MINIMALLY INVASIVE ULTRASOUND PROBE FOR GUIDING SPINE SURGERY

ECED4901: SENIOR YEAR PROJECT
FINAL REPORT

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Enclosed please find the progress report, "*Minimally Invasive Ultrasound Probe for Guiding Spine Surgery*", submitted in partial fulfillment of the ECED4901 Senior Year Project course requirements. This report details the project undertaken by Group 11, supervised by Drs. Adamson and Brown. This project regards fabrication of a high-resolution ultrasound endoscope array that can be used to image nerve rootlets during surgical procedures on the spine.

Included first is the project definition, objectives, and background. The design approach and proposed solution is then detailed. Results are presented and quantified, and a discussion of discrepancies between the proposed and final solution is included. Finally, project management details, specifically the project schedule and budget breakdown are explained.

Thank you for your consideration of this report and instruction throughout the Capstone process. Please reach us through the Dalhousie student email services, at any of the emails through which this document has been distributed, if you have any questions concerning the report.

Sincerely,

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Abstract

As part of the Engineering Capstone program at Dalhousie University, a project has been proposed to design, build, and test a new miniature ultrasound probe to be used in surgical procedures requiring a detailed view of the spinal canal. The probe is an extension to an existing prototype developed by the Dalhousie Ultrasound Group and interfaces with the Daxsonics beamformer and image generating software. Features of the original device include a forward-facing 64-element high-frequency phased array, and an operating frequency of 45 MHz. In spinal surgery, nerve roots are situated at an angle of approximately 45 degrees to the direction of the telescopic access tube, and many of the nerves are located on the opposite side of the spinal canal, which exceeds the penetration range of the current 45 MHz probe. Therefore, the new design has included modifications to adjust the field of view, depth of field, and the physical size of the probe to optimize it for spinal nerve imaging. This report outlines the changes in detail and describes the path of the project, with focus on results achieved.

Originally, roles within this project were split based on the different types of work that needed to be done. However, because of the collaborative nature of the lab work required to actually build the prototype, these roles were amalgamated, and responsibility was shared evenly amongst the team. In the lab, each team member contributed to the development of the piezoelectric sample, participating in lapping, building the epoxy backing layer, laser cutting, and aligning the sample with the circuit boards for wire bonding.

In terms of the tasks outside the lab, they were again divided equally amongst the group members. Sierra remained in charge of the simulations, working with Tom to build a better model for the new probe. Alexa was in responsible for making the required alterations to the supporting fixtures, changing the size of the lens mold, and developing a new stand to hold the probe while the new paint-on silicon is applied. Graeme and Megan were responsible for making the alterations to the PCB, creating several different designs with help from Dr. Brown that would serve to increase the ease with which they are manufactured and therefore decrease the overall cost of the probe.

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List of Acronyms

CAD – Computer-Aided Design
CT – Computed Tomography
FFT – Fast Fourier Transform
FOV – Field of View
KLM – Krimholtz–Leedom–Matthaei
ML – Matching Layer
MRI – Magnetic Resonance Imaging
NSHA – Nova Scotia Health Authority
PCB – Printed Circuit Board
SNR – Signal to Noise Ratio
US – Ultrasound
VNA – Vector Network Analyzer

Acknowledgments

The events and work detailed in this report were completed at Dalhousie University, with the support of various professors and the Dalhousie Ultrasound Group. They were conducted under the supervision and direction of professors and members of the aforementioned groups, and with assistance and cooperation from external companies such as Daxsonics and the Nova Scotia Health Authority (NSHA), who all contributed time and other resources. In particular, Debbie Wright deserves special mention for helping facilitate lab bookings and ensure that the facility operated in accordance with COVID-19 protocols. Finally, special thanks go out to Dr. Jeremy Brown, the project's external supervisor, and to Dr. Tom Landry, for their technical knowledge and support throughout the project. The project would not have been possible without their guidance.

1.0 Introduction

1.1 Problem Definition

The objective of this project was to design, fabricate, and evaluate a high-resolution endoscopic ultrasound array that could be used to image nerve rootlets during surgical procedures on the spine. Ultrasound was chosen as the imaging method of choice because other imaging technologies such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) do not have sufficient resolution to visualize the nerve roots, which are between 100 and 200 microns in diameter, and these technologies are not widely available for routine intraoperative use.

The probe must allow the user to determine the physical state of the nerves following laminectomy and/or discectomy for degenerative conditions such as lumbar disc herniation and spinal stenosis. The product will be used to determine whether nerve decompression has been achieved.

The current standard of care is to pull back on the nerves and prod beneath them with small, blunt dissecting instruments to determine their state of compression. This technique is recognized to be suboptimal by the medical community as it is invasive and considerably dangerous. The solution represented by this project offers a less invasive approach, eliminating the need to prod in the sensitive spinal region.

The minimally invasive approach for spinal surgery involves inserting tube shaped retractors into the incision to access the spine, which typically have diameters in the range of 14 – 22 mm and a length between 40 – 90 mm. Nerve roots are situated at an angle of approximately 45 degrees to the direction of the telescopic access tube, and many of the nerves are located on the opposite side of the spinal canal, which exceeds the penetration range of the original 45 MHz probe.

As the decompression of nerves in the spine is by far the most frequent procedure for spine surgeries [1], this ultrasound probe would be in high demand within the spinal surgery market. At the NSHA alone, approximately 75-80% of the 850-900 spinal procedures done each year have spinal cord or nerve root decompression as the primary objective [1]. As this surgery has a 5% revision surgery rate, ensuring adequate decompression with this new ultrasound probe design could prevent up to 32 trips back to the operating room each year, at the NSHA alone [1]. Broadening this scope to the United States, where 2-10% of the approximately 500,000 spinal procedures per year require follow-up surgeries due to inadequate nerve compression, ensuring the adequate nerve compression could eliminate from 10,000 to 50,000 surgeries each year [1].

1.2 Relevant Literature

To support the design of this ultrasound transducer and supporting assembly equipment, it was essential to investigate relevant literature to discover not only what is used today in the ultrasound and medical technologies industries, but to develop a deeper understanding of how ultrasound works in practice. All four team members, although having taken the Biomedical Engineering technical elective offered through Dalhousie’s Department of Electrical and Computer Engineering, had not had other experience in ultrasound transducer design when first undertaking this project. For this reason, incorporating the theories, ideas, and strategies developed by academics who are established in their respective fields was important.

Generally, ultrasound transducers are composed of several material layers – piezoelectric elements that are "sandwiched" between matching and backing layers meant to optimize the ultrasonic wave transmission. The piezoelectric plate is coupled to electric terminals, which are connected to an electric source with an impedance, and when a voltage is applied across the terminals, the piezoelectric material compresses and expands at a frequency corresponding to the voltage, which generates the ultrasonic wave [2]. This is an important description, as these are all components that will be featured in the design of the ultrasound transducer for this project, and thus an understanding of the operating principles and how various components work together is essential. A description of the design process that was undertaken to design some of the essential parts of the ultrasound transducer can be found in Section 2 of this report.

Designing ultrasound systems involves the consideration of several electrical quantities, many of which are inversely related – that is, in satisfying one criterion, another may suffer. Rhyne explains that one such trade-off that can be made is between the transient response properties against signal bandwidth, all while satisfying physical feasibility. He adds that another such trade-off that is difficult to avoid is that of trading the bandwidth characteristics of the ultrasound transducer against its impulse response characteristics – because of this, there are often added difficulties in implementing the desired design with the desired time and frequency responses [2]. Daft et al. further stress the difficulties of choosing the appropriate values for various electrical and mechanical components of the transducer. They suggest that instead of having the engineers manually varying parameters to improve the imaging quality, that statistical or computer processes be used to find the optimal characteristics for peak performance [3]. For these reasons, simulations were one of the primary design methods chosen by the team to complete the project requirements – namely, to choose the appropriate thicknesses for the matching layers and piezoelectric material, to model grating lobes produced by the pitch spacing, and to plot the impedance and pulse traces. These simulations were performed in MATLAB and are further discussed in Sections 2 and 3 of this report.

