CMSC 715 Project Report

3D Shape Detection Using Acoustic Tomography

ABSTRACT

The main objective of this work is to reconstruct the 3D shape of an object using cheap and low-power ultrasonic sensors. We propose two approaches: the time-of-flight approach and the back projection approach. Experiments on both methods are done in simulation using the COMSOL Acoustic module. The target object is a 3cmx3cm square, and the whole setup is in a tank filled with water to reduce the acoustic impedance mismatch. The result from both experiments is presented. The time-of-flight method gives a more promising result, especially after correcting the measurement with the knowledge of the angle of arrival. On the other hand, the result from the back projection method is not even close to the target object. The back projection approach assumes waves to travel in a straight line with little refraction, which fails when applied to ultrasonic waves.

1. INTRODUCTION

3D shape detection provides valuable information in a diversity of fields from medical technology and engineering to art and criminal forensics. There are many techniques to acquire 3D shape information that vary in precision and measurement speed. Laser triangulation, structured light projection, light pulse time-of-flight are the basis for popular and reliable methods to detect the shape of 3D surfaces in use today. These methods are deliberate measurements and are associated with measurement stations or apparatus along with calibrated camera or sensor ensembles.

Photogrammetry is science of extracting information about the physical world from photographic data such as that produced by conventional cameras It is quickly being adopted for its convenience and versatility in autonomous vehicles using computer vision and deep learning to boost the technology's effectiveness. The benefit of This kind of 3D shape recognition is clear as it requires less effort to measure in exchange for precision and physical resources, although lidar sensors could argue that as well. This method clearly also has a larger measurable area compared to targeted 3D scanners.

Extending the idea of more seamless measurement, the use of acoustic waves to measure form, for example sonar, comes to mind. Consider the omni-directional propagation of pressure waves, one can imagine measuring 3D surfaces of objects passively, or measuring without a direct line of sight as is done in ultrasound or mapping of hollow internal structures and much more. This is part of our motivation for focusing on acoustic measurements.

Tomography is a technique for imaging by using information gained from penetrating waves through a target. Image reconstruction in this context involves stacking multiple tomograms or slice images. This is the guiding principle of CT scans (Computrized Tomography) and PET scans (Positron Emission Tomography). A prominent example is ocean acoustic tomography where acoustic waves passing through ocean waters are used to measure temperature and currents [2].

We explore using ultrasonic waves propagating through an object to extract 3D shape information. To test our methods we focus on extending the analogy of tomography done in the style of traditional CT scanning, but the goal is to generalize the way of measurement to less restricted situations if feasible.

In sum, this paper makes the following contributions:

- *Acoustic Tomography 3D Scanning.* We attempt to use the principles of classic CT tomography with ultrasonic acoustic waves for 3D shape imaging and build up the experiment in a way that produces data that can be fed into the canonical inverse filtered back projection algorithm to recover the shape of the object which is the first of its kind.

2. A PRIMER ON SPATIAL ACOUSTICS

The main measurement being studied is the attenuation of the wave that passes through the target, which is produced and sensed at some distance from the center of the object. This corresponds to the length of the physical body between the sensor and receiver. Using the analogy to traditional CT, we proceed to subject the mesaurements to the Filtered Back Projection algorithm to learn the shape of the slice of the target.

This analysis of the problem is done using COMSOL Multiphysics. The behaviour of an acoustic signal, which is a pressure wave is to be analyzed, and hence we make use of the Pressure Acoustics, Time Explicit (pate) model/domain of COMSOL. The model solves the following equations:

$$\frac{1}{\rho c^2}\frac{\partial p_t}{\partial t} + \nabla \cdot \boldsymbol{u_t} = \boldsymbol{Q_m}$$

$$\rho \frac{\partial \boldsymbol{u_t}}{\partial t} + \nabla \cdot (p_t \boldsymbol{I}) = \boldsymbol{q_d}$$

