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Development of a Miniaturized Otoscope for Middle Ear Diagnostics by High Speed Holography

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Development of a Miniaturized Otoscope for Middle Ear Diagnostics by High Speed Holography

A Major Qualifying Project Proposal Report

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

In Mechanical Engineering

By

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Date: April 26, 2018

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Professor Cosme Furlong
In the United States, 17% of the adult population suffers from hearing loss. However, the diagnostic tools available to clinicians are imperfect and therefore make diagnosing middle-ear diseases extremely challenging. WPI’s CHSLT in collaboration with Massachusetts Eye and Ear Infirmary is developing a high-speed holographic system to provide physicians with a tool capable of shape and displacement measurements of the tympanic membrane (TM) with nanometer-scale resolution. We developed an optical head for the system with a 10 mm field-of-view, a 5 mm depth-of-field, and miniaturized optics to visualize the entire TM through an intact ear canal. The prototype was developed using advanced optical design and analysis tools, validated and tested on a controlled sample, and finally integrated into the high-speed holographic system for measurements on a post-mortem human TM. The prototype met all design specifications and is successfully integrated into the system for future otologic research.
SIGNIFICANCE

The tools available for diagnosing ear pathologies are extremely limited. Most tools only provide qualitative data on the ear’s condition. Although several technologies already can diagnose middle ear pathologies based on the tympanic membrane’s condition, there is currently no technology that can provide quantitative data on the movements of the entire eardrum. Quantitatively studying tympanic membrane movements could potentially provide a new diagnostic avenue for clinicians. This project aims to bring quantitative measurements of the entire tympanic membrane closer to a reality.

Digital holography could potentially fulfill some of these needs in the otology field. Holography provides full fields of view, real-time measurements, and nanometer resolutions of the tympanic membrane’s motion. Worcester Polytechnic Institute currently has a state of the art high-speed holography system that has been used collect shape and displacement measurements on several chinchilla and cadaver tympanic membranes in their Center for Holographic Studies and Laser Micro-mechatronics (CHSLT). The resulting prototype from this project will be integrated into the high-speed holography system to improve its imaging capabilities. Ultimately, by continuing to develop this system, doctors will have access to numerical data to assist them in their diagnoses and remove the ambiguity currently involved with diagnosing middle ear disorders.
ACKNOWLEDGEMENTS

This project team would like to thank Professor Furlong for his advice, expertise, support, and drive. It has been the team’s honor to work alongside such a brilliant leader, teacher, and coordinator. He pushed the team to produce the best work possible and provided us with priceless opportunities that are not typically available to undergraduate students. Next, the project team would like to thank Payam Razavi, Haimi Tang, Anthony Salerni, Koohyar Pooladvand, and the rest of the graduate students working in the Center for Holographic Studies and Laser mecha-Tronics for always making time to assist our undergraduate team and guiding us towards our success.

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1 PROJECT SCOPE

1.1 GOAL STATEMENT

The WPI Center for Holographic Studies and Laser mechatronics (CHSLT) has been developing a high-speed holographic system for over a decade to provide physicians with a diagnostic tool capable of shape and displacement measurements of the tympanic membrane (TM). The system requires further developments in order to bring this technology into clinics. These developments include a larger depth of field to minimize positioning time and a miniaturized optical head to improve access to the TM by allowing insertion into the ear canal. The goal of this project was to develop an otoscope head that meets these requirements and can be integrated into the existing system.

1.2 OBJECTIVES

The main objectives of this project include:

1. Perform Background Research to Determine Design Specifications for Optical Head
2. Conduct Preliminary Imaging to Select the Ideal Optical Configuration
3. Design and Optimize the Optical Head Using the Optical Software, Zemax
4. Validate the Prototype by Comparing Experimental Data Collected on a Known Copper Sample to Computational and Analytical Data
5. Perform Imaging on Post-Mortem Tympanic Membrane
6. Assess the Effectiveness of the Configuration and Provide Suggestions for Future Improvements
2 Background

2.1 The Ear

2.1.1 The Process of Hearing

The process of hearing begins in the outer ear, where the pinna funnels sound into the ear canal. This process amplifies the sound by the concept of the inverse square law; this law says that the intensity of sound is inversely proportional to the distance away from the sound’s source [1]. The process of traveling past the pinna and through the ear canal amplifies the sound by a factor of approximately two [1]. Next, the sound waves traveling through the ear canal strike the tympanic membrane and the sound waves transition from their original gas medium (air) to a solid medium (the tympanic membrane). The vibrating tympanic membrane (TM) connects the outer and middle ear and its purpose is to pass on the induced vibrations from sound waves to the three middle ear bones (more commonly known as the ossicles): the malleus, incus, and stapes. The ossicles act in the middle ear as linkages and transfer the vibrations from the tympanic membrane to the oval window (the beginning of the inner ear). The layout of the middle ear region can be seen in Figure 2-1.

![Figure 2-1: Auditory System Including the Outer, Middle, and Inner Ear [2]](image)

The oval window has a similar function to the tympanic membrane; however, it is about 18.6 times smaller than the TM [4]. The oval window is the transition from the air-filled middle ear to the fluid-filled cochlea. The size difference between the tympanic membrane and the oval window, as well as the ossicle amplification of the acoustic energy causes the pressures on
the oval window to be much higher than the pressures on the tympanic membrane. This is due to the formula for pressure: Pressure=Force/Area. The movement through the ossicles amplify the vibrations by a factor of 1.3. Therefore, the pressure at the oval window according to the equation (with the area equal to 1/18.6), is about 24.2 times greater than the pressure felt on the tympanic membrane [5].

The vibrations of the oval window cause the fluid in the cochlea to travel and stimulate the hair cells lining the cochlea. The movements of these hair cells produce synaptic activity which induces action potentials that travel to the brain.

2.1.2 Hearing Capabilities and Hearing Losses

The range of hearing for a healthy individual is 20 to 20,000 Hz [6]. Humans have a dynamic range of hearing, with the threshold of hearing being 0 dB and the threshold of pain being 130 dB [1]. Decibels can easily be converted into sound pressure levels (or SPLs) by the following equation [10]

\[
\text{SPL} = 20 \times \log_{10} \left( \frac{p}{p_{\text{ref}}} \right) \text{ dB},
\]

where \( p \) is the sound pressure being measured and \( p_{\text{ref}} \) is the reference (the smallest sound pressure humans can hear – 2.0 *10^{-5}). Table 2.1 shows examples of SPLs and dB levels for common daily noise exposures.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sound Pressure (Pa)</th>
<th>Sound Pressure Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf rustling</td>
<td>0.0000632</td>
<td>10</td>
</tr>
<tr>
<td>Normal conversation</td>
<td>0.01</td>
<td>54</td>
</tr>
<tr>
<td>TV set at home</td>
<td>0.02</td>
<td>60</td>
</tr>
<tr>
<td>Passenger car as heard from roadside</td>
<td>0.1</td>
<td>74</td>
</tr>
<tr>
<td>Jack hammer</td>
<td>2.0</td>
<td>100</td>
</tr>
<tr>
<td>Jet engine as heard from 100 yards</td>
<td>100</td>
<td>134</td>
</tr>
<tr>
<td>Extremely loud rock band</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>Jet engine as heard from 1 yard</td>
<td>630</td>
<td>150</td>
</tr>
</tbody>
</table>

In the United States, 17% of the adult population suffers from some form of hearing loss [11]. Conductive hearing loss occurs in the outer and middle ear and can be caused by several factors such as infection, blockages, or trauma. The scale of the severity of hearing loss is shown in Table 2.2.
Table 2.2: Scale of Hearing Loss Severity Based on Sound Pressure Levels [12]

<table>
<thead>
<tr>
<th>dB Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 to 15</td>
<td>Normal Hearing</td>
</tr>
<tr>
<td>16 to 25</td>
<td>Minimal Hearing Loss</td>
</tr>
<tr>
<td>26 to 40</td>
<td>Mild Hearing Loss</td>
</tr>
<tr>
<td>41 to 55</td>
<td>Moderate Hearing Loss</td>
</tr>
<tr>
<td>56 to 70</td>
<td>Moderately Severe Hearing Loss</td>
</tr>
<tr>
<td>71 to 90</td>
<td>Severe Hearing Loss</td>
</tr>
<tr>
<td>91 +</td>
<td>Profound Hearing Loss</td>
</tr>
</tbody>
</table>

There are two types of hearing loss: sensorineural and conductive hearing loss. This project will only deal with conductive hearing loss because sensorineural hearing loss is due to damage or disease in the inner ear. Sensorineural hearing loss develops due to inner ear damage, specifically, when the hair cells inside the cochlea are lost due to aging, damage, or disease. Once the hair cells die, the sound waves delivered to the cochlea can no longer be converted into electrical signals that are sent through the auditory nerve to the brain [11].

### 2.1.2.1 Conductive Hearing Loss

Interference of the acoustic energy propagating through the ear is the cause of conductive hearing loss [11]. This mechanical interference can be anything in the outer or middle ear that prevents the sound waves from traveling conventionally through the ear canal and middle ear. Conductive hearing loss is typically temporary and can be resolved with antibiotics or surgical measures.

Some obstructions include cerumen (otherwise known as earwax), foreign bodies, or bony lesions in the ear canal. These obstructions typically can be removed by medical personnel and do not require surgery. Even though these obstructions seem minor, they hinder the path of the acoustic energy traveling through the ear and require removal. Infections, allergies, and otitis media (more commonly known as an ear infection) can cause fluid buildup or effusion inside the middle ear. This effusion can minimize sounds by as much as 30-40 dB, which causes conductive hearing loss [13].

Otosclerosis is another disease that causes conductive hearing loss. It is caused by bone remodeling within the middle and inner ear; typically, this remodeling causes stapes fixation and does not translate proper vibrations to the oval window [14]. Anything from a perforation of the tympanic membrane, a dislocation of an ossicle, or a foreign body inside the ear canal is classified as conductive hearing loss since it hinders the propagation of sound waves through the ear.

### 2.1.3 The Tympanic Membrane

The tympanic membrane can be broken into different sections (as shown in Figure 2-2). The two main components of the tympanic membrane are the pars tensa and the pars flaccida. The pars flaccida is the very top portion of the membrane and its purpose is to maintain air pressure equilibrium between the outer and middle ear. The rest of the membrane is called the pars tensa. This section houses the umbo which is the center section of the membrane and
connects to the malleus [4]. Table 2.3 shows the physical characteristics of the tympanic membrane.