Another important to consider when completing this project is to figure out why this project is relevant to industry, and how it compares to existing technologies. As was completed in the first assignment for the course, several competing products were found. One of the key differences was that the probe that is being designed in this project operates at a high frequency, is not forward looking, and is compact and usable in size. Major producers including SonoSite, Olympus, Siemens Healthineers and GE Healthcare do not operate near 40MHz, and either have drawbacks due to their bandwidth or overall size [4]. In addition to these products, Bezanson et al. agree that it is valuable to have high-frequency, small form-factor phased array transducer to generate high-quality images, but that these devices are rare in industry due to fabrication challenges [5]. Throughout the project, these competing products, along with other patented ultrasound probes developed by researchers across the globe, will continue to be valuable resources to ensure that the drawbacks found in their devices are considered in this design.

Finally, it was important to understand what ultrasound images generated from this design could look like. For this reason, images from the previous probe were included as a reference, which are shown in Appendix A.

1.3 Project Background & Scope

The development of this probe was an extension of an existing prototype developed by the Dalhousie Ultrasound Group. Features of this original endoscope probe include a forward facing

64-element high-frequency phased array with an operating frequency of 45 MHz. It has been fabricated using novel micro-fabrication techniques in which the array elements are wire bonded to the thickness a flexible circuit board [5].

The original probe was not long enough to reach the spinal cord through the retractor, and its operating frequency did not allow it to image to the required depth as described in the problem definition section. Finally, the original probe did not have a sufficient field of view to image the spinal cord in its entirety due to the angle in which the probe must be inserted. Figure 1.1 shows a comparison of the original, forward-facing probe, and the new design detailed in this report, which incorporates an angled design.

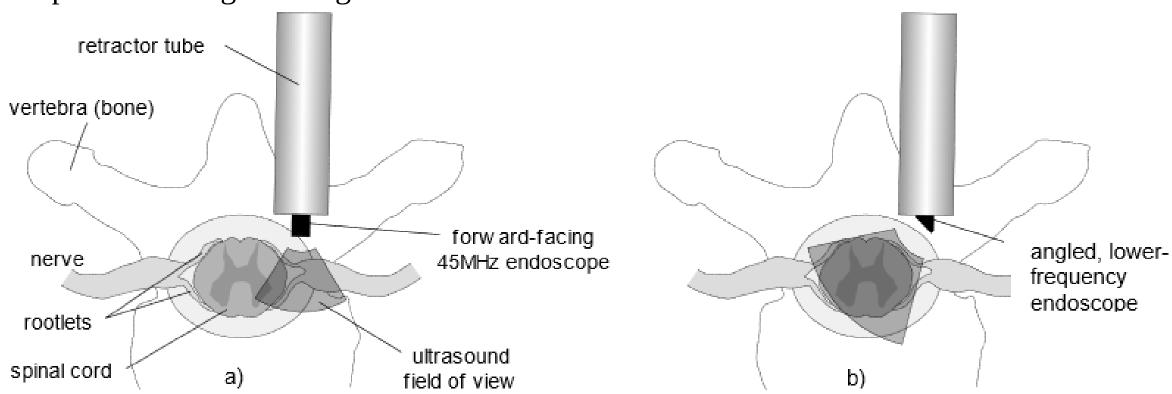

Figure 1.1 – Comparison of a) existing design, and b) required design [1]

The scope of this project involves redesigning the existing probe to meet the requirements of the new application, along with altering the existing supporting fixtures to facilitate its production or developing new ones specific to this design. It is also within the scope of this project to investigate new PCB production techniques that will decrease cost so the probe can be produced at scale.

1.4 Project Goals

The following list summarizes the goals for this project, related to both the physical design & fabrication of the probe, as well as the performance goals:

- Design a new circuit board to meet the demands of the new application.
- Determine possible production modifications for the PCB that will decrease cost.
- Determine the optimal angle for the array to create the pads for wire bonding, so the transducer array is mounted and bonded at said angle, in order to enable imaging at the determined angle, increase elemental pitch, and decrease operating frequency.
- Determine new matching layer properties required for new array.
- Design & fabricate a new mold for the silicone lens, along with a new stand to hold probe in place during coating.
- Test new paint-on silicone coating method for sealing.
- Interface with the phased array beamformer [6] in order to characterize and test the probe.

1.5 Sponsors/Supervising Group

This project was supervised by Dr. Jeremy Brown (External) and Dr. Rob Adamson (Internal). They are both involved with the Dalhousie Ultrasound Lab, which is a research group, directed by Dr. Brown focused on developing new cutting-edge ultrasound technologies. The resources and lab space used throughout the project are further sponsored by the NSHA and Daxsonics. Daxsonics was incorporated in 2011 by Dr. Brown and Dr. Adamson and provides services to other companies in ultrasound product development, specifically “technical expertise and engineering support for emerging applications in advanced ultrasound technologies”. Products and applications of their work include high frequency ultrasound transducers & beamformers, high-intensity focused ultrasound for thermal ablation and histotripsy, and advanced signal & image processing. Figure 1.2 below shows several probes and supporting equipment produced by Daxsonics.

Figure 1.2 – Daxsonics endoscopic US imaging probe [7]

2.0 Design Approach

2.1 Design Criteria and Constraints

The goal of this design is to create a product suitable for imaging the spinal canal during minimally invasive surgery after spinal trauma. To achieve this goal, several design criteria have been outlined in Table 2.1.

Table 2.1 – Design criteria for new probe design

Criterion ID	**Description**	**Importance (5: High, 1: Low)**
CR1	The probe targets the lumbar spine successfully	4
CR2	Probe is minimally invasive and safe for the patient	5
CR3	Probe can provide clear visualization of the nerves in the spine, with clear contrast	5
CR4	Probe is intuitive and easy to use	4
CR5	Probe is ergonomic in both size and design	3
CR6	PCB has a seamless design	5
CR7	Solid wire-bonding mold is flexible and can assemble all probe components as required	4
CR8	Array must be appropriate size	3
CR9	Matching layer designed to reduce signal losses through transmission	3
CR10	Probe has an extended field of view	5
CR11	Probe is less expensive than original design	5

There are also several constraints that will need to be adhered to throughout the project. These are outlined in Table 2.2.

Table 2.2 – Design constraints for new probe design

Constraint ID	**Description**	**Importance (5: High, 1: Low)**
CON1	Silicon mold must cover PCB with no holes or tears	4
CON2	Project must be completed on budget	3
CON3	Project must be completed on time	5
CON4	Project must be completed according to the availability of both the team and the internal/external sponsors	4
CON5	Project must be executed within the appropriate patents and intellectual property laws	5
CON6	Probe size must allow for usage within the spinal region, and allow for a fit in the probe holder	5

2.2 Probe Design

2.2.1 General Probe Modifications

In order to meet the design criteria, several changes are required. The first change to change the probe's viewing angle to approximately 45º, as nerve roots are situated at an angle of approximately 45 degrees to the direction of the telescopic access tube used in minimally invasive spinal procedures. This angle will move the field of view such that it points directly along the spinal cord. By spinning the probe 360 degrees, a very wide circular viewing area will be able to be achieved.

The probe must also be able to reach through the retractor all the way to the roots of the spinal cord – approximately 9 cm from the surface. Buffer length should also be added to allow the operator to easily and precisely maneuver the device without it being excessively tight to the point of entry.

2.2.2 Cost Reduction

Another significant modification involves the fabrication process of the flex PCB. The PCB was originally designed to have inner trace spacing of 3 mil, with 1.5 oz copper thickness. This design requires advanced manufacturing techniques, and as such many companies are not able to produce this board, or the cost is extremely high. Therefore, new manufacturing techniques were explored in an attempt to decrease the overall cost of the probe.

2.3 Supporting Fixtures

To successfully assemble the endoscopic transducer, supporting fixtures are required to assist in various steps of the assembly process. Because of the physical alterations to the PCB and subsequently the probe, alterations were required to several of the supporting fixtures to allow for production of the new probe. As the design progressed, these fixtures were kept top of mind. It was within the scope of the project to modify these fixtures as needed, and also to consider new production techniques that would reduce the need for their use.

2.4 Simulations

To characterize the performance of the design, simulations were chosen as one of the primary verification methods. Instead of having to produce each iteration of the design physically, the simulations allow for preliminary design results to be obtained. The simulations were all designed through MATLAB, both with programming and with external add-ons. Some of the simulations were developed from scratch, and others were built from existing simulations developed in the Dalhousie Ultrasound Lab.