3. INTUITION AND FEASIBILITY STUDY

Using ultrasonic waves in the measurement of 3D shape is not new. It is a common project undertaken by students. However, ultrasonic waves are typically used as range sensors which measure time-of-flight of a transmitted pulse reflected off a target. This method is valid but has its weaknesses. The short range and angle of the target surface are examples of sources of low reliability. Another reason to abandon this method is that sample collection is extremely slow and each measurement only collects one data point. This can not be fixed, it can not be scaled up using more sensors because they will interfere with each other.
A benefit of using penetrating waves is that a single source can supply the wave and several sources across the target can take independent (almost independent) measurements. The scaling benefits should be obvious here as they were in CT scanners when moving from Parallel Beam to Fan to Cone Beam.

4. SYSTEM DESIGN

From the literature review, there are two possible methods to extract the target object's shape using ultrasonic waves: the time-of-flight method and the back projection method.

The Time-of-flight principle is widely used in medical ultrasound and nondestructive testing. This method uses ultrasonic sensors to measure the distance from each probe to the object. The setup for this method is shown in fig 1A and fig 1B. Each ultrasonic sensor behaves as both source and receiver, generating a pulse and waiting for the return. By repeating the process for all probes, we can plot the target object's surface profile. To obtain the complete shape of the object, we have to completely rotate the object and get surface plots at different angles. Then, to combine all surface plots, we must multiply each plot by the corresponding rotation matrix.

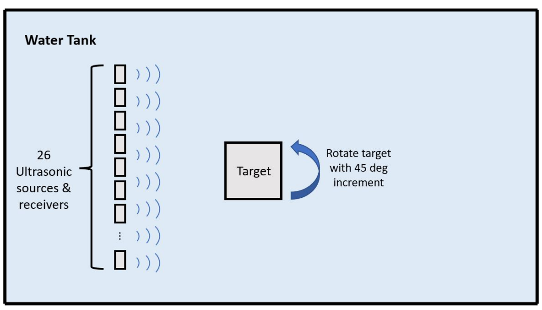

Fig 1A. Time of flight method experiment setup

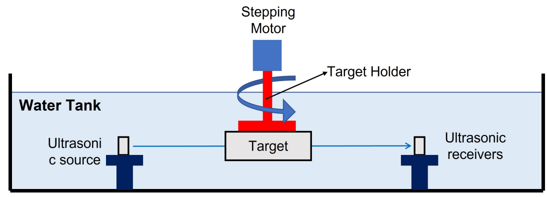

Fig 1B. Experiment setup side view

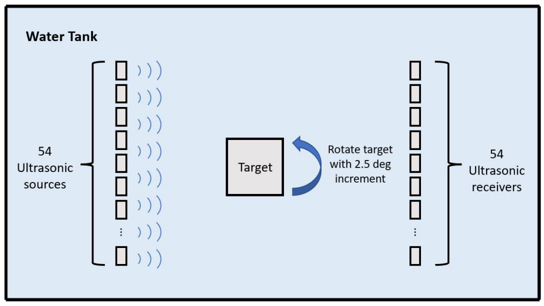

Fig 2. Back projection method experiment setup

The back projection method is the principle behind CT scans. The CT scanner shoots an x-ray beam through the target object and measures how much the beam is attenuated. The amount of attenuation is proportional to the amount of material inside the target object through which the beam traveled. By combining the measurement at different angles and feeding them to the back projection algorithm, we can reconstruct the 2D shape of the target object. The advantage of this method is we will also be able to see the internal profile of the target. The setup for this method is shown in fig 2. The ultrasonic sources and the receivers are placed on the opposite side of the target. At each angle, all ultrasonic sources will transmit the signal at the same time, creating a parallel beam. Some portion of the wave will go through the object, and some will reflect off the surface. The ratio between the wave reflection and transmission between 2 mediums is affected by the acoustic impedance. The higher the acoustic impedance mismatch between the two mediums, the more wave will get reflected. Since the acoustic impedance of air is extremely low and is nowhere near the acoustic impedance of any solid objects, a minimal amount of wave will be able to go through. Therefore, we consider using water as a medium. This is the reason why we need to apply the gel on the measured surface before doing the ultrasound.

