the second lens over it. The shrinkage affects only the top surface of the second part. The main benefit of this recommended process is that it takes into account volumetric shrinkage.

**Key advantages**
The advantages of resin casting are the low costs, and no additional or secondary processes are necessary to create a match set of lenses. The process does not require a major initial investment. The lenses are created without any secondary processes, eliminating chances for error to be introduced.
CHAPTER 4 DESIGN DETAILS AND ANALYSIS

OPTICAL ANALYSIS
The lenses are required to distort an image with one lens and to correct the image after applying the second lens. Therefore, the first stage deals with the characteristics of the individual lens. In the second stage the overall performance of the system is specified.

Assumptions
As stated earlier, each lens is a transparent plate with a random rough surface. When viewed sideways the rough surface appears as a sequence of hills and valleys. The hills are modeled as Plano-Convex lenses (Fig. 10) while the valleys as Plano-Concave lenses (Fig. 11). The lenses are estimated to vary in radii from to 0.01 to .25 in.

Lens Characteristics
Lensmaker’s equation, equation 1, is used to find the focal lengths. Here \( n \) is the index of refraction, a material optical property taken directly from the supplier specification sheet. In our case \( n = 1.43 \). \( R_1 \) and \( R_2 \) are defined to be the radii of the curvature of each lens. The geometric optics sign convention requires that if the radius is to the right of the lens the radius is positive, conversely, if it is to the left it is negative.

\[
\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)
\]

Equation 1

Applying equation 1 to the Plano-Convex lens, the plane surface has a radius \( R_1 = \infty \), and its inverse \( 1/R_1 \) equals to 0. Substituting variables yields \( (1/f_1) = (-0.43/R_2) \). Similarly, applying equation 1 to the Plano-Concave lens, the plane surface has a radius \( R_2 = \infty \), and its inverse \( 1/R_2 \) equals to 0. Substituting variables yields \( (1/f_2) = (0.43/R_1) \).
System Performance
The second stage is involved with the performance of the overall system. That is, looking at both lenses at operating condition. In our cases there is a pair of lenses separated by a distance \( d \) and are treated as one single lens. Therefore, it is necessary to find \( d \).

\( d \) is defined to be the distance separating a pair of mating lenses (Fig. 12). In estimating \( d \), it has been found that if \( d \) equals zero, \( R_1 \) equals \( R_2 \); this absurd cause if \( R_1 \) equals \( R_2 \), mating the lenses would be impossible. Then, based on Newton Fringes the lowest value of \( d \) has been defined to be 0.0005 in. The highest value for \( d \) could be determined using the shrinkage of the lenses. After shrinkage of the resin, the lenses radii change from \( R_1 \) to \( R_1 - \delta_1 \) for the first lens and from \( R_2 \) to \( R_2 + \delta_2 \) for the second lens (Fig. 11). At 0.5 in. thickness and 2% shrinkage \( \delta_1 = 0.5 \times 2\% = 0.01 \text{ in.} \). Therefore, \( d = |\delta_1 + \delta_2| = 0.02 \text{ in.} \). Because the random surface profile of the lenses, \( d \) also varies randomly within a range of 0.0005 in. to 0.02 in.
The combination focal length formula equation 2 is then used to estimate the distortion as the gap \( d \) varies. The mathematics of equations 2 enables treating the two lenses with focal lengths \( f_1 \) and \( f_2 \) separated by the distance \( d \) as one single lens with one overall focal length \( f_{overall} \) (Fig. 13). This formula is very powerful since it gives \( f_{overall} \) of both lenses combined without the need to calculate other details such as image location of each lens individually.

\[
f_{overall} = \frac{f_1 \cdot f_2}{f_1 + f_2 - d}
\]

Equation 2

With those assumptions, as shown in figure 14, the image is refracted through the lens and then reflected on the screen. Image tracing requires defining a coordinate system \((i,j)\) of origin \(D\) located at the center of the lens.
Ray 1 (red line) enters the system from point $B$ through $D$ then to the screen at point $E$. Ray 2 (blue line) enters the system parallel to the $i$-axis, hits the $j$-axis at $C$ and changes direction through $f_{overall}$, then to the screen at $E$. Both rays intersect on the screen at point $E$, which is defined to be at a distance $x$, $y$ from the coordinate system of origin $D$. The position of $E$ could be found by applying equation 3 to both ray 1 and ray 2, then solving the two linear equations for both unknowns $x$ and $y$. In equation 3, $m$ is the slope, which is calculated by taking the ratio of the rise over the run. And $b$ is the ordinate intercept.

$$y_i = m_i x + b_i$$  

**Equation 3**

Applying equation 3 to each ray requires defining:

$h$ is the height of point $B$ from point $A$ chosen to be 1 in.
$s$ is the distance of point $D$ from point $A$ estimated to be 3 in. 2.5 in. associated with the thickness of the spacer and 0.5 in. thickness of the lens.
$i$ is 1 for ray 1 and 2 for ray 2.