2.4.1 Grating Lobe Simulations

The first set of simulations that were required were for the grating lobes. When designing an ultrasound transducer, grating lobes must be considered, as they can ultimately impact the generated image quality – the image quality is drastically degraded by grating lobes which produce large areas of constructive interference at specific angles. This is avoided when the pitch is equal to or less than the wavelength of operation.

To calculate the specific angle that grating lobes will appear, equation (1) below can be used. This equation gives the centroid location of grating lobes for a specific wavelength and can be used to show grating lobes of a center frequency. This, however, does not calculate the relative size of the grating lobes, and so cannot directly be transferred to a plot – equation (2) below must be used to determine the amplitude of the grating lobe plots across the range of [0, 2π].

(1) $\theta = sin^{-1}(\lambda/p)$ where λ = wavelength,

(2) $Amplitude = cos^2(\frac{\pi p}{\lambda})$ and p = pitch

These equations gave the first iterations of the grating lobe plots, produced using a simple MATLAB script, shown in Appendix B. It should be noted that these plots do not account for the bandwidth of the transducer and offer only an approximation of what to expect of the grating lobes.

2.4.2 Matching Layer Simulations

The next simulations that were performed were to optimize the matching layer (ML) values. The purpose of the matching layers is to allow for the maximum ultrasound transmission energy through the layers. As was briefly mentioned in the introduction, manually testing various thicknesses to optimize the matching layer values for peak transducer performance can be tedious, and computerized methods are the preferred method to complete this analysis, whenever possible. It was decided that performing simulations would be the best approach – this was done in using the MATLAB Graphical User Interface (GUI) provided by Dr. Thomas Landry.

The transducer output was simulated using mass-spring (parylene-copper) and quarter wavelength (thicker parylene) matching layers, with the aim of having a high peak voltage, a low pulse width, and a low amplitude in the tail region, which are optimized using a weighted average of these components, known as the "magic number", *M*. Figure 2.1 shows the model for the transducer layers that was used in the simulation.

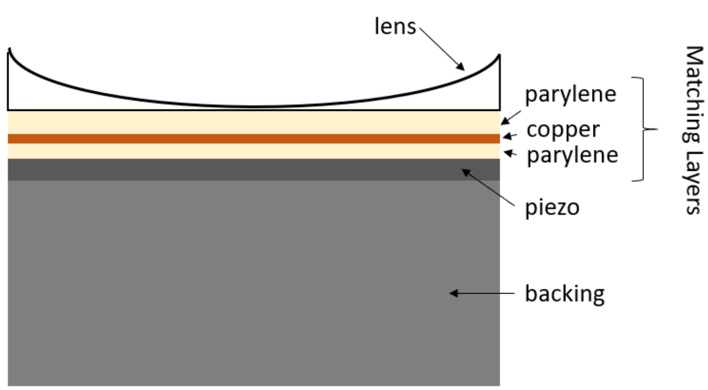

Figure 2.1 – Model of transducer layers [8]

The simulations were run using the KLM model in conjunction with an iterative approach – broad ranges of possible values for layer thicknesses were simulated, and the best result was flagged in each iteration. These ranges were first run coarsely so as to save time, and then when the range of values was condensed, the iterations could then become more refined to find the optimal combination, based on the high peak voltage, low pulse width, and low tail amplitude requirements seen with the overall lowest, or best, M number. The GUI for these simulations is shown in Appendix C.

After finding these optimal values through the simulation, they could then be entered to simulate the two-way pulse and impedance plots, described in the next subsection.

2.4.3 Two-Way Pulse & Impedance Simulations

The final simulations to perform were the two-way pulse and impedance simulations. These were also produced by the MATLAB GUI provided by Dr. Landry. These simulations produced four plots – an impedance, two-way pulse shape, phase, and two-way pulse FFT. Again, the same optimizations were desired – a high peak voltage increases the SNR and penetration depth, while a smaller tail amplitude can improve the imaging resolution and reduce the number of unpredictable image artifacts [8].

These simulations were run after the optimal values for matching layer thicknesses were found in the matching layer simulations. These values were then plugged into the GUI and were run along with the known transducer area of 7.97mm^2 and a measured piezo thickness of 52um, to produce the four plots. The GUI for the two-way pulse and impedance simulations can be found in Appendix C.

3.0 Proposed Solution

3.1 Probe Modifications

This section of the report will discuss all the decisions regarding the modifications to the endoscopic probe. Included in this section is the technical backing to the decisions made and justification.

3.1.1 Operating Characteristics

Given that the minimum line separation possible on the PCB is 38µm, and the pitch of the array was chosen to be 48µm, it was determined that the probe must be cut at an angle of:

$$cos\theta = \frac{38\mu m}{48\mu m} \quad \rightarrow \quad \theta = 37.7º$$

The probe uses a phased array and has the ability to view to an angle of 45º already, so this provides the necessary field of view in order to be able to observe the nerve roots in the spinal canal through the typical incision. Given the new angle of the tip and increased pitch, the frequency is reduced by the same factor by which the pitch was increased, in order to ensure that the grating lobes remain at their original profile. The new frequency can be calculated as follows:

$$f = 45MHz \cdot \cos{(37.7º)} = 35.625\ MHz$$

For simplicity, it was decided that the frequency used will be 36 MHz, as this small change will not affect the grading lobe angle to any significant degree. This frequency works well for the probe's desired application, as it is low enough to allow for the required penetration depth into the spinal canal, which could not be achieved at 45 MHz. It should be noted that the wavelength is inversely proportional to the frequency of operation, and can be calculated using:

$c = f \cdot \lambda$, where c = 1500m/s, and f = frequency, giving $\lambda = \frac{1500\ m/s}{36\ MHz} = 41.67\mu m$

3.1.2 PCB Modifications

In order to adapt the original probe design to fit the spinal probe application, several PCB modifications were necessary. As mentioned earlier, the probe needed to be extended in length to reach the spine through the retractor, and additional length added to improve mobility and overall ease of use. Since the PCB runs the length of the probe, this means the length of the PCB had to be increased to the desired 9.5 cm from the bend to the tip. As discussed previously, the PCB also needed to be cut at approximately 38 degrees. An image of this is shown in Figure 3.1.

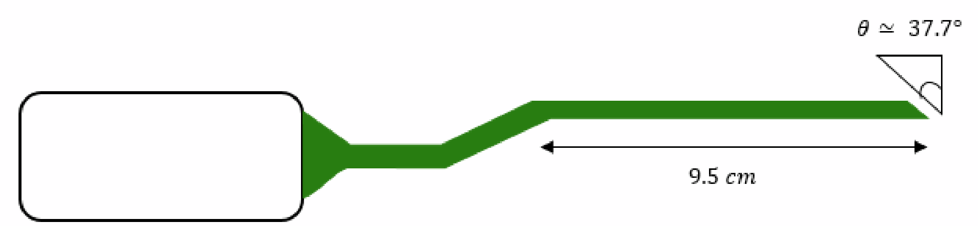

Figure 3.1 – New angle mock-up

3.1.3 OrCAD Alterations

In order to achieve the new design, the board outline and traces were extended and maintained in a straight rectangular shape. The ground planes and solder mask layers were also extended and terminated at the proper angle. These layers were not kept rectangular at the tip, because they are required to be set back slightly from the end of the probe to facilitate the wire bonding process – as the fabrication process requires manual wirebonding, it is essential to leave sufficient space to wirebond to the pads. Also, it was decided that the angled cut would be performed during the probe fabrication process instead of during production of the PCB itself, facilitating the editing process by allowing the board outline to remain square at the tip for production purposes. This way, the traces do not have to extend right to the end, and will be exposed only when the board is cut in the lab. Some unnecessary layers were removed, such as the route keep-out layers to simplify the design. Finally, the IPEX connector was removed, which would further reduce cost and manufacturing complexity.

3.1.4 PCB Cost Reduction

For this project, three modification options were selected for exploration. The first involved extension of the inner layers so that protruding parts could be coated up to 1.5 oz in the finishing process. This would provide the thickness required for wire-bonding, while leaving the true 'inner' section thinner. The second option was to bring inner traces out to the outer layers at the very end of the board. The outer layer would then be coated to 1.5 oz, as this is easier than producing 1.5 oz on the inner layers. The option of panelizing the design was also suggested, which involves producing multiple of the same design on one sheet and then cutting out the individual PCBs at the lab. In this case, the multiple PCBs could be produced at the same time, and would then be cut out when they reached the lab using either the laser or the dicing saw.