5. SIMULATION SETUP

Due to a limited amount of time, our experiment will be done with finite element simulation using COMSOL. The acoustic module in COMSOL provides the capability to simulate physics acoustic waves in different scenarios. Using *Pressure Acoustic - Time Explicit* and

Elastic Wave - Time Explicit studies in the Acoustic module, we can conduct a study of waves propagating through different mediums. Our simulation setup is shown in fig 3. As mentioned, we have two types of physics in our simulation setup. The Pressure Acoustic - Time Explicit is the study of the sound wave in liquid in the time domain and is applied to the surrounding water. The Elastic Wave - Time Explicit is the time domain study of acoustic waves in solid and is applied to the target. To create an interaction between 2 domains, we set an Acoustic-Structure boundary between 2 mediums. For the time-of-flight method, we created 26 probes for generating ultrasonic sources, in which each probe is 2mm apart. The same probes are also used for receiving the return signal. For the back projection method, additional 52 receivers will be placed on the opposite side of the source, as shown in fig 4. The source signal is a 2-3 cycles 1.5MHz wave pulse and is shown in fig 5. To minimize the effect of multipath, we created an absorbing layer around our experiment setup. The waves going through these layers will disappear and won't bounce back. We run each simulation for 60 microseconds, which is long enough for the wave to bounce back to all sensors. The target object's shape is a simple $3cm \times 3cm$ square, and the material is aluminum.