Referring to the geometry in figure 6 and applying equation 3 to ray 1 yields, $b_1$ equals to 0 as ray 1 passes through the origin $D$. $m_1$ is the slope, which is equal to $-h/s = -1/3$. Substituting values into equation 3 yields equation 4.
\[ y_1 = \frac{1}{3} x + 0 \]  

Equation 4

On the other hand, \( b_2 \) is the intercept for ray 2 with the coordinate system \((i, j)\). Since ray 2 intersects \( j \)-axis at \( C \), \( b_2 \) equals to \( h \) and therefore \( b_2 \) equals to 1. \( m_2 \) is the slope of ray 2 and equals to \( -\frac{h}{f_{\text{overall}}} = -1/f_{\text{overall}} \). Substituting back into equation 3 yields equation 5.

\[ y_2 = -\frac{1}{f_{\text{overall}}} x + 1 \]  

Equation 5

Since both ray 1 and ray 2 intersect in point \( E \) at the screen, it is possible to equate \( y_1 \) and \( y_2 \). Therefore, equating equation 4 and equation 5 yields equation 6.

\[ -\frac{1}{3} x = -\frac{1}{f_{\text{overall}}} x + 1 \]  

Equation 6

Arranging equation 6 and solving for \( x \) yields equation 7.

\[ x = \left( \frac{1}{f_{\text{overall}}} - \frac{1}{3} \right)^{-1} \]  

Equation 7

Once \( x \) is found, it is possible to solve for \( y \) by submitting the new value of \( x \) back in either equation 4 or equation 5. Both \( x \) and \( y \) will be used later to estimate distortion.

The iteration process starts choosing \( R_1 \) and \( R_2 \) then calculating \( f_1 \) and \( f_2 \). Then substitute \( f_1 \) and \( f_2 \) into the combination focal length formula. With that the only variable in the formula is \( d \). As \( d \) changes over its range there is a corresponding change in the overall focal length which in turn, results in a change in the position of point \( E \). The new position \( x \) and \( y \) on the screen differs from the original position \( x_0 \) and \( y_0 \). Knowing that by definition distortion is the change in lateral magnification versus the distance from the optical axis. The distortion factor \( L \) can then be quantified using equation 8. In our case, the relationship between the distortion factor \( L \) and the gap \( d \) is summarized in chart 1.
The chart confirmed that the distortion factor increases with the gap between the lenses. For a radius of 0.01 in., the distortion increases proportionally with the gap $d$ until about 0.1 in. Starting at this point an asymptote starts taking place suggesting a saturation of distortion. After $d$ equals 0.1 the distortion took its worst values up to a point where increasing $d$ does not affect the image any more. However, for a radius of 0.25 in., the distortion value is not saturated yet. Since there are no published standards to validate our statements, experimental results has been conducted and discussed in the next paragraph.

![Chart 1: Distortion effects with Gap increase](image)

The support lens (Fig 15) is used to vertically move one lens with the respect to the other. Here the assumption made on vertical motion only. After moving the lenses one with respect to the other by a distance of 0.1 about “3/32” in., two results are found. First the overall picture is still relatively clear, this is shown by comparing figure 16 to figure 17. Second, the areas modeled by small radii around 0.01 in. are completely distorted, while those modeled by radii around 0.25 in. didn’t distort completely (Fig. 16 and 17). This confirmed the assumptions
concerning, the chart, the radii and the formulas used for our analysis. The sensitivity of the distortion to the radius is discussed in the next section.