The final option was to split the single 4-layer design into two 2-layer boards, which would have no inner layers from the perspective of the manufacturing company. These two boards would then be combined during the fabrication process in the US lab. In this option, the original 4-layer design would be split onto two, 16-trace boards whose traces are offset. When the two sides are then glued together, the result is the equivalent of the original 4-layer board, but avoids having to produce boards with 1.5 oz copper on inner layers.

Each of these options will be explored with various PCB companies, and the best method will be determined based on cost and also practicality in terms of production.

3.2 Supporting Fixtures

The current developments and future ambitions of the fixture designs will be discussed in this section of the report.

3.2.1 Wire Bond Holder

Original concern was that the new probe would be too long to fit in the wire bonding holder. However, for the purposes of this project, it was determined by Dr. Brown that the existing wire bond clamp would suffice as the proposed tip would allow the board to be held at an angle while wire bonding such that it would still fit under the microscope. Therefore, no changes ended up being made to this fixture.

3.2.2 Lens Mold

For the silicone coating, a new technique has been introduced that no longer requires a mold. Instead, the probe is held in a stand, and silicone is applied in layers via brush or dipping. As such, no new mold is needed for the entire probe. For the lens, the original design was extended slightly, but the main components were kept very much the same. An image of the proposed mold can be seen in Figure 3.2.

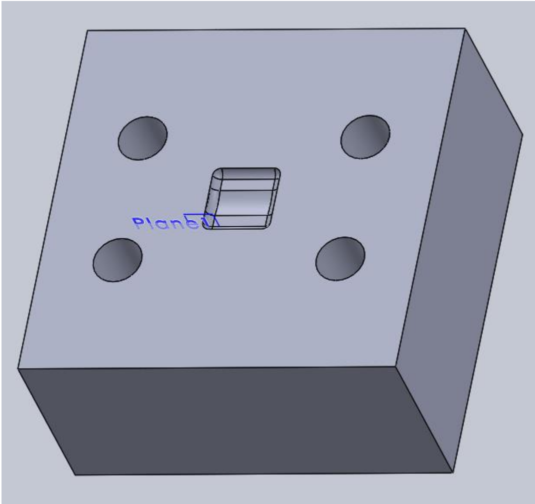

Figure 3.2 – Lens mold SolidWorks model

3.3 Simulations

This section of the report will be discussing the simulations that were completed.

3.3.1 Grating Lobe Simulations

The first simulations were run using a simple MATLAB script, without accounting for the bandwidth. This script can be found in Appendix B. Running the script for a pitch of 38 microns at 45MHz, and for a pitch of 48 microns at 36MHz, the following results were obtained to approximate the grating lobes that should be expected for the design.

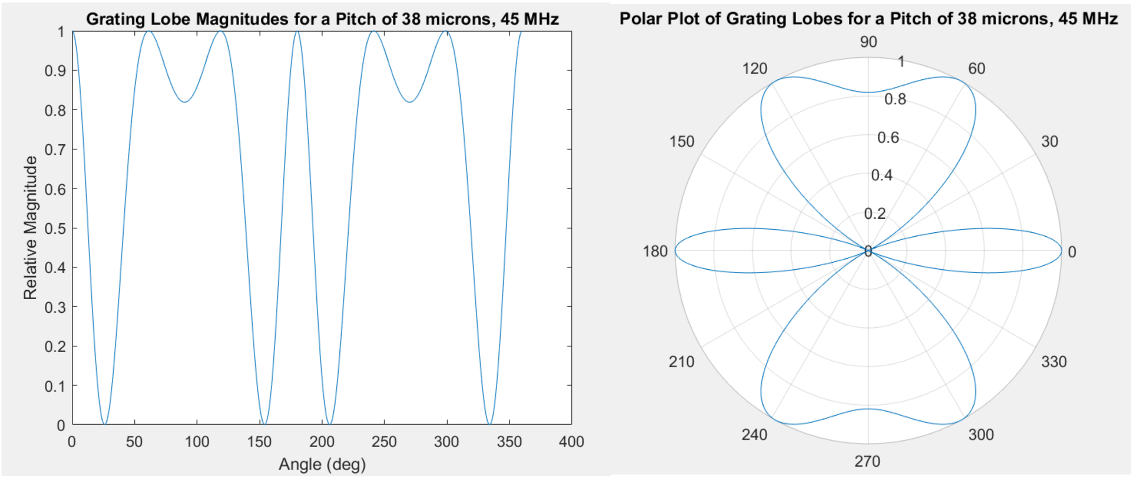

Figure 3.3 – Magnitude and polar plots of grating lobes for 38-micron pitch, at 45MHz

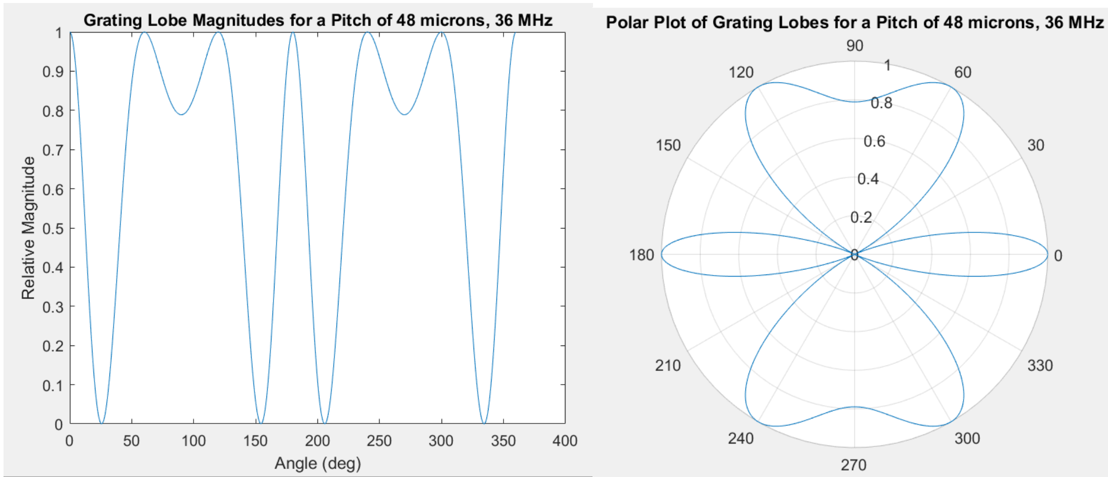

Figure 3.4 – Magnitude and polar plots of grating lobes for 48-micron pitch, at 36MHz

The goal was to achieve approximately the same grating lobe profiles as the original design. In increasing the pitch, according to the grating lobe formula, the wavelength would then have to be increased proportionally, which in turn decreases the frequency by the same factor – this yields the frequency of 36MHz. The two conditions both have grating lobe profiles that are extremely similar, if not identical, to each other, which shows that the simulations produced the expected results. This in turn means that changes in grating lobes are not a concern – the same grating lobe effects as were seen with the original design can be expected in the new design, and do not need to be further accounted for. The grating lobes were expected to be at an angle of:

$$\theta = sin^{-1}\left(\frac{\lambda}{p}\right) = sin^{-1}\left(\frac{33.33um}{38um}\right) = 61.3°,$$

This angle is seen in the plots, confirming the validity of the simulations. It should be noted that these grating lobes do not consider the bandwidth of the probe and are only using the center frequency. As was previously mentioned, at this time, the bandwidth has not been fully accounted for – this is an area for future work, when simulations using Field II are performed.

3.3.2 Matching Layer Simulation

The matching layer simulations were run multiple times, to obtain solid results while ensuring that the simulations did not take too long to run. Most iterations cycled through approximately 3000-5000 different combinations of values for the matching layers, beginning with coarse settings, and then refining the search criteria to focus in on the values that produced the best range of results, and re-running the simulations with these more refined iterations. The values for the final round of simulations are shown in Appendix C. After completing these simulations, the following plots were produced for the ten best combinations of matching layer values, as shown in Figure 3.5.