![Diagram of the Middle Ear](image)

**Figure 2.2:** Left: Middle Ear Elements Starting from the Tympanic Membrane, Left, to the Inner Ear, Right [3] Right: Elements of the Tympanic Membrane Separated into Quadrants Based on Function [5]

**Table 2.3: Physical Characteristics of the Tympanic Membrane**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Axis (average width of TM)</td>
<td>9-10 mm [6]</td>
</tr>
<tr>
<td>Vertical Axis (average height of TM)</td>
<td>8-9 mm [6]</td>
</tr>
<tr>
<td>Surface Area</td>
<td>Pars Tensa: 62.1 mm²</td>
</tr>
<tr>
<td></td>
<td>Pars Flaccida: 3.3 mm²</td>
</tr>
<tr>
<td>Density</td>
<td>1.2 * 10⁴ kg/m³ [8]</td>
</tr>
<tr>
<td>Thickness</td>
<td>Pars Tensa:</td>
</tr>
<tr>
<td></td>
<td>• posterosuperior: 100 – 500 μm</td>
</tr>
<tr>
<td></td>
<td>• posteroinferior: 20 – 200 μm</td>
</tr>
<tr>
<td></td>
<td>• anterosuperior: 50 – 340 μm</td>
</tr>
<tr>
<td></td>
<td>• anteroinferior: 30 – 430 μm</td>
</tr>
<tr>
<td></td>
<td>Pars Flaccida: 80 μm – 600 μm</td>
</tr>
<tr>
<td></td>
<td>Umbo: 820 – 1700 μm</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>Pars Tensa: 3.34 * 10⁷ N/m² [8]</td>
</tr>
<tr>
<td></td>
<td>Pars Flaccida: 1.11 * 10⁷ N/m² [8]</td>
</tr>
</tbody>
</table>

### 2.2 Existing Diagnostic Technologies

Hearing loss is one of the most common disabilities however, the technologies available to diagnose the ear are limited. Most of the existing technologies provide qualitative data on the pathology in the ear, but doctors have been seeking quantitative diagnostic tools to allow for consistency and accuracy in their diagnoses. Although there are several different diagnostic technologies, this report will only discuss the technologies relevant to the team’s research.
2.2.1 Otoscopes

The most common technology used to inspect the tympanic membrane is the otoscope. The otoscope is a handheld device that allows a doctor to look into the ear canal of a patient [14]. The otoscope is comprised of two main components, the handle and the head. The handle contains the bulb, which shines directly upward toward the otoscope head and acts as the illuminating mechanism. The light is able to be directed from the middle of the handle to the ear canal using fiber optic technology [16]. The head of the otoscope contains the lens (or lenses) that allows the doctor to view the illuminated eardrum.

There are three main otoscopes currently being used in the field. The first is a pocket otoscope. These are handheld devices and the most generic type of otoscope. The next otoscope is the full-sized otoscope, which operates similarly to the pocket otoscope but also has interchangeable heads. The pocket and full-sized otoscope require the doctor to peer through a lens to look into the ear canal. The last otoscope is the video otoscope. The video otoscope is directly connected to a TV or computer monitor to display images and videos of the tympanic membrane [16]. Within each type of otoscope, there are several different head attachments, as explained in Table 2.4.

<table>
<thead>
<tr>
<th>Head</th>
<th>Description</th>
<th>Diagram</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostic</td>
<td>Backlight lens that allows for 2.2x magnification and wide angle viewing of the ear canal and TM</td>
<td><img src="image" alt="Figure 2-3: Diagnostic Otoscope Head" /></td>
<td>Allows doctor to see blockages in the ear canal or visual abnormalities of the TM</td>
</tr>
<tr>
<td>Head</td>
<td></td>
<td><img src="image" alt="Figure 2-3: Diagnostic Otoscope Head" /></td>
<td></td>
</tr>
<tr>
<td>Pneumatic</td>
<td>Similar to diagnostic head, but also has an air bulb attached to the lens and tip. This air bulb puffs air into the ear canal to allow the doctor to study the movements of the TM</td>
<td><img src="image" alt="Figure 2-4: Pneumatic Otoscope Head" /></td>
<td>If the doctor observes very little or no tympanic membrane movement, it is usually indicative of fluid inside the middle ear</td>
</tr>
<tr>
<td>Head</td>
<td></td>
<td><img src="image" alt="Figure 2-4: Pneumatic Otoscope Head" /></td>
<td></td>
</tr>
</tbody>
</table>
0.5 mm  

Figure 2-5: Operating Otoscope Head [16]

Figure 2-6: Video Otoscope Head [16]

<table>
<thead>
<tr>
<th>Operating Head</th>
<th>This head is designed specifically for completing ear canal and tympanic membrane procedures because surgical tools can be passed through the head [16]</th>
<th>Allows for magnification of the TM as well as surgical assistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video Head</td>
<td>This head is used has a much higher resolution than the diagnostic head (150x magnification) and can be connected to a computer to save videos and photos of the specimen [16]</td>
<td>Higher magnification and recordable data collection</td>
</tr>
</tbody>
</table>

Otoscopes only allow the doctor to observe the motion or appearance of the eardrum. They do not provide the doctor with quantitative data and the diagnoses are based off of assumptions from the doctor.

2.2.2 Endoscopes

Endoscopes are optical devices that could be used to image the middle ear but are currently not used frequently. They are either flexible or rigid tubes with an eyepiece on one end and an objective lens on the other end to image the sample. A series of Gradient Index (GRIN) lenses transfer the image from the objective lens to the eyepiece of the endoscope. Meanwhile, a ring of illumination fibers typically surrounds the optics in order to provide light inside the body. A typical endoscope setup can be seen in Figure 2-7.

Endoscopes come in a variety of sizes and shapes, however they only provide an image to the clinicians and therefore cannot provide numerical data. Endoscopes typically come with extremely small working distances and small fields of view.
2.3 INTERFEROMETRY

2.3.1 Principles of Interferometry

Interferometry is an optical measurement technique that is designed to measure multiple experimental parameters such as vibrations and velocities. Tympanic membrane research uses this tool to measure the displacements of the eardrum after acoustic excitation. Interferometry utilizes the splitting and recombination of light beams (the interference of light), to make these measurements [19].

A traditional interferometer uses five main components. The light source sends a single light beam to a beam splitter. The two beams that are created from this splitter are known as the “reference” beam and the “object” beam. The reference beam remains untouched as it reflects off a mirror and towards the beam splitter [19]. The object beam is directed toward the sample surface, reflected off, and is recombined with the reference beam at the beam splitter [19]. The recombined beam now has a phase difference that can be analyzed by the detector [20]. This process creates an interference pattern. Interferometry requires the use of coherent light as the illumination source. Coherent light is used in interferometry because the wavelengths produced by a laser are all parallel to each other. Therefore, when the object beam recombines with the reference beam, it produces interference fringes which can be transformed into images. The challenge of using coherent light is it produces a speckled image.
This reduces the resolution of the image when captured by a camera. Figure 2-8 shows a basic Michelson interferometer setup.

![Diagram of Michelson Interferometer Setup](image)

Figure 2-8: Diagram of Michelson Interferometer Setup [20]

The differences in the phase between the two separated beams can be detected because they produce noticeable differences in the interference pattern. These interference patterns are known as “fringes” [20]. These fringes are light and dark patterns produced by the changes in phase that the detector picks up between the two beams that were recombined [19]. The fringe patterns show the movement of the surface. The accuracy of interferometry is dependent on the wavelength of the light but can measure to the resolution of nanometers [19].

### 2.3.2 Holography

Holographic systems utilize the concepts of interferometry to allow researchers to collect shape and displacement measurements of the specimens. Holography allows the observer to be able to see the foreground and background in one shot, just by adjusting the camera focus. The length to which the camera can be adjusted while staying in focus is called the depth of field. An example of depth of field is displayed in Figure 2-9.

Currently, in the lower speed holographic systems at WPI, a holographic software called Laser View is used to process images from the sensor. LaserView is a program that utilizes the three imaging types. They are Live, Double Exposure, and Time Averaged. The live view is the typical camera view, meanwhile double exposure and time averaged modes are holographic viewers. The higher-speed systems require MATLAB codes to create the holographic images since LaserView is not equipped for the high-speed cameras.
2.3.2.1 Double Exposure Holography

The key feature to holography, as described previously, is the difference in the phase of the two beams. Double exposure holography is able to determine the deformation of an object. Double exposure holography calculates the difference in the phase difference between the original beam and a second beam that undergoes a stimulus. This stimulus can be noise from a speaker or physical movement caused by a piezo shaker. The first light will be shown on an undeformed surface of an object, then the object is deformed and a second light hits the object [24]. This process is shown visually in Figure 2-10.

The following formula shows how the basic idea for the determination of displacement due to a force

\[ 2d = m\lambda, \]

where \( \lambda \) is the known wavelength, \( d \) is the amount of deformation in the surface, and \( m \) is a constant integer equal to the number of bright fringes produced by the surface. This formula is used to calculate \( d \) [24].
To conduct the full calculations for finding the displacement due to a force the object beam and reference beam must be calculated using the following formulas [25]

Object Beam: \( F_0 = A_0 e^{i(\phi_0 + \theta_0)} \),

Reference Beam: \( F_r = A_r e^{i\phi_r} \),

where \( A \) is the amplitude of the beams, and \( \phi \) is the phase of the beam. To determine the intensity of the wave front at any frame, \( I_0 \), the following computation is performed [25],

\[
I_n = (F_o + F_n)(F_o + F_n)^* = A_o^2 + A_r^2 + 2A_oA_r \cos((\phi_o - \phi_r) + \Delta \theta_n),
\]

where ( )* indicates complex conjugated. The following formula characterizes phase changes, \( \Omega \), after the object has undergone deformations [25],

\[
\Omega = 2\pi m = (K_2 - K_1) \cdot L = K \cdot L,
\]

where \( K_1 \) is the vector of illumination, \( K_2 \) is the vector of observation, \((K_2 - K_1)\) is the sensitivity vector, and \( L \) is the displacement vector. To determine the intensity of the wave fronts after the object has been deformed, at any frame, \( I'_n \), the following computation is performed

\[
I'_n = I_o + I_r + 2A_oA_r \cos(\Delta \phi + \Omega + \Delta \theta_n).
\]

This is an important concept because holography was originally created to determine the shape of an object, but by developing double exposure holography it allows researchers to determine the change in position of an object due to forces applied to it. For the ear, it means it can determine the displacement of the tympanic membrane when it is exposed to sounds of different amplitudes and frequencies.