Radius Effect
Further investigation of the chart confirmed that the bigger the radius the bigger the gap is permissible. For a perfect case shown in figure 18, a collimated light focuses on one single point when the light is refracted through the lens on the screen. In contrast, as shown in figure 19, the real case suggests a whole range of lateral focus. Therefore, as showed in figure 18, it is important to distinguish between a Paraxial ray, one that is close to the optical axis, and a Marginal ray, one that is further away from the optical axis. On the convex side of the plano-convex lens, the furthermost marginal ray intersect with the optical axis in position P1 closest to the lens, however, the closest paraxial ray intersects with the optical axis in a farther position from the lens P2 shown in figure 19. The distance between these two intersections is known as the Longitudinal Spherical Aberration (LSA). Mathematically stated, LSA is the difference between the positions of the two intersections. \( \text{LSA} = P_2 - P_1 \). The longitudinal spherical aberration is associated with the Transverse Spherical Aberration (TSA). The latter is the vertical distance between marginal ray and the optical axis at P2 when showed on the screen. The greater TSA is the more distortions we notice on the image. One way to compensate for this problem is to increase the radius of the lens. In fact for an infinitely large radius all rays will be almost parallel and the TSA effect will be almost eliminated. However, infinite radius will result in a flat surface. Practically, the image will be always clear, which is contrary to the objective of the design, which requires a distorted image with one single lens. Therefore, the range chosen above is what we need to consider for making the lenses while casting the resin.
Resin Experiments
Based on the recommended process and design analysis, we decided to conduct a resin curing experiment to obtain proper resin to catalyst ratio. Since the process involved using plastic sheet to separate the two lenses, finding a plastic sheet that doesn’t react with the mix of resin and catalyst was equally important.

Resin Curing
Initial attempts to create parts using the sponsor’s method resulted in parts that were not fully cured. The top surface tended to be uncured and sticky. After analyzing the procedure and discussions with the vendor, the cause of the problem seemed to be the top surface being exposed to air. An experiment was conducted with one sample of resin covered with a clear transparency and one that was not. The results showed that the resin cured fully when it was not exposed to air.

Plastic Sheet Selection
The sponsor’s method required the plastic sheet to be pliable to be able to manipulate the surface of the resin. An experiment using different plastic sheets was conducted. The plastic samples were obtained from an oven bag (heat resistant nylon), shopping bag (polyethylene), saran wrap, and sandwich bag (Ziploc™). The results of the experiment showed that the oven bag sheet would allow the resin to cure and easily removed from part. The saran wrap and shopping bag sheets became fused with the resin parts and could not be removed and did not allow the part to cure fully, indicating that air was interacting with surface. The biggest surprise was that the Ziploc™ sample did not fully cure. The plastic sheet was immersed between two layers of resin and not a problem in the original method.
Alignment fixture
The lens alignment by the presenter detracts form the demonstration about the benefits of adaptive optics. Improving the lens manufacturing process was the first objective of the project, creating an alignment fixture for the lenses would fulfill the sponsor’s needs. The alignment fixture (Fig. 20) requires two components: the lens fixturing and the alignment mechanism. These components will be discussed in the following section.

Lens fixture
The concept for holding the lenses is to allow the lens to sit in a step above the hole for light to pass through. The base encircles the perimeter of the lenses and holds it in place. This will hold each lens and provide a mount for the guide channel or the guide rod in the alignment mechanism.

Alignment mechanism
To align the lens, the use of two chamfered guide channels and two guide rods was used. The bottom lens fixture has a guide channel mounted to it. The guide channels locks into place via use of a ball detent and a pivot point. This feature allows the channels to pivot down to compact the device during transportation. The guide rods are screwed into the top lens fixture. The chamfer in the channels allows the user to easily position the guide rods. The top lens would be aligned to the bottom lens as it is placed onto it. By designing a fixture, which aligns the lenses and a manufacturing method for the lenses with a better yield rate, the cost requirement of the device will be the remaining concern. The next section will address the cost of the device.
Costs Analysis
As previously stated the group was given an upper cost limit of $75/unit. For development cost, it was necessary to include all expenditures towards the project. These costs are divided into two categories; recurring cost (cost per unit) and non-recurring cost (one-time cost). Only items listed as "price per part" (Table 1) would appear for the sponsor’s manufacturing cost. Even with all expenditures included, the device meets the cost requirements of $75 so long as more than 8 units are made (Chart 2). The cost/ unit over the 100-unit run is under $45.
Table 1: Cost break down