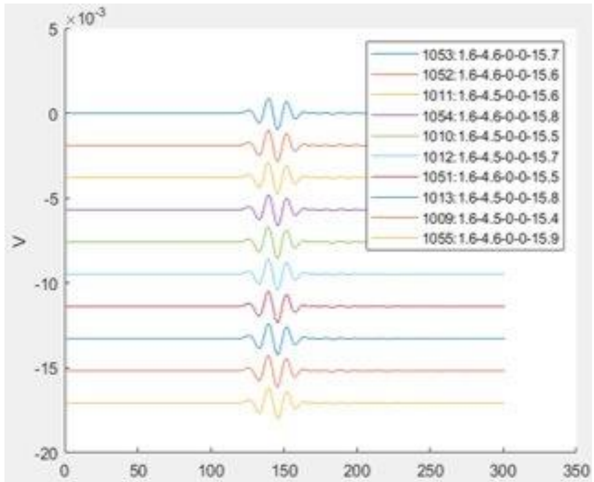

Figure 3.5 – Optimized ML simulation results

From the results as shown by index 1053 on the right, the optimized values were found to be:

- Mass-Spring 1 Parylene: 1.6µm
- Mass-Spring 1 Parylene: 4.6µm
- Mass-Spring 1 Parylene: 15.7µm

These numbers were then plugged into the two-way pulse and impedance simulations, to obtain plots of the simulated two-way pulse and impedance.

3.3.3 Two-Way Pulse & Impedance Simulations

After plugging in the values found in the previous simulations, using a piezo thickness of 52um as measured using a micrometer in-lab, and using a transducer area of 7.97 mm^2, the following plots were produced, shown below in Figure 3.6.

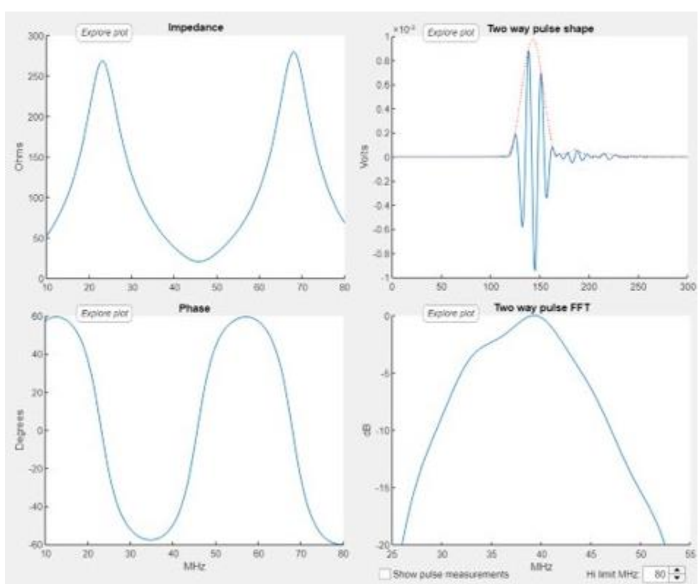

Figure 3.6 – Two-way pulse and impedance simulations

These plots show a high peak voltage, a low -6dB pulse width, and a low tail peak amplitude, which are all results that were desired in the design, and ultimately have a low M number as desired. This confirms that the values determined in the previous simulation were good choices for matching layer thicknesses.

These plots will be compared with the acoustic measurements obtained from the VNA in Section 4.2.

3.4 Assembly Process

To fully understand the scope of this project it is necessary to deconstruct the product that is being developed. This subsection will demonstrate the physical fabrication of the 64-element high-frequency endoscopic phased array that will be built for this project. For reference, the information presented in this section has been collected from Andre Bezanson, Rob Adamson and Jeremy A. Brown's article entitled "Fabrication and Performance of a Miniature 64-Element High-Frequency Endoscopic Phased Array" [5]. Photos of the assembly process have also been taken from the referenced article for clarity of visualization, shown in Figures 3.7 to 3.10.

Figure 3.7 – Photograph of the mounted piezo sample

Figure 3.8 – Photograph of sample being lapped

Figure 3.9 – Photograph of laser etcher from Oxford Lasers

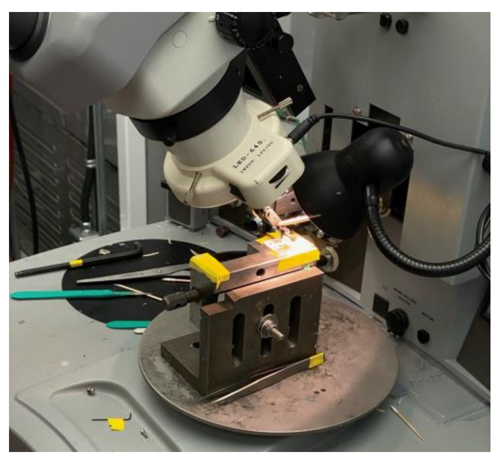

Figure 3.10 – Photograph of sample being wirebonded

In the following Table 3.1, the major steps in probe fabrication will be discussed. The assembly of the endoscope has been divided into 15 major steps, however, each of these steps contain smaller steps which will be briefly described in the "Description" column. It should be noted that on occasion, the order of these steps may be switched, depending on the progression of tasks.

Table 3.1 – Endoscope assembly process

Step	Title	Description
1	Prepare the piezo samples	The piezo-electric samples must be diced to the desired size and mounted to the glass slides for lapping preparation.
2	Lapping the samples	The thickness of the mounted piezo-electric sample must be measured using a micrometer, and then lapped to the desired thickness using the lapping machine.
3	Deposit copper	The lapped sample is placed in the "sputtering machine" to deposit a thin layer of copper over the sample.
4	Parylene coating	The amount of parylene required for the sample is determined from both the simulations and by the parylene calibration tool in the lab. Once calibrated, the sample is placed in the parylene coater overnight to deposit a thin film of parylene over the sample. This is done by vaporizing the parylene powder in the parylene coater, and thus this machine must be thoroughly cleaned regularly.
5	Applying the matching layers	The matching layer is applied, according to the required thickness determined in the KLM optimizations.
6	Applying the backing layer	The backing layer is applied.
7	Laser etching the elements	The elements are laser etched using the laser from Oxford Lasers, and the programs developed in-lab.
8	Epoxying the electrode to the PCB	The flex PCBs are aligned and epoxied onto opposite sides of the transducer stack, allowing the diced vias to be aligned with the wire-bonding pads on the array.
9	Wire bonding	Wires are bonded between the vias and the array's wire-bonding pads using wire-bonding hardware and a fixture to hold the flexible circuit boards.
10	Soldering grounding wires	The grounding wires on the back side of the array (outward-facing from the flex PCBs) are soldered to grounding pads on the surface of the flex circuits.
11	Sides are encapsulated	Sides of the assembly are encapsulated in insulating epoxy.
12	Wire bonds are encapsulated	The wire bonds are encapsulated with a thick insulating epoxy.
13	Lens mold is applied	The lens is fabricated and bonded onto the front of the endoscope with a thin layer of Epotek 310 (glue).
14	Coaxial cables are soldered onto the flex	64 micro-coaxial cables rated for 50Ω impedance are directly soldered to soldering pads on the flex cable.
15	Endoscope is packaged into small casing	The finished endoscope is packaged into a small plastic casing that is 3D printed, in addition to coating the transducer with silicone.

It should be noted that due to COVID-19 restrictions, several fabrication steps were done by the Dalhousie Ultrasound Group directly. These included completing the wire-bonding, applying the matching layers, backing layers, and lens, dicing and laser etching, soldering the connections, and the final casing.

3.5 Verification & Testing Strategy

Table 3.2 below describes a brief summary of the verification goals developed by the group. These are broken down into 4 categories, including flex PCB, cost reduction, transducer, and overall design.