### 2.3.2.2 Time Averaged Holography

Time average holography is advantageous in situations when researchers want to measure the vibrations of a surface all at the same time. This technique can quantitatively measure vibration amplitudes at the magnitude of \(10^{-7}\) meters [26]. The change in the displacement across the entire area is measured. The reflection of light across the entire surface is compared to the reference wave and this is used to determine the displacement of the surface. Mathematically the light field is shown by the following formula [25]

\[
F_t(x, y, z) = A_t(x, y, z) e^{i\phi_t(x, y, z)},
\]

where \( A \) is the amplitude, \( \phi \) is the phase, and \( F \) is the light field. This formula is also used when capturing the reflection off the object [25],

\[
F_o(x, y, z) = A_o(x, y, z) e^{i\phi_o(x, y, z)},
\]

The displacement of the object with respect to all three dimensions and time is as follows,

\[
L_t(x, y, z, t) = L_o(x, y, z, t) \cos(\omega t),
\]

\( L \) is the deformation of the object in \((x, y, z, t)\), \( t \) is time, and \( \omega \) is the frequency of vibration. Another important quality to consider is the intensity distribution function,
\[ I_t(x,y,z,t) = I_o(x,y) + I_r(x,y) + 2A_o(x,y)A_r(x,y)\cos[\Delta\phi(x,y) + \Omega_r(x,y,t) + \Delta\theta_n]. \]

The camera records intensity over a given period of time and this formula can be derived to determine the intensity as a function of \( x \) and \( y \) as follows

\[
I(x,y) = \frac{1}{\Delta t} \int_t^{t+\Delta t} I_t(x,y,t) dt.
\]

Measuring an entire surface at once shows how different parts of the tympanic membrane react. For this reason, when measuring shape under a stimulus, Time Averaged is the desired mode. This can improve tympanic membrane diagnostics by not only determining if the membrane is reacting accurately but also by identifying what parts of the membrane are diseased.

2.3.3 Current CHSLT Systems

The following holographic system is the current setup used in CHSLT. This is the system that, at the end of this project, integrates the team’s optical head. The existing holographic system was designed to measure tympanic membrane responses to acoustic clicks and other induced sounds.

The system used to measure the response of the tympanic membrane is instrumented in Figure 2-11. The process begins when a 532 nm laser is sent through a beam splitter. The reference beam illuminates the camera detector and the object beam is directed towards the specimen, the temporal bone. A telecentric lens captures the irradiance reflected off the temporal bone and recombines with the reference beam. The interference between the two beams is recorded by the SA-Z High-Speed Camera.

To prepare the temporal bones for measurement, the ear canals must be removed, along with the inner ear and stapes. Remaining in the specimen is: the TM, tympanic ring, the malleus, incus, and supporting ligaments. To increase reflectivity of the surface, the researchers typically paint the tympanic membrane with a zinc oxide (ZnO) solution.
To measure displacements of the tympanic membrane, acoustic impulses, or clicks, generated by 50 microsecond square voltage, pulse through a power amplifier. This is sent to the lateral side of the TM via a loudspeaker.

The SA-Z high-speed camera used in the experiments has the capabilities to allow for frame rates to range from 7,000 fps at full resolution to $10^6$ fps at a reduced resolution of around 1000 pixels. For experimental purposes, the camera was set to 42,000 fps at 384 x 384 pixels. The desired spatial resolution was around 22 microns per pixel and a temporal resolution of less than 24 microseconds for 25 ms after stimulus. One constraint that remained when considering camera settings was that the displacement resolution and floor noise was about 10 nm.

Currently, Worcester Polytechnic Institute and Massachusetts Eye and Ear Infirmary are gathering measurements on both cadaver tympanic membranes and chinchilla tympanic membranes. However, to have the ability to gather measurements on cadaver tympanic membranes, the temporal bone must be surgically removed from the skull, and the ear canal entirely removed. To be able to bring this technology to clinics and hospitals around the world, the contributors to this research must find a way to gather measurements without performing massively invasive procedures to patients. This project addresses these problems by designing a diagnostic head for this holographic system.

2.3.3.1 Other Holographic Systems in the CHSLT Lab

Since the high-speed system was being used for doctoral research, another system was used for the MQP work. This system was equipped with a PIKE 505 Camera and therefore lacked the high-speed capabilities. The MQP group used this system for preliminary imaging and validation purposes, however the final imaging of the post-mortem TM was performed with the high-speed system. Also, the team designed their prototype to fit the high-speed system camera’s sensor size. This lower speed system is called, ‘Holo 2’.

Holo 2 is a holographic interferometry system that has components packaged in a clear, sound/vibration limiting box. Within this box, there is a 532 nm laser that is split into the reference and object beams. These beams are coupled into fiber optic bundles that are then brought outside of the box to be used for imaging. The couplers can be misaligned within the box to increase or decrease the intensities of either beam as desired. This feature can be used to adjust for a proper reference to object beam ratio. There are also shutters within the system that can be toggled on and off using the imaging software.

2.3.3.2 Major Differences Between Holo 2 and the High-Speed System

In order to implement this project’s prototype from the experimental holographic interferometer system (Holo 2) to the current CHSLT system, there were some considerations and changes that needed to be accounted for in order to successfully make a transition.

To begin, the two interferometer systems use two different cameras, and therefore have different sensor sizes. The camera used for Holo 2 was a Pike 505 Megapixel. This camera has a maximum resolution of 2452 x 2054 with a pixel size of 3.45 microns x 3.45 microns, this approximates to about a 7 mm x 8 mm sensor size. This camera has a maximum frame rate of 14 fps. The current CHSLT holographic system is using a Photron FASTCAM SA-Z high speed
camera. The SA-Z high speed camera has a resolution of up to 1024 x 1024 pixels, 20-micron pixel size, and a sensor size of 25.4 mm x 25.4 mm. The SA-Z camera can also image up to 21,000 fps. However, the software equipped to the high-speed system can only handle 512 x 512 pixels at 60,000 fps.

Since the prototype would be implemented into the high-speed system, the team designed the system for the SA-Z’s sensor size. This meant that the field of view would be ‘cropped’ when imaging on the PIKE Camera. Another difference between the two systems were the software used to execute the holography. When using Holo 2 for testing, CHSLT has a software specifically tailored to completing holographic measurements, it is called LaserView. The current system does not have this software due to the high-speed capabilities of the SA-Z and therefore requires Matlab code to complete the post processing and analysis.

2.4 Design Specifications

The purpose of performing the biological and interferometry research was for the team to establish design requirements for the design phase. First, the team established the preliminary design specifications by using the biology of the ear. The objective lenses of the device must be small enough to fit into the human ear canal, which averages approximately 7 mm in diameter. Therefore, the lenses, illumination fiber, and casing of the optics must all be less than the 7 mm limit. The team cannot design an exactly 7 mm prototype because then the device would seal the ear canal and the acoustic clicks would not be able to travel to the tympanic membrane. The field of view of the design should be 10 mm by 10 mm to ensure it can capture the entire tympanic membrane. The depth of field of the design should be at the bare minimum 2 mm because of the tilt of the tympanic membrane inside the ear. However, the team determined that it should be greater than 4 mm to ensure for easier positioning of the device.

From the interferometry research and by investigating the tools available in the lab, the team devised the following design specifications. The current high-speed system has a resolution of about 8 lp/mm, and therefore the team must design an optical head with a resolution of at least 8 lp/mm. The pixel size of the team’s camera is 20 µm with a resolution of 1024x1024 [26]. However, the current holographic system is only capable of using 512 x 512 of the sensor in order to maintain high speed measurements. 512 x 512 with a pixel size of 20 micrometers yields a sensor size of approximately 12.7 mm x 12.7 mm, and therefore the team will design for a sensor size of this magnitude. Also, the team must ensure that the relay lens must have a long focal length to ensure that there is enough room for the team to place a beam splitter or simply the reference beam.

In order to complete this project in the required time frame, all of the optics introduced must be off-the-shelf optics. Creating custom optics is not only time consuming, but also expensive. This project will only utilize parts that are widely available from Optics Manufacturers such as: Edmund Optics and Thorlabs.
3 METHODOLOGY

3.1 PRELIMINARY IMAGING

As mentioned in Chapter 2, there are several technologies available to image the tympanic membrane. In this section, the project team will compare their results from imaging with three different technologies: a Fujikura Fiber Bundle, a Karl Storz Endoscope, and a Welch Allyn Otoscope. The team obtained images and holograms using each of the devices to determine which optical configuration was suitable to proceed into the optical design phase.

3.1.1 Fiber Bundles

The project team used the FASTCAM SA5 in conjunction with a 10K fiber bundle to gather preliminary images. The team imaged a USAF target using the fiber bundle with coherent light. Lasers utilize coherent light; meanwhile white light is considered incoherent light. The entirety of this project will image strictly using coherent light sources. The team used the collected images of the USAF target to calculate the setup’s imaging resolutions. The SA5 FASTCAM utilizes a light sensitivity of 10,000 monochrome and 4,000 colors. It also contains a CMOS sensor with a 20-micrometer pixel size [28]. The green laser used as the coherent illumination source had a wavelength of 532 nm and a power output of 300 mW.

The setup of the components had the fiber bundle connected to the SA5 camera via a C-mount. The distal end of the fiber was then mounted in front of the USAF Target. First, the team took images of a 10 mm by 10 mm portion of the USAF target. This area was chosen to simulate the area of the tympanic membrane. However, these fiber bundles are designed for small working distances and small fields of view. Therefore, better resolution is achieved when you minimize the working distance and in turn, minimize the field of view. The team took images of the 10 x 10 range (9 mm working distance), then of the 2-3 grouping (5 mm working distance), then of half of the 2 group (4.5 mm working distance). An example of the USAF target is shown in Figure 3-1, the green box represents the 10mm x 10mm trial, the red box highlights the 2-3 group, and the blue box represents the portion of the 2 group. The team conducted three trials, as shown in Table 3.1.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Working Distance</th>
<th>Portion of USAF Imaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>4.5 mm</td>
<td>Half of Group 2</td>
</tr>
<tr>
<td>Trial 2</td>
<td>5 mm</td>
<td>Groups 2-3</td>
</tr>
<tr>
<td>Trial 3</td>
<td>9 mm</td>
<td>10 x 10 mm FOV</td>
</tr>
</tbody>
</table>
The team used the images collected of the USAF target to calculate the resolution of the fiber bundle. The resolution is the highest density of lines that can be seen by the operator using the system.