<table>
<thead>
<tr>
<th>Expense summary</th>
<th>Per part</th>
<th>Per 100</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin</td>
<td>$ 7.00</td>
<td>$ 700.00</td>
<td></td>
</tr>
<tr>
<td>Wood for fixture</td>
<td>$ 2.35</td>
<td>$ 235.00</td>
<td></td>
</tr>
<tr>
<td>Fixture hardware</td>
<td>$ 5.00</td>
<td>$ 500.00</td>
<td></td>
</tr>
<tr>
<td>Mold release</td>
<td>$ 10.00</td>
<td>$ 10.00</td>
<td></td>
</tr>
<tr>
<td>Urethane</td>
<td>$ 65.00</td>
<td>$ 65.00</td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td>$ 85.00</td>
<td>$ 85.00</td>
<td></td>
</tr>
<tr>
<td>Springform pans</td>
<td>$ 50.00</td>
<td>$ 50.00</td>
<td></td>
</tr>
<tr>
<td>Plastic sheeting</td>
<td>$ 1.00</td>
<td>$ 100.00</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>$ 10.00</td>
<td>$ 10.00</td>
<td></td>
</tr>
<tr>
<td>Wax</td>
<td>$ 10.00</td>
<td>$ 10.00</td>
<td></td>
</tr>
<tr>
<td>Labor for fixture ($50/hr, appx. 15 min. per fixture)</td>
<td>$ 12.50</td>
<td>$ 1,250.00</td>
<td></td>
</tr>
<tr>
<td>Labor for resin ($7.25/hr, appx. 2hr per set of lenses)</td>
<td>$ 14.50</td>
<td>$ 1,450.00</td>
<td></td>
</tr>
</tbody>
</table>

| Total                     | $ 4,465.00 |
| Total/unit                | $ 44.65    |

Cost vs. # of units

![Cost vs. # of units graph](chart2.png)

Chart 2 Cost Analysis
CHAPTER 6 SUMMARY

FUTURE CONSIDERATIONS
There are a few recommendations that could be used to further improve on the manufacturing process. First improvement would be the use of a master mold. Second would the use of different resin. Finally, would be the use of different plastic sheet.

Having a master mold results in repeatability in production and interchangeability of lenses. Therefore, if one lens were damaged, it would be possible to replace it, either from another set or by making a new matching one.

A faster curing resin means a faster curing time therefore faster production run. For instance, the UV curing resin, cures in about 20 minutes. Comparing to the current resin, which requires 24 hours to cure this UV curing resin allows the production of many more units at the same time frame. In addition, its dependency on UV to cure gives it greater control over its pot life.

CONCLUSION
The project is to improve a simple Adaptive Optics demonstration device by developing a more reliable manufacturing process for the distortion lenses and designing a lens fixture. Based on the problem analysis, it was determined that a more controlled manufacturing process is needed. Initially thermoforming was considered to be the solution. However, experimental results showed that the plastic breaks before it conforms to the shape desired. Finally, improving Dr. Chanan’s resin casting has been chosen as a manufacturing solution for making the lenses. Optical analysis showed that image quality is sensitive to the surface profile and to the gap separating the lenses. The gap depends on the shrinkage, therefore, by controlling the shrinkage better quality images are achieved. It is important to specify that the volumetric shrinkage causes the inherent mismatch between the lenses. Improving our sponsor’s manufacturing process, would be the best approach. By allowing first layer of resin must be fully cured before the second layer is poured, the shrinkage mismatch effect will be negligible. In addition to addressing the manufacturing problems, the lens alignment during the presentation is another concern addressed.

To improve the operation of the current demonstration device, we designed an alignment fixture to solve the manual alignment issue. The time it takes to align two mating lenses will be dramatically reduced. The alignment fixture is made from wood. Since wood can be purchased at very low cost and it is widely available, it was chosen as a building material. The estimated cost per demonstration device is estimated under $45, which is under our sponsor’s cost requirement of $75 per unit. As a conclusion, this project meets the needs of the sponsor.
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GLOSSARY

Adaptive Optics: refers to optical systems, which adapt to compensate for optical effects introduced by the medium between the object and its image.

Compression Molding: is a process, which is somewhat similar to forging of metal. A slug of heated raw plastic is placed on a mold cavity. A press pushes the partially molten plastic into the bottom half of the mold giving the desired shape.

Distortion: a change in lateral magnification versus distance from the optical axis.

Focal Length: the distance of a focus from the surface of a lens or curved mirror.

Focal point: In a spherical surface is the point at which incident parallel rays converge.

Hydrophilic: having a strong affinity for water absorption.

Injection Molding: a process used for creating repeated numbers of parts, which require equality in tolerance.

Longitudinal Spherical Aberration: The distance along the optical axis between the intercept of the rays which are nearly on the optical axis (paraxial rays) and rays which went through the edge of the lens (marginal rays) is called the Longitudinal Spherical Aberration.

Marginal ray: is the ray that just barely makes it through the optical system (farthest away from the optical axis).

Monochromatic Aberration-caused by the use of paraxial approximation, which assumes light rays intersect a single point, but this does not happen normally.

Optical Axis: is a straight line that lies in the center of any spherical surface or opening in optical systems.

Paraxial rays: are rays that take paths through the optical system, which are very similar to the path taken by the optical axis.