Table 3.2 – Brief verification goals

Task	**Brief Description**	**Quantifying Verification**	**Qualifying Verification**	**Applies To**
Flex PCB Modifications	New ultrasound probe PCB changed to provide visibility to spinal nerve rootlets.	Comparing the grating lobes to the simulations obtained.	Are rootlets visible? Does the ultrasound angle provide visibility?	CR1, CR3, CR8, CR9, CR10 CON6
Manufacturing Cost Reduction	Reduce production cost of flex PCB used in this project.	Compare the past cost to the new and improved cost.	Is cost of modified flex PCB less than that of previous versions?	CR11 CON2
Electrode Matching Layer Design	New design must perform to the standard defined by the client.	Comparing impedance and waveform measurements to the optimized values obtained in the simulations.	Does the real waveform allow for sufficient resolution and contrast?	CR3, CR9, CR10
Overall Design	Ensuring that the overall design meets the client requirements.	Ensuring that all design criteria are complete, and that probe is ready for use.	Are both the team and client satisfied with the work that was done? Does the resulting product meet client needs?	CR2, CR4, CR5, CR6, CR8 CON3, CON4, CON5

These categories each involved subtasks for testing and characterization. Throughout the fabrication and assembly process of the probe, continuous testing was done to ensure all modules were functioning as expected and that the project remained on track. There were many possible errors throughout the fabrication process that could have negatively impacted performance, including variations in flex traces and coaxial cables, imperfections in the array elements, deformities during wire bonding, and inactive or shorted elements, among other things. To avoid some of these fabrication errors, the main considerations in testing were measurements of the electrical impedance, bandwidth, 2D imaging, and tissue phantom imaging performance. The testing plans were continuously developed with direction from the project supervisors and relevant publications and were continuously adapted to comply with the constantly evolving COVID-19 restrictions, which limited lab access at times. The major required testing steps were identified and are broken down below.

First is electrical impedance testing of all elements. The magnitude and phase of the electrical impedance of each array element was measured, using a vector network analyzer that was calibrated to measure the impedances of each element, and that could easily multiplex between elements. The pressure voltage relationship of any piezoelectric transducer can be simulated using the circuit model developed by Krimholtz–Leedom–Matthaei (KLM) [9], which is what was used to further characterize the acoustic performance of the transducer. The experimental impedance test results were compared to the KLM simulation models that were used during the design phase as a verification method.

The probe was then connected to the imaging platform and beamformer to gather images of tissue phantoms – essentially, the transducer was put to the test by analyzing the extent to which it could produce a quality ultrasound image. The phantom contained anechoic voids that would absorb the sound wave, which was known to provide a contrast measurement of an object with properties close to the desired application.

4.0 Results

4.1 PCB Design

The final PCB design and the alternative manufacturing methods and companies will be detailed in the following subsections.

4.1.1 Final Design

The final PCB design is a 4-layer design with three possible sets operating of operating cases, with the final design overview shown in Figure 4.1 below. The first section, at the tip of the probe, is meant specifically for the spine surgery imaging application. The other sections have traces fanned out to a different pitch and a silkscreen lines for guidance during cutting, which results in the varied sets of operating characteristics. Figure 4.2 shows a zoomed view of the tip of the probe, with the three unique sections.

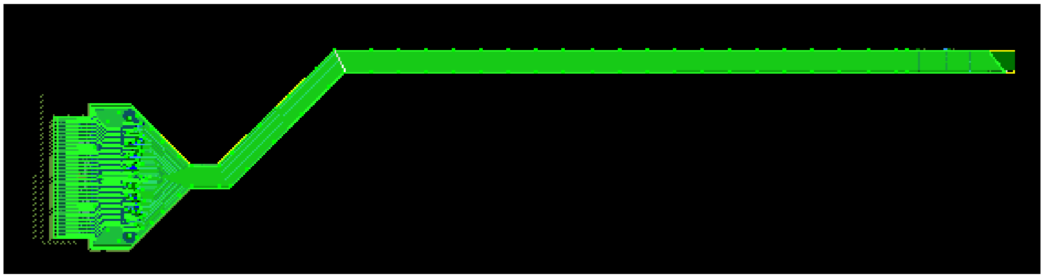

Figure 4.1 – PCB design overview

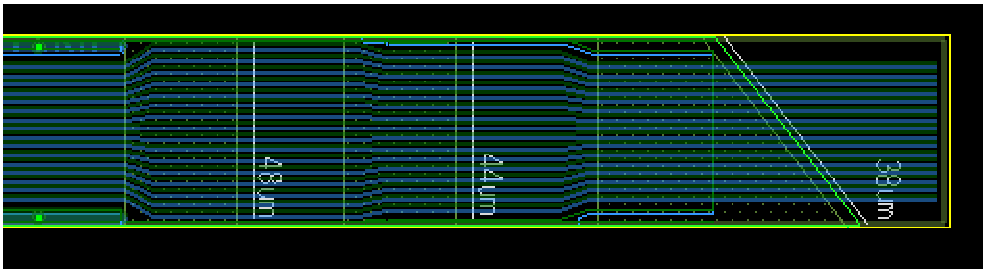

Figure 4.2 – Zoomed view of the tip of the PCB

The three sections of the probe and the associated operating characteristics are summarized in Table 4.1 below. As in seen is the row for case 2, the achieved design is very close to the theoretical values selected in the proposed design.

Table 4.1 – PCB characteristics summary

Case	Length of Arm (mm)	Total Length (mm)	Pitch (µm)	Angle (°)	Effective Pitch (µm)	Frequency (MHz)	Wavelength (µm)
1	97.348	138.092	38	37.7296	48.046	35.591	42.146
2	93.812	134.556	38	0	38	45	33.333
3	90.544	131.388	44	0	44	41.250	36.364
4	86.776	127.520	48	0	48	35.625	42.105

Figure 4.3 and 4.4 show the stack-up of the PCB. The design requires the trace impedance to be in the range of 50 to 75 Ω. As can be seen in Figure 4.3, the trace impedance is 49.879 Ω, which was deemed acceptable. Analysis of the trace impedances for the probe fabricated in lab is included in section 4.2. These results show slightly different values than estimated by OrCAD, as the probe used for fabrication and testing contained the original model PCB, not the new design. The overall thickness of the board is 0.44944mm, which fits the requirement for the ZIFF connector used at the base of the PCB. Figure 4.5 shows that base of the PCB, where it will connect to a cable to interface with the computer and allow images to be generated and collected.