The patterns, as seen in Figure 3-1, come in pairs of vertical and horizontal lines. Each pair is called an element and a collection of elements are sorted into groups. Once the limiting resolution, or smallest element that can be distinguished, the image resolution is calculated using the formula \[ R = 2^{K + \frac{N-1}{6}} \],

where \( K \) is the group number and \( N \) is the element number. This formula provides the resolution in line pairs per millimeter (lp/mm). Table 3.2 shows the collected images and calculated resolutions of each trial.

Figure 3-1: USAF Target Used to Characterize Spatial Resolution of an Imaging System.
The Added Squares Highlight Different Levels of Resolution
Table 3.2: Preliminary Images using 10K Fujikura Fiber Bundles and SA-5 FASTCAM

<table>
<thead>
<tr>
<th>Trial</th>
<th>Collected Image</th>
<th>User Determined Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td><img src="image1" alt="Image" /></td>
<td>0 lp/mm</td>
</tr>
<tr>
<td>Trial 2</td>
<td><img src="image2" alt="Image" /></td>
<td>4 lp/mm</td>
</tr>
<tr>
<td>Trial 3</td>
<td><img src="image3" alt="Image" /></td>
<td>4.49 lp/mm</td>
</tr>
</tbody>
</table>
Although the images improved as the team moved the fiber bundle closer to the target, the overall quality of these images was poor. There seemed to be significant barrel distortions in the images and each had extremely low resolution. The team decided from this preliminary imaging that the fiber bundles would not be an avenue to pursue for the optical design phase.

3.1.2 Endoscopes

The team utilized several different endoscopes in their preliminary imaging. However, the imaging quality from the Karl Storz Hopkins 26033 AP model was superior. Table 3.3 shows its preliminary imaging versus the other endoscopes tested. For this phase, the team developed a Matlab code that would determine resolution of the images.

Table 3.3: Preliminary Images using Various Endoscopes and SA-5 FASTCAM

<table>
<thead>
<tr>
<th>Endoscope Model Used</th>
<th>Image Collected</th>
<th>User Determined Resolution</th>
<th>Matlab Determined Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storz Hopkins 26033 AP</td>
<td><img src="image1.png" alt="Image" /></td>
<td>8 lp/mm</td>
<td>6.35 lp/mm</td>
</tr>
<tr>
<td>Storz Hopkins 8702 D</td>
<td><img src="image2.png" alt="Image" /></td>
<td>4.49 lp/mm</td>
<td>4.49 lp/mm</td>
</tr>
</tbody>
</table>
It is evident from that table that the imaging quality produced by the 26033 AP Endoscope was superior. Therefore, the team proceeded with that model. A picture of the model is shown in Figure 3-2. Endoscopes function using an objective lens at the proximal end of the device and then a series of Gradient Index (GRIN) Lenses through the length of the device, and then an eye piece at the distal end. In order to equip this device to a camera, a relay lens must be attached to the distal end of the device.

The team utilized the endoscope to gather images using coherent illumination and the SA5 camera, and then collected holographic images using the PIKE Camera. The holography setup of the system can be shown in Figure 3-3 and Figure 3-4. The resolution provided was 8 lp/mm with a working distance of 14 mm and a FOV of 10mm x 10mm. The holography performed was on a latex membrane with a 10 mm x 10 mm square traced onto the surface. The best hologram acquired by the team is shown in Figure 3-5.
Figure 3-3: Endoscope Setup to Capture Preliminary Holographic Image of an Artificial Sample

AOM  Acousto-optic Modulator
BS   Beam Splitter Cube
M    Mirror
C    Fiber Coupler
OBJ  Object Beam
SAMPLE Artificial Sample
OBJ   Objective Lenses
GRIN  GRIN Lenses
EP    Eye Piece
REL   Relay Lens
REF   Reference Beam
D    Detector

Figure 3-4: Optical Schematic of Endoscope Setup
Although the images collected showed decent fringes, the endoscope provided the team with several challenges and concerns with carrying this optical configuration into the design phase. Endoscopes do not have a focusing capability, therefore, the team spent a significant amount of time positioning each and every element of the system. Also, the diameter of the endoscope used was a 10 mm diameter. The design specifications required that the optical system be less than 7 mm in order for the configuration to fit inside the ear canal. However, about 3 mm of the 10 mm diameter was used for illumination fibers (which would be removed for the team’s design). Also, the long cantilever arm of the endoscope would experience several natural vibrations and cause the imaging quality to be poor. Finally, the replication of this design would require several GRIN lenses. GRIN lenses are typically expensive, so this design would not be cost efficient. The team noted the benefits and pitfalls of this optical configuration and then repeated this process with an otoscope configuration.

### 3.1.3 Otoscopes

For the otoscope set up, the team used a mounted Welch Allyn Otoscope to perform holographic testing. The Welch Allyn Otoscope functions using a series of objective lenses and relay lenses. Figure 3-6 shows the image of a resolution target obtained using the otoscope, which has a resolution of 5.66 lp/mm. Next, the team utilized the PIKE Camera and a latex membrane to gather holographic images, as described in Section 3.1.2. The holography set up is shown in Figure 3-7 and Figure 3-8. Using similar methods to the endoscope setup, the obtained holographic images for the otoscope can be seen in Figure 3-9.
Figure 3-6 Otoscope Image of USAF Target. The User Determined and Matlab Resolutions were 5.66 lp/mm

Figure 3-7: Otoscope Setup to Capture Preliminary Holographic Image of an Artificial Sample
Unlike the endoscope, the otoscope has focusing capabilities which provided the team with a simpler imaging process. Based on these focusing capabilities, the otoscope can be utilized at several different working distances to obtain different fields of view. In the holographic images, the otoscope was placed at a 45 mm working distance to obtain a 20 x 20
mm field of view. However, this otoscope is capable of imaging the 10 x 10 mm field of view at a smaller working distance.

3.1.4 Preliminary Imaging Results

After getting satisfactory images with both the endoscope and otoscope, the team needed to decide which optical device would be best to emulate. Therefore, a weighted decision matrix was made using only quantified data to avoid bias. It was decided to weight resolution the heaviest along with the device’s ability to meet the current lens specifications because those are the factors that are crucial to this project’s success. After the data was presented, two members scored each aspect of performance on a 1 to 5 scale. The average of the two was taken and multiplied by its respective weight. One big discrepancy was the fact that the otoscope is designed to inserted into the ear, whereas the endoscope was wide and rigid. In conclusion, the otoscope edged out the endoscope by a narrow margin. The complete matrix can be seen in Table 3.4.

Table 3.4: Weighted Decision Matrix to Determine the Ideal Optical Configuration for Design Phase

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Otoscope</th>
<th>Endoscope</th>
<th>Total:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated Resolution</td>
<td>0.4</td>
<td>5.66 lp/mm Score 1: 3 Score 2: 3</td>
<td>8 lp/mm Score 1: 4 Score 2: 4</td>
<td>Otoscope: 1.2 Endoscope: 1.6</td>
</tr>
<tr>
<td>Current Lens Specifications</td>
<td>0.2</td>
<td>Adjustable Otoscope head with relay lens Working Distance= 45 mm Score 1: 3 Score 2: 3</td>
<td>Working distance: 14 mm 7mm diameter GRIN lenses Score 1: 4 Score 2: 4</td>
<td>Otoscope: 0.6 Endoscope: 0.8</td>
</tr>
<tr>
<td>Stability/Rigidness</td>
<td>0.15</td>
<td>Designed to be inserted into the ear Score 1: 5 Score 2: 5</td>
<td>Current Length= 13 inches (may experience cantilever motion) Score 1: 2 Score 2: 3</td>
<td>Otoscope: 0.75 Endoscope: 0.375</td>
</tr>
<tr>
<td>Cost</td>
<td>0.15</td>
<td>1. Lenses Score 1: 4 Score 2: 4</td>
<td>1. New endoscope 2. Possibly new relay lens 3. Magnification lens Score 1: 2 Score 2: 2</td>
<td>Otoscope: 0.6 Endoscope: 0.3</td>
</tr>
<tr>
<td>Ease of Adjustment</td>
<td>0.1</td>
<td>Head is currently on sliding rods Score 1: 4 Score 2: 3</td>
<td>Cannot be adjusted (based on borescope in possession) Score 1: 1 Score 2: 1</td>
<td>Otoscope: 0.35 Endoscope: 0.1</td>
</tr>
<tr>
<td>Total Score:</td>
<td></td>
<td><strong>Otoscope: 3.5</strong></td>
<td>Endoscope: 3.175</td>
<td></td>
</tr>
</tbody>
</table>
3.2 **OPTICAL DESIGN**

3.2.1 Design of Optical Head

3.2.1.1 *Selection of Imaging Lenses*

As mentioned in the previous Section, the team decided to proceed into the optical design phase with the otoscope configuration, while only utilizing off-the-shelf optics. After speaking with our advisors, the team believed it would be better to mimic the configuration with off-the-shelf optics rather than attempt to alter the existing otoscope device. This is mainly due to several unknown specifications in the Welch Allyn Otoscope (such as substrates, radius of curvatures of the lenses, coatings, etc.) that the company would not release due to confidentiality purposes.

The operating principle of an otoscope is an initial objective lens and then either an eyepiece or a relay lens (depending on whether the final destination is an eye or a camera sensor). The team investigated several different otoscope designs, previous MQPs, and patents to help narrow down which lenses to select. The biggest finding was a patent published in May 2017 [33]. It was an optical design of a light field otoscope for inner ear imaging. The optical configuration is seen in Figure 3-10.

![Figure 3-10: US Patent of an Otoscope Configuration [33]](image)

This design consisted of three achromatic doublet lenses (serving as objective lenses), a relay system, a removable aperture, a second relay system, and then a sensor. Although this patent and the team’s design both have the same purpose, to image the tympanic membrane, this patent would not be exactly suitable for the team’s project. Therefore, the team adapted the design significantly.

The idea of the achromatic doublet pairs serving as objective lenses was carried into the team’s final optical design. This is because achromatic doublets are designed to correct for spherical and other Seidel aberrations in optical systems. Also, they are available in sizes down
to 2 mm. However, in this patent, the designer used three achromatic doublets all increasing in size. However, the team’s goal was to minimize the number of lenses utilized in order to reduce the amount of back scattering seen at each lens. Therefore, the team selected two 5 mm achromatic doublets to serve as the objective lenses. These lenses correct for aberrations at the very first surface of the optical design and are small enough to easily be inserted into the ear canal to image the tympanic membrane. The team selected the Stock #45-206 from Edmund Optics due to its small diameter (5 mm), short focal length (10 mm), substrates (N-BAF10/N-SF10), and coating (MgF2). Complete lens specifications for the team’s design can be found in Appendix A: Lens Specifications. This lens’ substrates and coating makes the lens designed for wavelengths ranging from 400-700nm. The team’s laser is 532 nm and therefore falls within this range. The team decided to place two of these lenses back to back in order to delay the focus of the light until the end of the ear canal (~25 mm) and to reduce aberrations in the system. Figure 3-11 shows significant aberrations in the off-axis fields and a divergent nature, meanwhile Figure 3-12 shows fewer aberrations and a better controlled output of the lens system. Therefore, the team proceeded with two achromatic doublets.