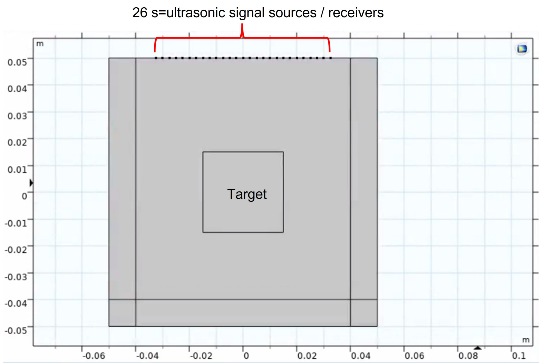

Fig 3. Time of flight method simulation setup

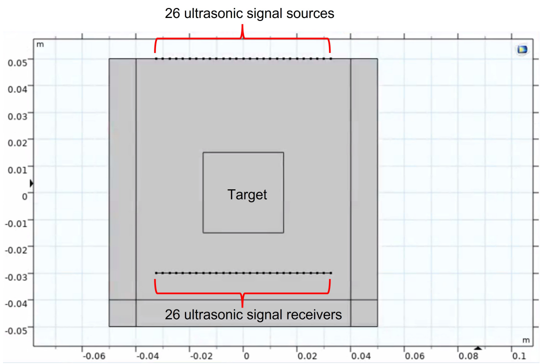

Fig 4. Back projection method simulation setup

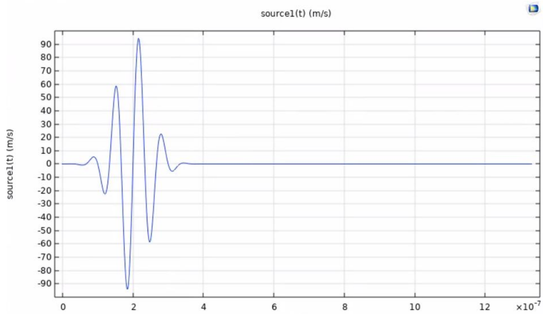

Fig 5. Source signal

6. EVALUATION

6.1 Time-of-flight method

In this method, we fire one probe at a time and measure the time of flight. We created a surface plot for the target object at 0 and 45 degrees rotation angle, as shown in fig 6 and fig 7. By symmetry, 0 degree surface plot is identical to the 90, 180, and 270 degrees plots. Likewise, the 45 degrees plot will be identical to the 135, 225, and 315 plots. We also neglect the measurement with pressure amplitude lower than a certain threshold to discard noises. Fig 8 and fig 9 show target shape construction from 0 and 45 degrees measurement individually. We found that the result from 0 degrees measurement, in which the beam is projected on a flat surface, gives an accurate target shape. On the other hand, the plot from 45 degrees measurement, which projects the beam on a corner of the square, gives an obtuse angle instead of a right angle. Fig 10 shows the result from combining all plots together, taking into account the target rotation angle. As expected, the plot from both measurements doesn't coincide. The reason behind the error is illustrated in fig 11. When measuring the square at 45 degrees rotation, the return signal is not actually from the target location in the probe line of sight but rather from a surface normal to the transmitted wave. Therefore, the measured distance appears smaller than expected, resulting in an obtuse angle. An improvement to account for this error will be discussed in a later section.