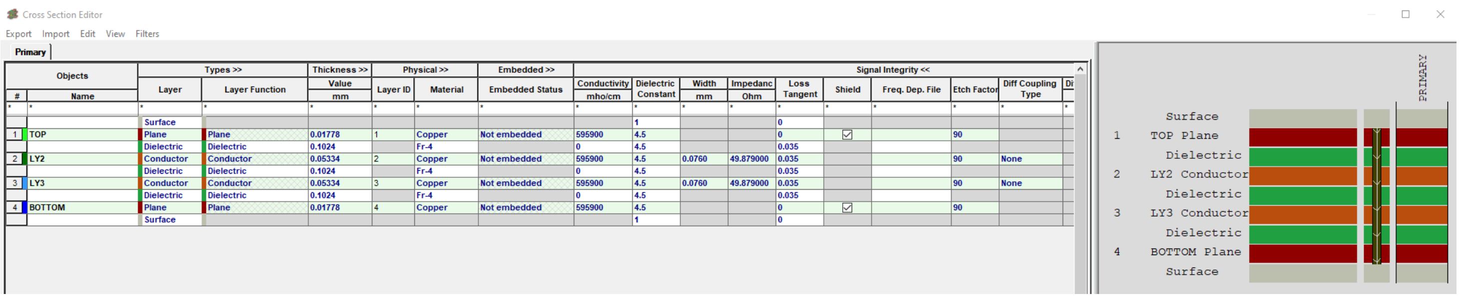

Figure 4.3 – PCB stack up I

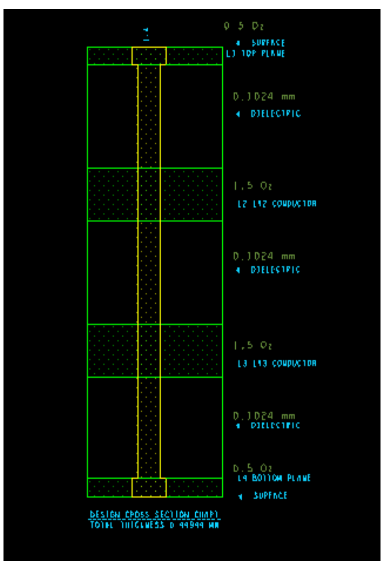

Figure 4.4 – PCB stack up II

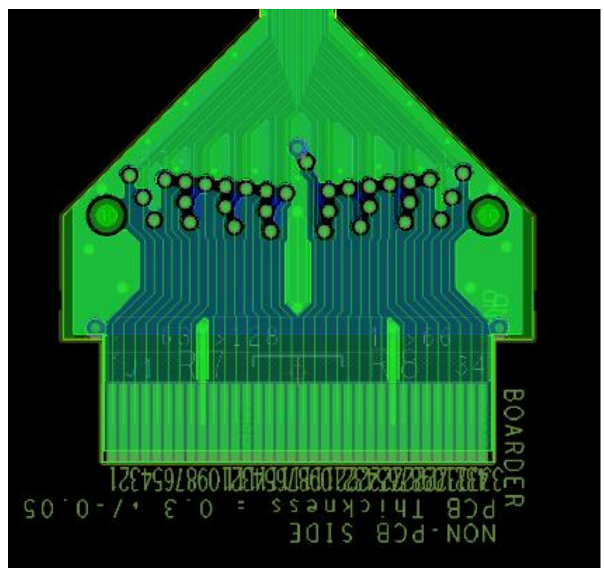

Figure 4.5 – Base of PCB

4.1.2 PCB Manufacturing

This modified final design was sent to three new companies to determine if their manufacturing processes would be able to meet the design requirements for the 4-layer board. Various issues were encountered, primarily due to the small trace spacing and 1.5oz copper thickness for the traces on the inner layer, which are not typically supported. Other alternatives, as described in Section 3.1.4, were then proposed to see if they would work. First, the possibility of using regular PCB instead of flex was considered, which was not generally possible for manufacturers to use and still meet the requirement for overall board thickness.

The option of panelizing the design was then proposed, however, this was not selected as it would increase the complexity of the fabrication process in the lab, which increases the labor cost. As the reduction in PCB price was not substantial, this option was not deemed feasible.

The 2-layer flex design was then examined thoroughly, as manufacturers were continuing to express concerns regarding the 1.5oz inner layer copper thickness. The PCB files were modified to split each side into 2 separate designs, each with either the top or bottom layer and one etch layer (1 set of 16 traces), yielding 4 designs overall. This alternative was possible for one of the companies, but was still not viable for another.

At this point, one company – ALLPCB – discovered that one of their factories could, in fact, produce the 4-layer design with 1.5oz inner layers. This was the preferred option, as it reduced overall fabrication time in the lab and simplified the process, and was therefore confirmed as the final design. It was also decided that only one board was needed, and with slight modification to the PCB files, could be adapted to be used on both sides. The final design was sent to ALLPCB for production.

4.2 Probe Assembly

Despite the restrictions imposed by COVID-19, the group was able to carry out the entire assembly process as described in Section 3.4, developing and laser-etching a sample, adding the backing layer, and mounting it with a PCB. To complete the prototype, an old PCB from Microconnex was used. The only difference between this and the new PCB is the length, and the fact that it was not designed to be cut at an angle. However, for prototyping purposes, it was enough to construct and test whether it served the purposes it was designed to.

Several new approaches were used in the assembly of this probe. First, several 2-layer boards similar to our proposed design were acquired from Daxsonics, and the ability to align the two sides and glue them together was tested. This was relatively successful, as the resulting alignment was good and did not end up requiring an external alignment tool. The results, as seen through a microscope, can be seen in Figures 4.6 and 4.7.

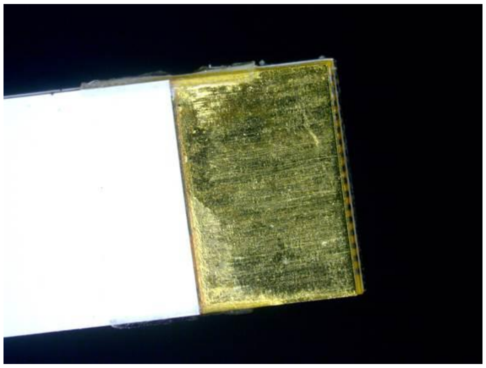

Figure 4.6 – Side view, 2-layer PCB assembly

Figure 4.7 – Top view, 2-layer PCB assembly

This result is promising, as it suggests that the additional work required to assemble the 2-layer option may not be as cumbersome as originally thought.

The ability to assemble the board with the new angled tip was also tested. Using one of the electrodes produced by the group and an old Microconnex PCB, a prototype was created with this new angled tip. It was found that, although the board's shape was different than any that had been built previously, it did not significantly affect the assembly process. With the angled tip, the electrode could still be attached without problem, and wire-bonding could take place using the existing wire-bonding holder. Images of the completed probe are shown in Figures 4.8, 4.9, and 4.10.

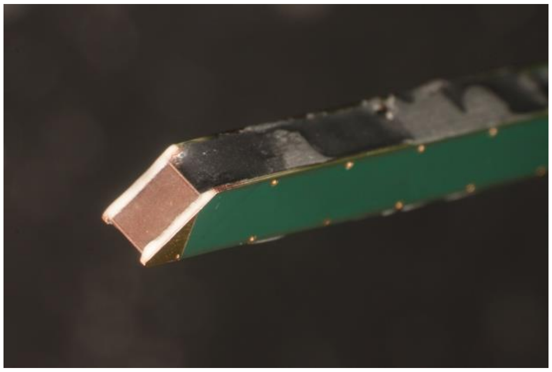

Figure 4.8 – Close-up image of final prototype with angled tip

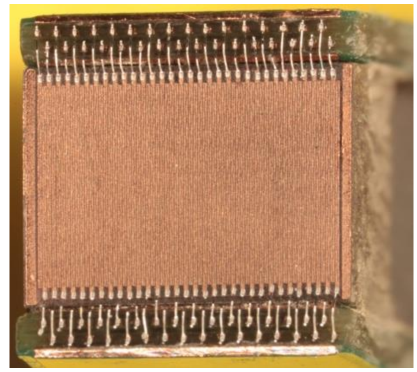

Figure 4.9 – Close-up of wire bonds on probe with angled tip

Figure 4.10 – Completed prototype for new angled probe

With the prototype's assembly complete, the probe's effectiveness could now be tested according to the testing strategy outlined in Section 3.5.

4.3 Impedance Testing

To characterize the performance of the transducer, Impedance results were obtained for some of the elements of the transducer array to analyze the impedance. As was shown in Section 3.3, simulations were performed to model the acoustic performance of the transducer, however, to truly verify the success of the probe and the accuracy of the simulations, these results had to be compared to results obtained by in-person tests.

The tests were performed using the VNA in the Ultrasound Lab, where both the impedance and phase were measured against the frequency of measurement. Of particular interest were the impedance measurements, and so the phase measurements are not shown as they are not as important for the classification of the acoustic properties.

Five of the 64 elements were chosen to show the impedance measurements against frequency – specifically, elements 5, 8, 12, 16, and 21. These plots are shown below, in Figures 4.11 to 4.15, respectively.