![Figure 3-11: 5 mm Single Achromatic Doublet Lens Ray Trace from 10mm Sample Located on the Left](image-url)
In the patent, the designer then placed a relay system to direct the light through the aperture and towards the final relay system. The first lens in their relay system is placed at its focal length in order to have the output of the lens be collimated light. The team mimicked this idea of collimating the light, however instead of using a three-lens system, the team simply used one aspheric lens. Aspheric lenses are similar to achromatic lenses because they help correct and prevent aberrations. The typical strategy for Seidel aberration correction is to incorporate several different lenses, however, by utilizing an aspheric or achromatic lens, the same quality image can be produced with one lens. The team selected a 15 mm diameter, 9 mm focal length aspheric lens to collimate the light from the achromatic doublets. The layout is shown in Figure 3-13.
The team placed an iris between the aspheric lens and the relay lens in order to control the speckle size and the brightness of the system. By introducing this iris, the team could control the power output of the system and in turn, match it with the known output of the reference. Finally, the team needed to implement a relay lens into the system to focus the collimated light from the Aspheric Lens onto the sensor. The team searched on Edmund Optics and found the Steinheil triplet. Steinheil triplets are symmetric and therefore minimize aberrations. The team selected the 12.5 mm diameter triplet with a focal length of 25 mm. The team selected a relay lens with a long focal length in order to maximize the space between the relay lens and the sensor. This is because the team needed to save room for either a beam splitter cube or simply for the reference beam.

Once the team had a general idea of what lenses would be implemented into the system, the team utilized the optimization tools in Zemax (an optical design software) to find the specifications that would provide the best system possible.

3.2.2 Optimization of Optical Head

Zemax has several features to allow for optimization of a lens system. Features such as ‘Visual Optimizer’ can be utilized to allow the user to move distances between lenses to see how it is affecting the aberrations. For a more efficient method, the ‘Merit Function Generator’ and ‘Optimization Wizard’ can be used to place in the desired output for a system (i.e. magnification values, low spherical aberrations, minimize field curvature, etc.) and it will automatically generate the distances that achieve the user’s inputs. By using these techniques, the team came up with the final design in Zemax.

![Figure 3-14: Final Lens Configuration Designed in Zemax](image)

After the lenses and overall layout of the optical setup was determined using Zemax, the system needed to be analyzed to ensure that it is not only functioning at the optimal performance, but also that it is meeting all performance design specifications needed to produce proper images. There were multiple simulations executed in Zemax to observe certain parameters of the system. These parameters were aberrations, depth of field, spot diagrams, and eventually, a real time image simulation.
3.2.2.1 Sequential Mode Analysis

Aberrations are when the light going through a system does not travel perfectly through each surface and distorts. The five order aberrations that were simulated and analyzed were spherical aberrations, coma, astigmatism, field curvature, and distortion. In order to determine what kind of aberrations the system was experiencing; a Seidel Diagram was generated and is shown in Figure 3-15.

![Seidel Diagram of the Design Shown in Figure 3-14](image)

The Seidel diagram, Figure 3-15 illustrates the aberrations present at each individual surface in the system. The color-coded bars show which aberration can be seen where and the final SUM column to the right shows the total aberrations the image will see after being projected onto the detector of the camera. The graph shows the system’s most significant aberration to be distortion, and more specifically barrel distortion due to the direction of the yellow bar. To see how much this maximum distortion would affect the image quality, a grid distortion analysis was also completed and is shown in Figure 3-16.
The image shown in Figure 3-16 visually shows the distortion found on the sensor of the camera. The grid shows the camera sensor (12.7 x 12.7 mm) and the x’s show how much the distortion is affecting the image. The farther away an x is from the grid, the greater the effect of the distortion. The maximum distortion shown from this graph was -6.8%, which is not significant. One way to correct for this mild distortion is through the use of MATLAB codes.

Another important parameter for the optical system is the depth of field. This parameter is important to make maneuvering and placement of the system easier because the sample would be in focus during a greater range. A specification within the system was to have a depth of field of greater than 4 mm. In order to determine the depth of field of the system, a simulation was run on Zemax which created a graph called a FFT through focus MTF (Fast Fourier transform through focus modular transfer function). This graph is essentially the efficiency of the system on the y axis with the focus shift (mm) on the x axis. The produced curve can be used to show the total range an image would be in focus using a selected spatial frequency and is shown in Figure 3-17.

The graph, Figure 3-17 shows the specific bell curve for our system at 12 lp/mm. The two vertical black lines were drawn from the curve at 50% performance efficiency and land at about 2.25 and -2.25 mm on either side. This intersection shows that for the system to maintain 12 lp/mm, the depth of field would be approximately 4.5 mm.
Other methods that were used to ensure that the system would perform as expected was through the use of simulation features in Zemax such as spot diagram charts and image simulations. The spot diagram is a chart that allows the user to see how each individual field of light is behaving at the sensor of the camera. The smaller the field radius and more circular, the better in focus and aberration free that field will be. However, with the system designed, it is expected to see some aberrations present towards the edges of the detector. This can be seen in Figure 3-18.
This spot diagram shows grids that are 12.7 mm x 12.7 mm in size and represent the sensor of the camera used. The coordinates at the bottom of each image show the location on the sensor the specific fields are hitting the sensor and the distorted lines are present due to the barrel distortion and slight field curvature.

Image simulation was also used to simulate how an image would move through the system. Using Zemax, an image was placed into the software simulation and produces another image of how the camera sensor will see the object in question. The simulation illustrated that the system performs well and is able to relay the picture with acceptable picture quality. The image simulation is shown in Figure 3-19. The picture on the left was the original and the picture on the right shows how the system would see the picture and relay it to the camera sensor (the sizes are different simply due to the rectangular shape of the sensor in question).

![Image Simulation](image1.png)

Figure 3-19: Image Simulation Using Design in Figure 3-14. Left: The Original Image. Right: The Simulated Image Through the Optical System

### 3.2.2.2 Non-sequential Mode Analysis

After the team finalized the imaging lenses, it was important to consider how to illuminate the TM using the object beam, and where to place the reference beam to balance the two. The first beam considered was the reference beam.

In previous holographic optical systems, it is necessary to use a beam splitter to achieve reference illumination of the sensor. This is due to the short focal lengths of the final imaging lenses, and therefore there was no room to shine the reference beam and hit the entire sensor without using a cube. The main drawback from using a beam splitter is that light is lost from both the reference illumination and the object illumination due to back reflections caused by the glass. Since the team uses small lenses, power must be conserved at all costs. Therefore, the team needed to determine a way to create even reference illumination over the surface without using a beam splitter. The team accounted for this when they selected the Steinheil
triplet, which had a very long focal length. The team’s design has over 50 mm of free space between the last imaging lens and the sensor. This is more than enough room to place a reference fiber, but the team must determine the optimum placement to ensure that the power matched that of the object beam and that the reference illuminated the entire sensor.

The team used the non-sequential function of Zemax to simulate reference illumination at various angles and distances. The “Detector Viewer” function shows the power of light hitting each pixel in the sensor. It also shows the total power of light hitting the sensor (Watts) and the highest power hitting one single pixel (Watts/cm²). The image shown from Detector Viewer simulating the reference beam is shown in Figure 3-20.

The peak irradiance from the reference is 0.155 Watts/cm² and the total power of light hitting the sensor is 0.116. This was important information because the team wanted to have the total power of the reference illumination match the total power of the object illumination light that hits the sensor. This image also shows that there is a centralized peak of power in the center of the sensor due to the Gaussian nature of optical fibers.

The object illumination was much more challenging than the reference illumination. The numerical aperture of each fiber was 0.12. The team designed their optical design with a working distance of 15.5 mm and the object beam needed to illuminate the entire TM (10 mm diameter), from that working distance. With using the bare fiber, only half of the TM would have been illuminated. Therefore, the team incorporated a GRIN lens from Thor Labs to expand the illumination angle. The specific GRIN lens can be found in the Bill of Materials in Appendix B: Optomechanics Bill of Materials. The team also found a pigtailed ferrule and mating sleeve on Thor Labs to help align the illumination fiber with the GRIN lens. These three components created the team’s ‘illumination bundle’ and it can be seen in Figure 3-21 and Figure 3-22.
It is important that the object illumination power has a similar power distribution to the reference illumination. To test this the team was able to use the same Detector Viewer function in non-sequential Zemax as used in the reference illumination test. However, this time the reference beam was turned off and the object illumination beam was pointed at the sample. The rays were traced through the optical system to the sensor. For object illumination it is standard practice to have the illumination come from the smallest angle and distance from the optical axis as impossible. The team determined that the closest the GRIN lens could get to the optical axis was 11 mm off-axis and the angle of the GRIN lens was 22 degrees. However, the team still needs to ensure that the distribution of illumination is as close to that of the reference as possible. Once the team found the optimal illumination distance and angle Figure 3-23 was captured.

The detector viewer showed that the object beam had a peak power of 0.509 Watts/cm² and a total power of 0.232 Watts. The image shows that the distribution of light is similar to the reference light. However, it is also apparent that the light is slightly offset from the center of the sensor, this is due angle of tilt of the illumination hitting the tympanic membrane. The team did not find this off-axis illumination overly concerning because they could further adjust the illumination when building the prototype. Overall, the use of non-sequential Zemax analysis showed that our reference and object illuminations matched up well to achieve high quality images. The final non-sequential Zemax file is shown in Figure 3-24.
3.2.3 Opto-mechanical Design

After finalizing the Zemax file, the next step was to come up with an opto-mechanical design to house the optics. This prototype had to be capable of locking into the optical table and must be on a cage system to keep a consistent optical axis and allow for adjustability. A caged system is where each lens has its own mount and cage plate, and all the components are connected by four cage rods. A bill of materials for the prototype can be found in Appendix B: Optomechanics Bill of Materials
The team started the opto-mechanical design by searching the available cage system options on Thorlabs. The team devised that the 5 mm objective lenses should be in a 16 mm cage system and the rest of the lenses should be in a 30 mm cage system. After finding specific adapters for each lens, the team had a list of the parts that they believed would sufficiently house the optics. To ensure that these parts fit together properly, the team downloaded each part off the Thorlabs website and assembled the opto-mechanical design in Solidworks.