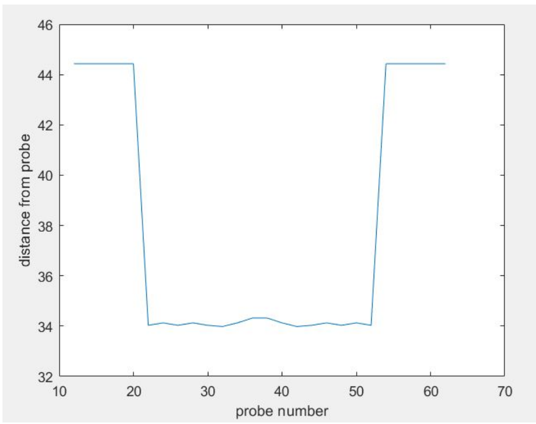

Fig 6. Surface plot at 0 degree rotation

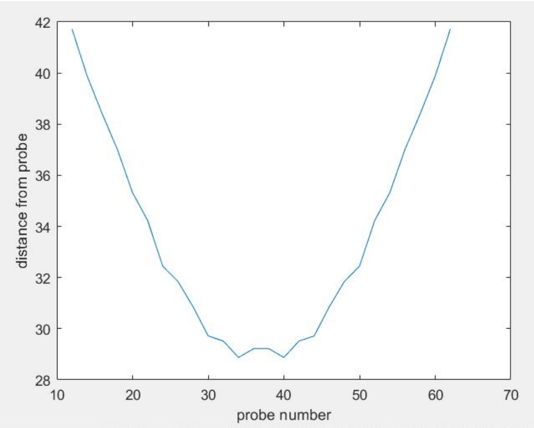

Fig 7. Surface plot at 45 degree rotation

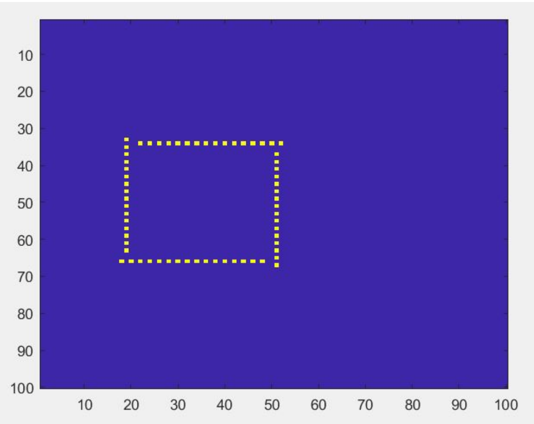

Fig 8. Target reconstruction from 0 degree measurement

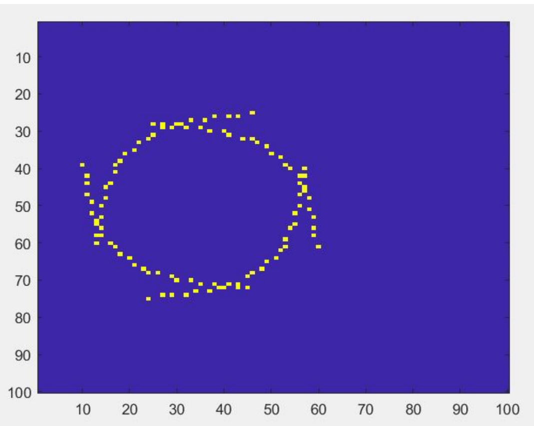

Fig 9. Target reconstruction from 45 degree measurement

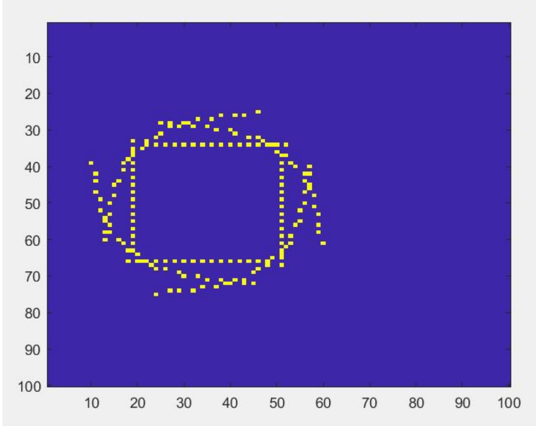

Fig 10. Target reconstruction from all measurements

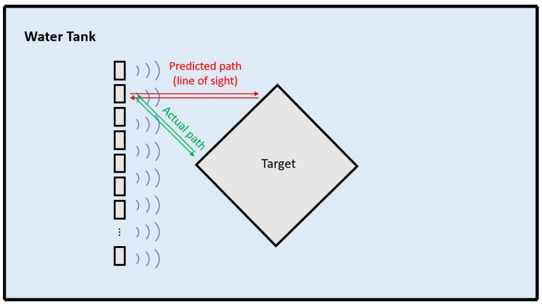

Fig 11. Measurement error on slanted surface

6.2 Back projection method

In this method, we fire all probes simultaneously, creating a parallel beam, and then measure the pressure amplitude with receivers on the other side of the source, expecting an attenuation in pressure as the wave travels through the target. We repeat the process every 2.5 degrees of target rotation. Some samples of received pressure amplitude are shown in fig 12 and fig 13. Plotting all probe measurements at different angles will give us a sinogram, as shown in fig 14. From the sinogram, we can reconstruct a 2d shape by using “irandon” function in MATLAB. The result from “irandon” is shown in fig 15. The result is quite different from the target shape. After investigating each plot, we found some unexpected measurements. Notice the measurement at 45 degrees rotation angle, as shown in fig 13. The plot shows a peak in pressure amplitude in the middle of the plot. According to our hypothesis from how CT scan works, this point should have the lowest pressure amplitude because the wave travels through the longest distance inside the object. By observing the simulation, we found that the source of the high pressure at this middle point doesn’t come straight out of the object but from refraction from the two bottom edges of the square. The assumption for the back projection method is that waves travel in a straight line with little refraction, which is valid for x-ray waves in CT scan applications. However, in our case, there is significant refraction when waves travel through the target, which is why "irandon" gives out an incorrect image reconstruction.