Plano-Concave: flat on one side and concave on the other

Plano-Convex: flat on one side and convex on the other

Plexiglas: (trademark)-- used for acrylic plastic sheets and molding powder

Probe: a usually small object that is inserted into something so as to test conditions at a given point

Resin: any of various solid or semisolid amorphous fusible flammable natural organic substances that are usually transparent or translucent and yellowish to brown, are formed especially in plant secretions, are soluble in organic solvents (as ether) but not in water, are electrical nonconductors, and are used chiefly in varnishes, printing inks, plastics, and sizes and in medicine

Resolution: refers to the sharpness and clarity of an image, and is measured by dots per inch (dpi).

Spatial voids: gaps created during the cooling process.

Tolerance: the allowable deviation from a standard; especially: the range of variation permitted in maintaining a specified dimension in machining a piece.

Transverse Spherical Aberration: The difference in the height at which the rays that intercept the paraxial focal plane called Transverse Spherical Aberration.

Turbulence: irregular atmospheric motion especially when characterized by up-and-down currents.
APPENDIX A: ADAPTIVE OPTICS DEMO. PROCEDURE

“Instructions for using the static AO demo:

With the lights off on the overhead projector, place the transparency on the glass in the usual way. The projector should have been focused in advance. [The spherical aberration due to the aberrator and corrector is not significant.] I included a transparency with the words ADAPTIVE OPTICS, but you may prefer the Center logo or something else. Place the plastic ring on top of the transparency and then one of the two aberrating lenses, flat side down, on the plastic ring. Having the plastic spacer ring between the transparency and the aberrator scrambles the image better. Note the arrow on the aberrator. Turn on the light on the overhead projector. The image on the screen should be sufficiently scrambled that you can barely tell that there are words under there.

Locate the matching arrow on the other aberrating lenses (now the corrector) and place it on the aberrator, wavy side to wavy side, so that the arrows line up. You may have to rotate the corrector slightly so that it falls into place.”
APPENDIX B: DR. CHANAN PRODUCTION PROCEDURE

"Making the static AO display

The AO display consists of a "positive" and a "negative." The positive has one smooth surface and one aberrated surface. The negative has an aberrated surface that exactly matches the positive, such that when you mate the positive and negative the aberrations disappear when viewed on an overhead projector. To make this display, use EP4101 crystal resin with catalyst EP4920. First pour the resin (300-400 ml) into a pan (8-inch non-stick circular baking pan) to create a positive about 1 inch thick. Then place a plastic sheet (part of a zip-loc bag, cut into a single sheet) over the positive. Make sure there are no air bubbles in between, and spread the plastic sheet over the entire surface of the positive (which is still in liquid form). Create aberrations by pressing down slightly on the plastic sheet in various places. Initially the resin just straightens it out because it's still a liquid; but after a few minutes, the resin will start to accept the aberrations. It will start to harden. At this point we pour the resin for the negative directly over the plastic sheet (200-400 ml). It is interesting to see the aberrations completely disappear at this point. Now you have 2 layers of semi-liquid resin sandwiching a layer of a plastic sheet. One more step: because the negative will actually dry somewhat aberrated if left alone, you need to enforce a strictly level top to the negative. To do this, place an acetate sheet over the liquid negative. You will need to be careful about air bubbles, and the spillage (the acetate sheet might be somewhat submersed by the liquid). That's the basic outline.

Use EP4101 crystal resin with catalyst EP4920. This resin hardens to a clear plastic. After mixing 10 drops of catalyst to every fluid ounce (30 ml) of resin, the resin stays in a stir able liquid form for about 8 minutes. After 12 minutes, it starts to harden to something like really thick syrup. At this point, if you stir it, you won't be able to get rid of streaks caused by the stirring rod. A few minutes later it's quite hard (obviously you should let it cure longer though; the instructions say overnight). The problem is to have the "positive" harden just enough such that aberrations will stay, yet have the negative still be in liquid form at that point so you can pour it over the positive. On the other hand, you should mix the negative solution as soon as possible after mixing the first solution because you want to minimize the amount of negative shrinking as it dries. If you mix the negative solution long after the positive solution has begun to dry, the positive will have shrunk already, and the negative will shrink after being poured on top of the positive. This will reveal the aberrations (in some places) to an unacceptable amount. Thus, you have to stick to an exact, pre-planned schedule. Here is my best schedule. It takes about 45 seconds to count 130 drops of catalyst. It takes 1 to 2 minutes to stir. It takes ~45 seconds to pour resin into the pan.