![Figure 3-25: Opto-mechanical Housing of the Designed Lens System Created in Solidworks](image)

After that, the team wanted to ensure that the system securely held the optics at the distances determined from Zemax. A Solidworks Add-on Feature, called LensMechanix, is a tool used to import Zemax files into Solidworks and run different kinds of simulations with the optical head also in the file. The team imported their Zemax file into Solidworks and then placed the planned opto-mechanical system around the lenses. Ray traces were performed in LensMechanix to confirm that the optical head would not interfere with the light running through the lenses, which is shown in Figure 3-26.

As mentioned in the non-sequential mode section, the illumination beam would need to be 11 mm off axis and at a 22-degree angle. The cage plate housing the achromatic doublets did not have a port for the GRIN lens and therefore, the team needed to take the aluminum cage plate to the machine shop and create a port. The before and after picture of the cage plate can be seen in Figure 3-27.
Angle blocks were used to clamp the piece at a 22 degree angle and a CNC machine drilled through the part within a 5% tolerance. After machining, the team assembled the final prototype.
Figure 3-28: Final Optical Prototype, With the Proximal End on the Right and Distal End on the Left
4 Validation of Prototype Performance Using Copper Sample

4.1 Selection of Sample

The team needed to find a way to determine that the final system was accurately imaging the motion of a surface. To achieve this the team needed to create a membrane that has consistent mechanical properties and predictable motion. The specifications to create such membrane is a solid material whose mechanical properties are consistent at room temperature and throughout the entire surface of the material. The team also needed to determine a way to hold the system with constant boundary conditions to ensure that the sample behaves consistently throughout the material. The goal of the validation testing is to show that analytical calculations of natural mode frequencies, match the computational analysis simulated using Finite Element Analysis, which should match the mode frequencies captured using lensless holography, and finally match the mode frequencies captured with the team’s otoscope lens holography. The team calculated the error between these four tests to show that the expected reaction of a sample is the same as the experimental results to ensure the team’s otoscope lens system is accurately capturing vibration patterns.

Using information from past MQP’s the team’s that attempted to solve this same problem, the team determined an ideal material to use was Copper Foil with a thickness of 0.001 inches. The relevant material properties for this material are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1: Material Properties of Copper Foil Sample Utilized to Validate Optical Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>Poisson ratio</td>
</tr>
<tr>
<td>Modulus of Elasticity (GPa)</td>
</tr>
</tbody>
</table>

Next the team then had to find a way to hold the sample as consistently as possible. The team determined the best way to do this was to use circular magnets. The magnets chosen had an internal diameter of 12.7mm which is to simulate a surface slightly larger than our ideal field of view of 10mm by 10mm. The magnets, with the foil in between, clamped it evenly around the perimeter ensuring that the forces holding the sample are even. The magnets were then mounted to the front of a magnetic stand, ensuring that the face of the foil is perpendicular to the optical system. The copper sample attached to the stand is shown in Figure 4-1.
4.2 **Analytical Analysis of Copper Membrane**

Using a similar process to a past MQP [31] resonance frequencies of three different modes of vibrations were calculated analytically, using derived equations from McLachlan (1961) and Reddy (1999) [32]. The three factors that can affect modes of vibration are geometry, boundary conditions, and material properties. Copper Foil was selected because the material properties are commonly known, as demonstrated above. To control the boundary conditions, the sample was clamped uniformly around the edges. Therefore, the equation of the motion of an isotropic plate is derived starting with [32],

\[ D \nabla^2 \nabla^2 W + k W - I_p \omega^2 + I_R \omega^2 \nabla^2 W = 0, \]

where \( k \) is the modulus of elasticity of substrate the plate is on, \( D \) is the modulus of rigidity of plate, \( I_p \) is the principle inertia of plate, \( I_R \) is the rotary inertia of plate, \( W \) is the deformation equation, and \( \omega \) is the frequency of vibration [32]. To make the frequencies easier to find and eliminating negligible variables, \( I_R \) can be eliminated. The equation is then rewritten as [32],

\[ D \nabla^2 \nabla^2 W + k W - I_p \omega^2 = 0, \]
\[ W \nabla^4 = (I P \omega^2 - kW)/D. \]

\( \beta^4 \) can be a variable that is also equal to \((I P \omega^2 - kW)/D \). Therefore, \( \beta^4 = W \nabla^4 \) and rewritten as [32],

\[ W \nabla^4 - \beta^4 = 0. \]

It is assumed that the solution to this equation can be characterized in the following Fourier Series [32],

\[ W(r, \theta) = \sum_{n=0}^{\infty} (W_n(r) \cos(n\theta)) + \sum_{n=0}^{\infty} (W_n^*(r) \sin(n\theta)). \]

The Fourier Series is a sum of sine waves that decompose any periodic function. By using the Fourier series as a solution to the Partial Differential Equation equals two identical equations when solving for \( W_n \) and \( W_n^* \). They are written as,

\[ \frac{d^2W_{n1}}{dr^2} + \frac{1}{r} \left( \frac{dW_{n1}}{dr} \right) - \left( \frac{n^2}{r^2} - \beta^2 \right) W_{n1} = 0, \]

\[ \frac{d^2W_{n2}}{dr^2} + \frac{1}{r} \left( \frac{dW_{n2}}{dr} \right) - \left( \frac{n^2}{r^2} - \beta^2 \right) W_{n2} = 0. \]

By using first and second order Bessel Functions, modified and unmodified, the pair of equations can be solved for \( W_{n1} \) and \( W_{n2} \) as follows,

\[ W_{n1} = A_n J_n(\beta r) + B_n Y_n(\beta r), \]

\[ W_{n2} = C_n I_n(\beta r) + D_n K_n(\beta r). \]

By combining the previous equation and the Fourier series the general solution is as follows,

\[ W(r, \theta) = \sum_{n=0}^{\infty} A_n J_n(\beta r) + B_n Y_n(\beta r) + C_n I_n(\beta r) + D_n K_n(\beta r) \cos(n\theta) \]

\[ + \sum_{n=0}^{\infty} A_n^* J_n(\beta r) + B_n^* Y_n(\beta r) + C_n^* I_n(\beta r) + D_n^* K_n(\beta r) \sin(n\theta). \]

\( A, B, C \) and \( D \) are all coefficients that can be used to determine the mode shapes. Because the sample was circular and symmetric, terms with \( \sin(n\theta) \) are neglected. Also, terms with modified Bessel functions get neglected in order to get a finite value of deflection at the center of the sample. The simplified equation is computed as,

\[ W_n(r, \theta) = (A_n J_n(\beta r) + C_n I_n(\beta r)) \cos(n\theta), \]

where the boundary conditions are \( W_n = 0 \) and \( \frac{\delta}{\delta r} W_n = 0 \) at \( r = a \), for any \( \theta \). Applying the conditions to the equation for \( W_n(r, \theta) \) yields the following matrix,
\[
\begin{bmatrix}
J_n(\lambda) & I_n(\lambda)
\end{bmatrix}[A_n] = [0],
\]

\[
\begin{bmatrix}
J'_n(\lambda) & I'_n(\lambda)
\end{bmatrix}[C_n] = [0],
\]

where \(\lambda\) is substituted for \(\beta^*r\) when \(r=a\). The ‘ symbolizes differentiation with respect to \(\lambda\).

Setting the determinant of the matrix above is equal to,
\[
J_n(\lambda)I_{n+1}(\lambda) + I_n(\lambda)J_{n+1}(\lambda) = 0.
\]

Next, the roots of \(\lambda\) are approximated by using the asymptotic series for the Bessel functions,
\[
\lambda_{n,m} = \theta - \frac{4n^2 - 1}{8\theta}\left(1 + \frac{1}{\theta} + \frac{28n^2 + 17}{48\theta^2} + \frac{3(4n^2 - 1)}{8\theta^3} + \frac{83n^4 + 54.5n^2 + 161.19}{120\theta^4}\right),
\]

where \(\theta = (2m+n)^*\pi / 2\) for \(m \geq 1\). When solving for the frequency modes of vibration, it is important to note that \(m\) is the rank of the root and \(n\) is the order of the root. These are the variables that will ultimately change the mode and shape.

Solving for frequency can be found by rewriting the definition of \(\beta\) as follows,
\[
\omega = \frac{D\beta^4 + k}{I_p},
\]

where \(\omega\) is the frequency. By assuming that the membrane foundation is rigid, \(k\) becomes negligible and is equal to \(a\). Finally, the equation to determine frequencies is rewritten as,
\[
\omega = \frac{\lambda_{n,m}^2}{a^2} \frac{D}{\sqrt{I_p}}.
\]

By adjusting the \(m\) and \(n\) variables which are the ranks and orders of the root of the asymptotic series, the frequencies for each of the respective modes can be calculated.

Analytical analysis of the modes of frequency were determined using a Mathcad code. This Mathcad code is attached in a zip file for this MQP. By using this methodology, the team achieved the natural frequencies for the first three modes of vibration. These are shown in Table 4.2 below, along with the description of each shape.
### Table 4.2 Shape Description of the Modes of Vibration of Copper Sample with Analytical Calculations of the Resonant Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>m (Nodal Diameters)</th>
<th>n (Nodal Circles)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Mode</td>
<td>0</td>
<td>1</td>
<td>1541</td>
</tr>
<tr>
<td>Second Mode</td>
<td>1</td>
<td>1</td>
<td>3203</td>
</tr>
<tr>
<td>Third Mode</td>
<td>2</td>
<td>1</td>
<td>5233</td>
</tr>
</tbody>
</table>

### 4.3 Computational Analysis of Copper Membrane

The computational analysis of the copper membrane was determined using the SolidWorks add on feature called “Frequency Analysis”. The team created a Solidworks part file of the copper with a diameter of 12.7 mm with the same thickness and material properties as the real sample. With this part and the frequency analysis function, a finite element analysis showed a mode (0,1) at the frequency 1565.6 Hz. The mode (1,1) was shown to be 3264.3 Hz, and the mode (2,1) was 5359.1 Hz. The expected shape for each mode is shown in Table 4.3.