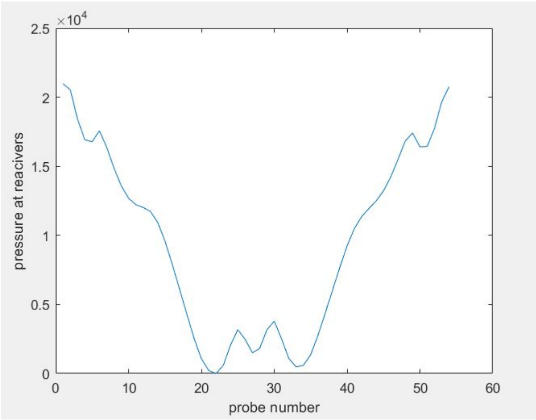

Fig 12. Pressure on receivers at 0 degree

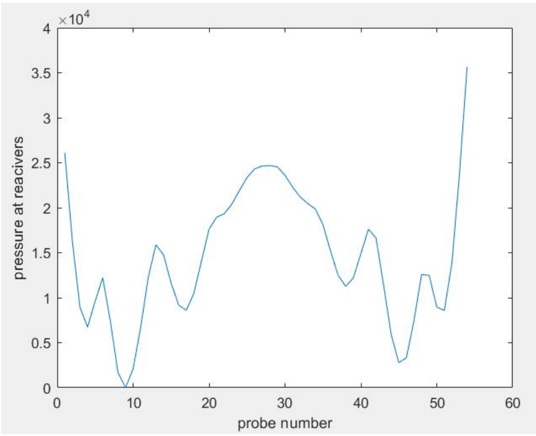

Fig 13. Pressure on receivers at 45 degrees

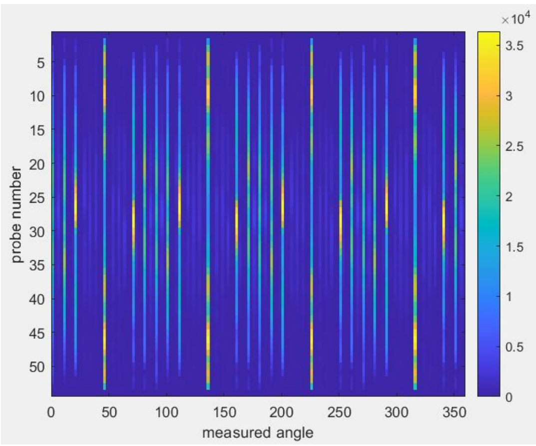

Fig 14. Sinogram from measurements at different angles

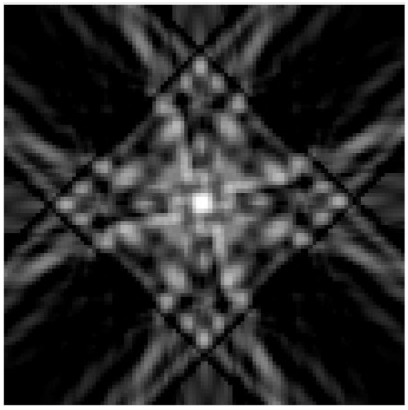

Fig 15.Result from inverse randon transform

7. RELATED WORK

To gain an understanding of the method we want to use, acoustic tomography, and the intended application, acoustics based shape detection, we reviewed several contemporary efforts. [3] developed a way to do acoustic imaging using a synthesized meta-material. The material amplifies acoustic waves reflected along the edges of objects allowing for the creation of acoustic domain contour detectors. [1] developed a technique using acoustic tomography to assess the level of decay in hardwood trees. Acoustic Tomography has been used for oceanic parameter measurement using the properties of sound propagation in water. The changes in the speed of sound relate to the temperature of the medium and also to the speed of the water currents that the sound propagates through. A promising field of algorithms is called Non-Line-of-Sight (NLOS) approaches which try to capture 3D shape information without direct line of sight. These methods are based on probabilistic models to estimate the position and correlation of data points from reflected signals. this paper extends the approach to acoustic sensing with state-of-the-art results [4]. We observe that related work on acoustic tomography is focused on the mechanical properties of solids. These properties are inferred using changes in measured velocity and attenuation of the sound for recognized conditions of the solid medium. however, these differ from our approach in that they maintain direct contact with the targets during the measurements. Our approach will

8. LIMITATIONS AND DISCUSSION

8.1 Simulation time

Both time-of-flight and back projection method requires a lot of measurements and simulations. With the time-of-flight method, we need to run 26 simulations per measurement angle to represent firing 26 ultrasonic probes in sequence. Assuming that eight measurement angles can cover the entire target object's surface, we have to run a total of 208 simulations per target object. For the back projection method, we have to run a simulation per measurement angle with an increment angle of 2.5 degrees, resulting in 144 simulations per target object. COMSOL on Citrix takes approximately 15 minutes to run a simulation. Therefore, it takes 52 hours and 36 hours to run the time-of-flight and back projection methods on a single shape. We are limited to symmetric shapes as we are able to reuse the simulation result. With limited time and computation resources, we are able to do an experiment on only one target shape.