Table 4.3: Modes of Vibration of a 12.7 mm Copper Sample Using Finite Element Analysis in Solidworks, Element Size is 0.302 mm, Boundaries are Constrained at the Circumference of the Sample

| Mode 0,1: Frequency 1565.6 Hz

---

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4.4 LENSLESS HOLOGRAPHIC IMAGES OF COPPER MEMBRANE

The next step in the validation was determining the actual mode frequencies of a copper sample. To conduct this experiment, the team set up the holographic system using the PIKE camera without any lenses. Once the sample was determined to be in focus, the team stimulated the sample at various frequencies until the first, second, and third modes were determined. This led the team to determining the sample first mode (0,1) was at 1573 Hz, the second mode (1,1) was 3210 Hz, and lastly the third mode (2,1) was determined to be 4307 Hz. A comparison of all three validation techniques with the team’s final results will be shown later. Table 4.4 shows the image captured for each of these modes and the corresponding frequency.

Table 4.4: Modes of Vibration of Copper Sample Using Lensless Holography

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
<th>Image</th>
</tr>
</thead>
</table>
| 0,1    | 1573 Hz         | ![Image](image)
| 1,1    | 3264.3 Hz       | ![Image](image) |
| 2,1    | 5359.1 Hz       | ![Image](image) |
The final goal of all of these copper membrane samples was to compare the analytical, computational, and experimental data to determine the accuracy of the optical prototype. Analytical and computational analysis assume a perfect sample and make assumptions for boundary conditions to simplify the analysis, therefore, the final results did see some errors between the theoretical and the experimental data. The results are shown and compared in Table 4.

For the three modes that the team used to analyze the system the first mode showed an exact replication between lensless and digital holography. The second mode had an error of 7.2% and the third mode had an error of 3.2%. The majority of error can be attributed to the fact that the team had to use a different sample for the lensless holograms and otoscope holograms and the copper foil had a thickness tolerance of 10 percent. Another difference to address is the variation in image shape between lensless and otoscope holographic images. The relay lens in the prototype, inverts the image along both the x and y axis. So, for modes (1,1) and (2,1) which are not symmetrical shapes if the otoscope image were to be translated over
both the x and y axis, the shape would match much more to that of lensless holographic images.

Table 4.5: Validation of the Prototype Using Analytical, Computational, and Experimental Methods

<table>
<thead>
<tr>
<th>Mode</th>
<th>Analytical Frequency (Hz)</th>
<th>Computational Frequency</th>
<th>Lensless Image</th>
<th>Otoscope Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,1)</td>
<td>1541</td>
<td>1565 Hz</td>
<td>1573 Hz</td>
<td>1573 Hz</td>
</tr>
<tr>
<td>(1,1)</td>
<td>3203</td>
<td>3264 Hz</td>
<td>3210 Hz</td>
<td>2977 Hz</td>
</tr>
<tr>
<td>(2,1)</td>
<td>5233</td>
<td>5359 Hz</td>
<td>4307 Hz</td>
<td>4445 Hz</td>
</tr>
</tbody>
</table>
5 RESULTS

After the designed optical system was validated using the copper sample, other design parameters were verified such as resolution and depth of field to ensure that it matched what was predicted on the Zemax file. After those tests, Massachusetts Eye and Ear Infirmary brought a post-mortem human tympanic membrane, and the team collected holographic images on the membrane using both the Holo 2 system and the high-speed system.

5.1 DEPTH OF FIELD, FIELD OF VIEW, AND RESOLUTION DETERMINATION OF PROTOTYPE

The team utilized the optical prototype, the coherent illumination fiber from Holo 2, and the SA5 Camera in order to determine the Depth of Field, Field of View, and Resolution of the prototype. Figure 5-1 shows the collected image on the PFV Software. By eye, the team determined that the prototype could image 3 – 2 on the target, which yields a resolution of 10.02 lp/mm and the team's MATLAB code determined the resolution to be 8.98 lp/mm.

![Figure 5-1: USAF Resolution Target using Realized Prototype, SA5 Camera, and Coherent Illumination. The Obtained Resolution was 8.98 lp/mm which meets and exceeds the Design Specification of 8 lp/mm](image)

Also, based on the size of the collected image, the team was achieving a field of view of approximately 10 mm by 10 mm. However, the prototype was built on a cage system, therefore, by sliding the relay and changing the working distance of the target, multiple fields of
view are possible with the system. Finally, the team determined the depth of field using a depth of field wedge, shown in Figure 5-2.

This wedge has markers that allow the user to ‘count’ the millimeters of focus of the system. However, many markers are crisply in focus is what the team can count to be their depth of field. The collected depth of field image is in Figure 5-3. The team determined from this image that the prototype has a depth of field of about 4.5 mm.
5.2 HOLOGRAPHIC IMAGING ON POST-MORTEM HUMAN TYMPANIC MEMBRANE

Testing of the optical system with a human tympanic membrane started by using an interferometer system (Holo 2) and a Megapixel camera, Pike 505. The Pike 505 camera has a resolution of 2452 x 2054 with a pixel size of 3.45 microns x 3.45 microns. The Pike 505 has a maximum frame rate of 14 fps.

The optical system was placed in front of the Pike 505 to be used as the imaging system. The reference beam was then placed to fully illuminate the sensor of the camera. The human tympanic membrane was painted with a white ZnO paint to ensure proper reflectance and then placed 15 mm away from the optical system to ensure proper imaging/resolution. The final component to the system was a fixed speaker that excited the tympanic membrane with a continuous acoustic tone at a frequency of 4 kHz. The entire setup can be seen in Figure 5-4.

The holo 2 interferometry system in conjunction LaserView were then used to take displacement images of the eardrum while it was being acoustically excited by the speaker. The following images are portions of the cadaver human eardrum during a 4 KHz acoustic excitation. The images have a field of view of about 6 mm x 6 mm due to the reduced sensor size on the Pike 505 camera. Figure 5-5 shows time-averaged mode on the left, and double exposure mode on the right.

![Figure 5-4: Holographic Images Collected on a Post-Mortem Human TM using Pike 505 Camera and Optical Prototype]
After the optical system was used in conjunction with the Pike 505 and Holo 2 setup, the prototype was then placed in the high-speed system using a Photron FASTCAM SA-Z high speed camera.

The designed optical system was placed in front of the SA-Z camera at a 90-degree angle using a wedge mirror. The cadaver human TM sample was then placed 15 mm in front of the system. The two images in Figure 5-6 show the setup of the optical system using the FASTCAM SA-Z. Open coherent illumination was used to illuminate the TM and a speaker was also placed behind the optical system to acoustically excite the human eardrum.

Due to the larger sensor of the SA-Z high speed camera, the field of view of the images were improved to about 10 mm x 10 mm. Figure 5-7 and Figure 5-8 are the cadaver human tympanic membrane solely using the optical system to image. The 10 x 10 mm field of view was cropped to 7 x 7 mm FOV to have the eardrum alone in the frame. Figure 5-7 was illuminated using incoherent white light and Figure 5-8 was illuminated with coherent laser light.
Once the system was set up and ready to image, two displacement measurements were taken using this setup and camera. The eardrum was observed and analyzed during 0.2 V and 0.1 V excitations. The human eardrum displaces for 16 ms after the acoustic click. Table 5.1 illustrates an image taken at a time during the excitation and then shows the 3-D displacements that can be calculated from that image 0.16 ms after the excitation.
Table 5.1: Displacement Map of Post Mortem TM Using Optical Prototype with High-Speed Holographic System

<table>
<thead>
<tr>
<th>Excitation Voltage</th>
<th>Double-Exposure Image @ 0.16 ms</th>
<th>3-D Displacement @ 0.16 ms</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

Integrating this prototype into the system did not sacrifice speed, resolution, or overall quality of the collected images. But, this prototype was equipped with a depth of field three times the original value. This allowed for much easier positioning of the specimen. Positioning of the specimen in front of the camera used to take the researchers hours, but with the new system, we took the prototype from the Holo 2 optical table, inserted it in front of the SA-Z camera on the high-speed optical table and placed the temporal bone in front of the prototype, all within under ten minutes. The prototype is now successfully integrated into the high-speed system and will continue to contribute to the cutting-edge otologic research in the CHSLT Lab.
6 CONCLUSIONS AND FUTURE WORK

6.1 FUTURE WORK

Now that the team has assembled a prototype cage system, the next step would be to develop a final opto-mechanical housing assembly, since a cage system is not adequate optical housing for imaging within human ear canals. As a result, the next step of the project is to design and manufacture an optical housing assembly. The best tool available for developing this final housing is LensMechanix. It is an Add-On in Solidworks and is extremely user friendly. The team even created a preliminary opto-mechanical design. This project team will be attaching the Zemax file to the final report so that future students can download the file and import them into LensMechanix for the final housing.

Figure 6-1: Preliminary Opto-mechanical Housing for the Optical Prototype

The team was unable to create a more in-depth design due to time constraints. However, by creating this preliminary shape in LensMechanix, the team was able to perform a preliminary analysis to ensure the imaging quality is not affected by the natural vibrations of the final mechanical assembly housing. One test to ensure the mechanics are accurate is by determining the modal frequencies of the simulated aluminum shell. The goal is to ensure that it does not have a modal frequency in the testing range for the human ear. The human ear can
hear frequencies between 20 Hz and 20 kHz. Therefore, the opto-mechanics of the system cannot have a modal frequency within that range. After testing the shell in Solidworks, the team was able to conclude that the design in Figure 6-1 does not have a modal frequency within that range. The first frequency of the opto-mechanical assembly is 21 kHz, slightly above hearing range. This means that if the next researchers follow a shape similar to that in Figure 6-1, the imaging quality of the system should not be affected.

Another important simulation the team needed to test is thermal deformation of the opto-mechanics. This is important because when the system is used in a living sample the contact with the ear canal will reach temperatures up to 37 degrees Celsius. The opto-mechanics need to be designed so thermal expansion of the materials doesn’t affect imaging quality and characteristics. This can be completed by running thermal simulations where the distal end of the mechanics is 37 degrees and the proximal end is 20 degrees. Then cross sections throughout the system can be used to calculate the mechanical size changes using the formula ΔL/L=αΔT. This system will have a maximum expansion at the distal end of the system of 4x10^{-4} mm. This should not affect any of the imaging capabilities of the lens system.

Further work needs to be completed to determine a more in-depth final housing design shape and repeat the simulations listed above. It is critical that the final design have a groove for the speaker and stay under 7 mm in diameter to ensure that the ear canal is not sealed upon insertion.

Other future work that the team suggests is to further develop the LaserView software to make it compatible with high-speed cameras such as the SA-5 or SA-Z. Finally, the team urges further design and realization of the illumination bundle to continue to miniaturize the illumination.