8.2 Time-of-flight method

As mentioned earlier, while the measurement on a flat surface is accurate, the measurement on slanted surfaces is inaccurate since the return signal doesn't come from where we expected. As an improvement, since we already have a sensor array, we can measure the direction of arrival and accurately localize the surface that the wave bounces off. Unfortunately, with a time limitation, we did not finish implementing this concept. However, we test this concept by manually inputting the angle of arrival. The result is shown in fig 16. As seen, considering the angle of arrival results in a more accurate measurement of slanted surfaces.

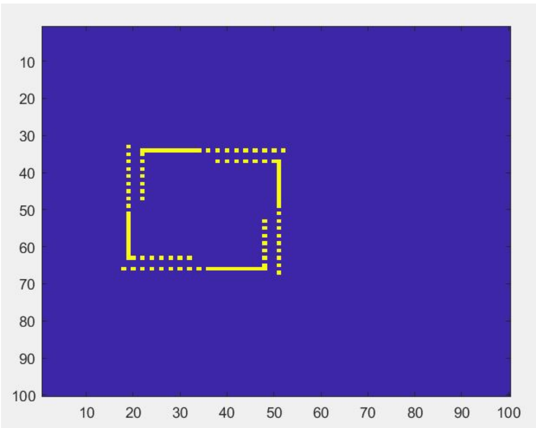

Fig 16.Target reconstruction from all measurements with angle of arrival correction

8.3 Back projection method

The main limitation of the back projection method is wave reflection. Since the method was created for x-ray waves containing high energy and low refraction angle, it assumes that the wave travels in a straight line with little refraction. On the other hand, our experiment is based on ultrasonic waves and suffers a lot from refraction. In our case, the refraction index between aluminum and water is around 2, which will worsen if we use air as a medium.

9. CONCLUSION

Through this project, we have shown one approach using acoustic tomography to find the shape of objects. We build our approach from the bottom up, modeling our approach on x-ray CT scanners but using ultrasonic waves with the necessary changes. The first of these was that air could not be used as an interface between the source and target because of a large acoustic impedance mismatch which canceled out penetration (refraction). Replacing the transmission medium with water appeared to perform well in the simulation, where all experiments were performed in the interest of time. Several probes were used to make measurements of the attenuated source signal which was emitted from the lagging (not facing the source) edge of the solid target. Using the attenuation data collected at all angles from the simulation, and the iradon functionality of MatLab, we produced the sinogram and filtered back projection representation of a slice of the target. This process is to be looped over at all height values of target and resultant images stacked to obtain the 3D model. The deviation seen in the images compared to what is expected from the back projection of x-ray data can be attributed to the scattering of acoustic waves which doesn't affect x-rays in the same way. We also cast the problem to find the contours of the target slices using time-of-flight. We implemented steps to correct errors that arise from using acoustic waves instead of x-rays by adjusting the time of flight with the expected angle of arrival to get more accurate measurements of distances. From the results, we can say that the multipath effects of acoustic waves add significant noise to the measurements of the transmitted signal. There might be a machine learning solution to finding the true attenuation levels and determining the path length of the propagating wave through the object. This, we believe would require a complex calibration scheme to develop a way to label measurements, which was not pursued in the scope of this project but could add validity to this method of 3D shape detection.

10. REFERENCES

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[3] Molerón, M., Daraio, C.. (2015). Acoustic metamaterial for Subwavelength Edge detection.
[4] David B. Lindell, Gordon Wetzstein, Vladlen Koltun (2019). Acoustic non-line-of-sight imaging