6.2 **Conclusions and Impact**

The team designed, realized, validated, and then integrated the otoscope head for the high-speed holographic system. The team performed background research to develop design requirements for the design, then delivered a design that either met or exceeded all of those requirements, finally, the team thoroughly tested the prototype to verify that the requirements were fulfilled. The device developed delivered the depth of field, field of view, resolution, and dimensional requirements required by those design specifications. It lessens the amount of positioning time required to achieve an in-focus image, it maintains imaging quality and speed, and most importantly, it contains lenses small enough to be inserted into the ear canal. The otoscope will be used for imaging tympanic membranes in WPI’s CHSLT lab in all future testing. This will allow researchers increase their knowledge of the tympanic membrane by getting both a higher quantity and quality of images during their experimentation days.

An important finding that the team made during the process of this project is that it is possible to conduct holographic imaging without the use of a beam splitter. The team was able to achieve this by creating a holographic system with their prototype in front of the PIKE 505 camera. The removal of the beam splitter can allow for further miniaturization of systems, as well as reduction of back scattering caused by the glass beam splitters. This technique can be used in the future to improve future holographic systems.
The lens system developed in this project was strictly designed to aid in the research and development of the high-speed holographic system used for middle ear diagnostic research and is located in WPI’s Center for Holographic Studies and Laser mecha-Tronics. This system has the potential to become a clinical holographic imaging device to help physicians diagnose the pathologies of the middle ear.
REFERENCES


## Appendix A: Lens Specifications

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### Coating Curve

![Coating Curve](https://www.edmundoptics.com/optics/optical-lenses/aspheric-lenses/15mm-dia.-0.83-numerical-aperture-vis-coated-aspheric-lens/)

**VIS [425-675nm] Anti-Reflection Coating Performance**

Typical Energy Density Limit: 5 J/cm² @ 532 nm, 10ns FOR REFERENCE ONLY
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## APPENDIX B: OPTOMECHANICS BILL OF MATERIALS

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APPENDIX C: ZEMAX TUTORIAL

Zemax Sequential Mode:

Zemax is a professional optic design studio that is used to design optical systems and analyze/optimize those systems to ensure that they perform as intended. When Zemax is opened, the user can see a table with headings of “surf: Type”, “Radius”, “Thickness”, “Material”, etc. Figure C-1 below shows the window as Zemax is opened in sequential mode.

![Figure C-1: Home Screen of Zemax Showing Lens Data](image)

The “OBJECT” surface is the object that is being imaged. The “IMAGE” surface is the column that represents the sensor of the camera. This allows for the sizes of the object and sensor to be set to the parameters for the specific system. As lenses are added to the system, it would become surfaces 1 and 2, after the object and before the sensor. The “Radius” row shows the radius of each surface (1-entrance and 2-exit). The “Thickness” row stands for the distance between the surface and the next surface. Thickness at surface 0 (object), represents the distance from the object to the first lens. The thickness at surface 1 (first surface of the lens) represents the distance between the first surface of the lens to the second. “Material” and “Coating” columns represent the material (Example: BK-7) of the lens and the coatings of that specific surface(s).

Since sequential mode is a 2-D simulation (X-Y planes), Y coordinate sizes need to be assigned to the object, sensor, and lenses. “(Clear/Mech) Semi-Diameter” represents the radius size of the components in question.

The window on the left that denotes aperture, fields, wavelengths etc. allows for manipulation of light rays traced (number of rays and where on the object they originate from), entrance pupil diameters, as well as ensuring the proper wavelength through the optical system. The example window is in Figure C-2 below.
To add a new field, go to the fields tab, select Paraxial Image Height, press add a new field, and then enter in your desired coordinates. This is shown in Figure C-3 below.
To insert lenses into Zemax, the user simply needs to select “Libraries” in the main upper left-hand tab. From there, selecting “Lens Catalog” allows for the user to select certain parameters such as vendor, shape and specify focal lengths and EPDs. The lens can be inserted at any surface in the system. If off-the-shelf optics are needed, vendors such as Thorlabs and Edmund Optics have Zemax files of their lenses that can be inserted directly into a system. By going to file, and then pressing insert lens, shown in Figure C-4 below.

Figure C-4: Example of How to Add a New Lens in Zemax

After the optical system is in the program, optimization of the system needs to be done. To do this, the “Analyze” tab in the upper left-hand corner of the window contains multiple features to ensure the performance. The tab is shown in Figure C-5 below.

Figure C-5: Analyze Tab in Zemax

Aberrations can be viewed by selecting “Aberrations”, then Seidel diagram to see all aberrations in the system. “Rays & Spots” can be used to view the size and shape of spot diagrams that the detector will be viewing. A spot diagram is shown in Figure C-6. The “MTF” tab allows for graphs to be created to show the efficiency of the system in relation to different parameters such as resolution (FFT MTF, shown in Figure C-7) and depth of field at a specific resolution (FFT Through focus MTF, shown in Figure C-8).
Figure C-6: Spot Diagram in Zemax.

*Found by:* Analyze → Rays and Spots → Standard Spot Diagram

Figure C-7: FFT MTF Example in Zemax, Used to Determine Resolution Based on the Modulus of the OTF (0.5 is usually the Modulus Selected)
Another tool that can be used is the “Extended Scene Analysis”, “Image/geometric Simulation”, and “Relative Illumination”. These features can be used to see how an image would look if it were to be the object and was imaged through the system. The image simulation gives information about image size and visually shows how aberrations affect the quality of the image. After the system is analyzed, it can be optimized to ensure proper performance. You find this feature by Analyze → Extended Scene Analysis → Image Simulation. An example of the Scene Analysis is shown in Figure C-9 below.
In the ‘Optimize’ tab, the user can alter different aspects of the optical design to achieve different properties. In order to optimize aspects of your system, the user must go to the lens data column and select which parameters are fixed (which means that these parameters will not be changed during optimization) and which parameters are variable. This process is shown in Figure C-10 below.

The team found that the visual optimizer and merit function editor were the most useful tools in this tab. The Visual Optimizer lets the user slide the lenses to achieve the desired output. For example, in our lens design, we set all distances to variable and slid the lenses to find an approximate layout to ensure that the system was focusing on the sensor. The visual optimizer is the first tool to achieve a preliminary layout of the system. An example of the Visual Optimization Screen is in Figure C-11 below. To achieve a better focused image, use the ‘quick focus’ section in the optimize tab.
Finally, to achieve different optical parameters such as magnification and reducing aberrations, you can use the merit function editor. The ‘Optimization Wizard’ and the ‘Merit Function Editor’ are connected in Zemax. You can easily enter in the parameters in the ‘Optimization Wizard’ and they are inputted into the Merit Function Editor table. This is shown in Figure C-12 below. To apply these values to the optical design, select RMS for the type, Spot Radius for Criteria, Gaussian Quadrature for the Pupil Integration (and maximize the rings and arms to allow for the most accurate simulation), and keep the rest of the parameters at the default. Then use the ZEMAX manual to select which operand to enter to achieve your desired output. For example, if you want to achieve a specific magnification from object to sensor, you would enter in the operand PMAG and enter in the desired value and how important this operand is to the final function. Assign each operand in the Merit Function Editor a weight to be able to achieve a final solution that meets your desired outcome.

Figure C-11: Visual Optimization Screen with Four Variable Thickness. To change the thickness manually, slide the bars located Zemax to Optimize, press the Animate Button on the Bottom

Figure C-12: Example of Optimization Wizard Screen with the Necessary Parameters to Properly Perform the Simulation in the Merit Function Editor
The team did not utilize the ‘tolerance’, ‘libraries’, ‘part designer’, or ‘programming’ tabs in our optical design. If you have any problems in the optical design software, the ‘help’ tab is extremely helpful. Also, the team utilized the ‘email technical support’ option several times. The responses were timely and extremely helpful. When emailing the technical support, you must provide your license key to be able to receive assistance. For any other issues, utilize the online ZEMAX forums and the ZEMAX manual.

**Zemax Non-Sequential Mode:**

The function of Non-Sequential Zemax is to portray the reaction of light in three-dimensional space. This is useful when analyzing how object and reference beams interact with the sample and camera sensor. For holographic imaging purposes, a significant use of this program is to determine the beam ratio and distribution of the beam intensity on the sensor.

The first step of using Non-Sequential Zemax is converting your sequential lens file to non-sequential. This is done by selecting File, “Convert To NSC Group”. This is shown in Figure C-13 below.

![Figure C-13: How to Convert Sequential Mode to Non-Sequential Mode in Zemax](image)

The next step is to make sure the simulation has an object, reference source, and object source. To create your object right click on your first objective lens, select add object above, then open the “Object Properties”. In this program you can determine the “Type” to determine the general shape, then determine the dimensions and position in the component editor. This process is shown in Figure C-14 below.
Then to make the object reflective select “Coat/Scatter”, select the front face, and assign “Face is: Reflective”. This will make the object reflect the object beam towards the objective lenses.

Next to create a source the initial step is the same, create another object in the “non-sequential component editor” and open the object properties again and assign “Category: Source” Then determine the “Type” to match the project’s source beam. In object properties determine the position and angle of the object beam so it illuminates the object at the required distance. Also, in object properties you need to determine the power, wavelength, and angle of the beam. For simulation purposes you also need to insert the “# Layout Rays” and “# Analysis Rays”. Select “Ray Trace” to simulate the Rays through the system. This is shown in Figure C-15 below.
Repeat these steps for the reference beam except position the reference beam illuminates the camera sensor.

Continue to adjust the angle and positioning of sources and object until desired setup is completed. Once completed it is necessary to use the “Detector Viewer” function to check the illumination of the sensor. This is shown in Figures C-16 and C-17 below.

Figure C-16: How to Run a Detector Viewer Simulation in Non-Sequential Mode

![Detector Viewer Simulation](image)

Figure C-17: Detector Viewer Example for the Optical Prototype

The intensity of light on the sensor is shown by the scale on the right of the image. Also, the important numbers to consider is the “Peak Irradiance” stating the intensity of power hitting the most exposed pixel on the sensor and the “Total Power” stating the total power of light hitting the sensor.
By performing this test using the object beam and reference beam one at a time, you can make sure that the shape of the illuminations, peak irradiance of the illuminations, and total power of the illuminations are at the desired intensity ratio to receive high quality holographic images. The final “NSC 3D Layout” should look similar to the image in Figure C-18 below.

Figure C-18: Final Optical Assembly in Non-Sequential Mode