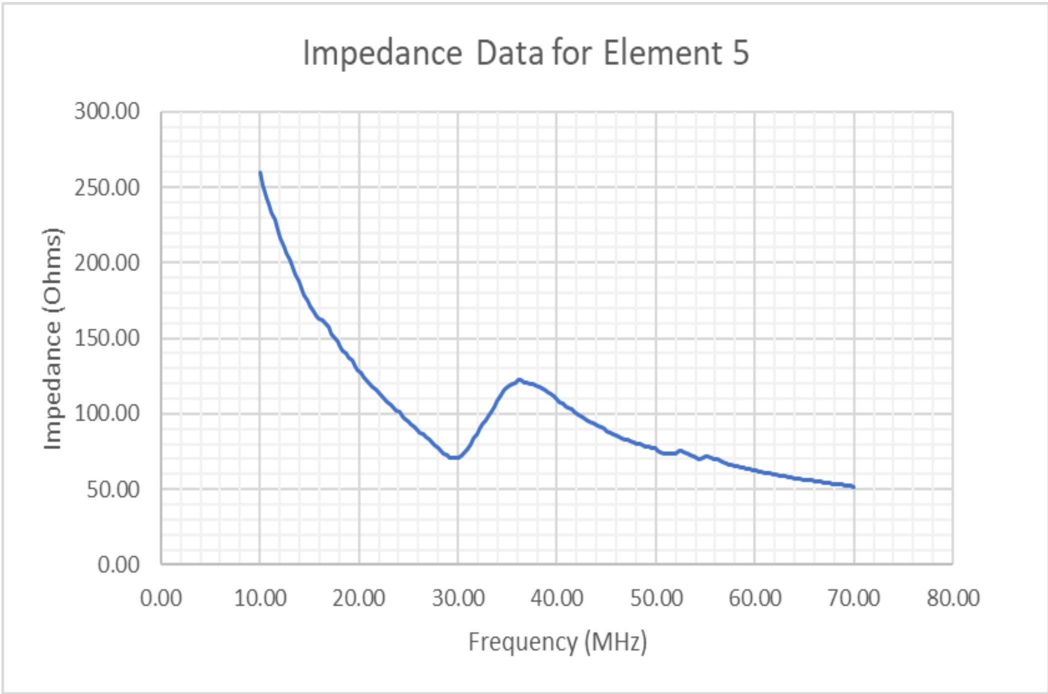

Figure 4.11 – Impedance data for element 5

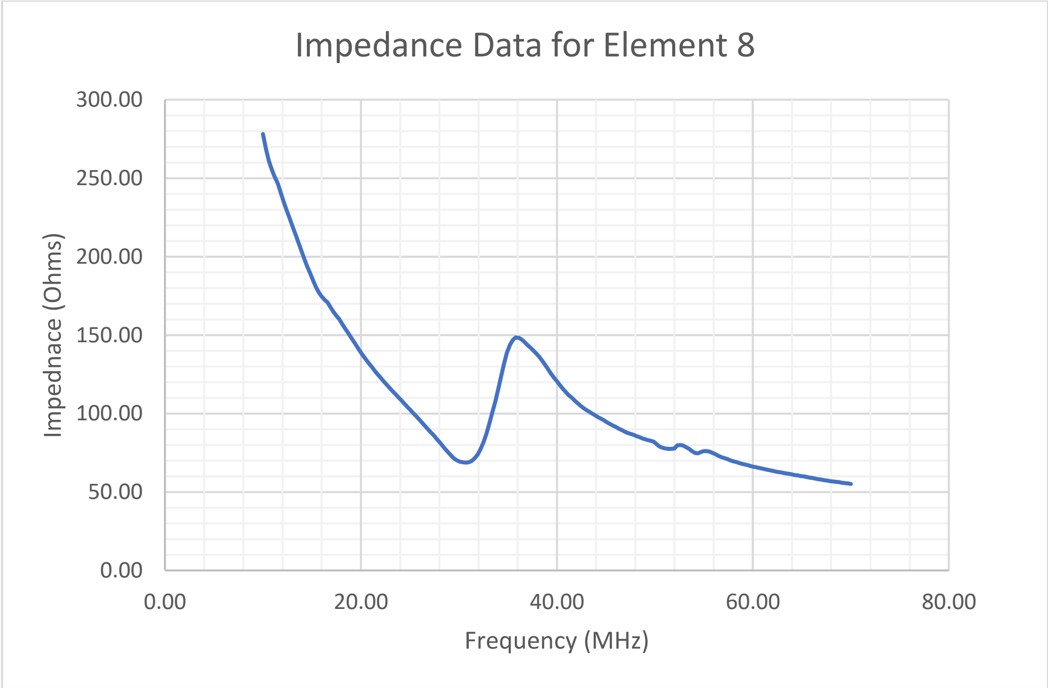

Figure 4.12 – Impedance data for element 8

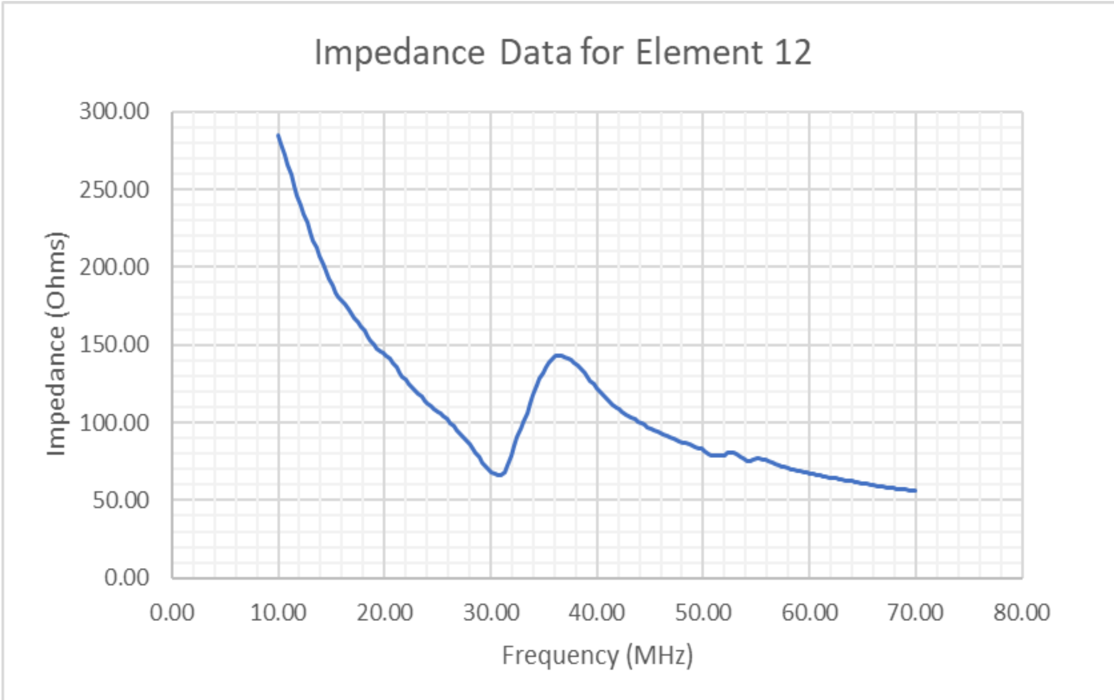

Figure 4.13 – Impedance data for element 12

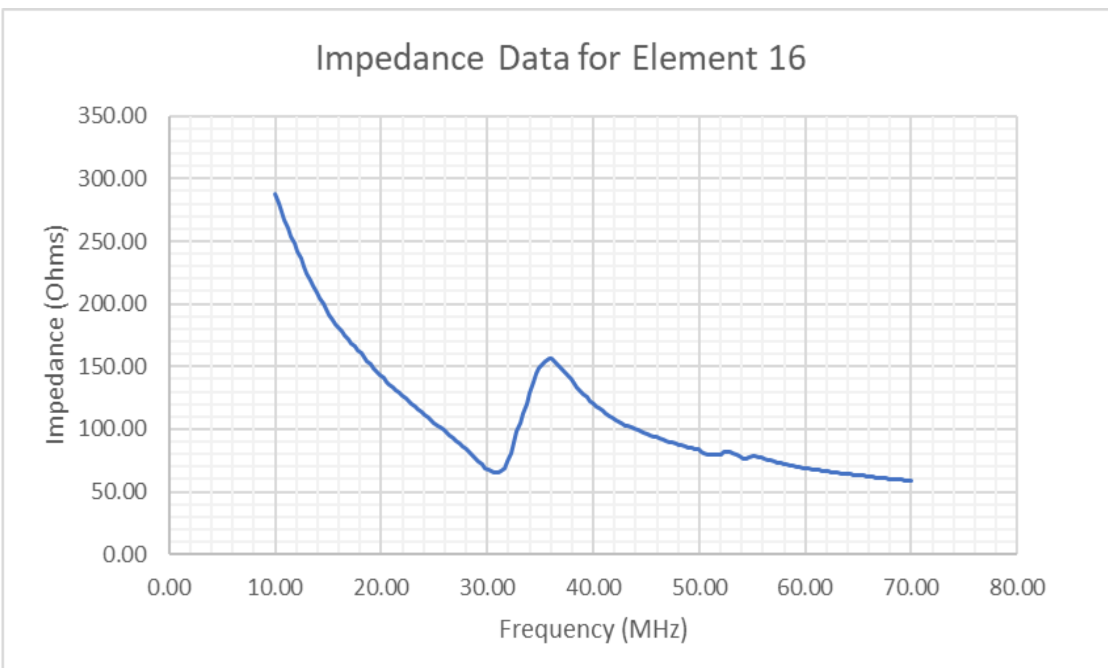

Figure 4.14 – Impedance data for element 16

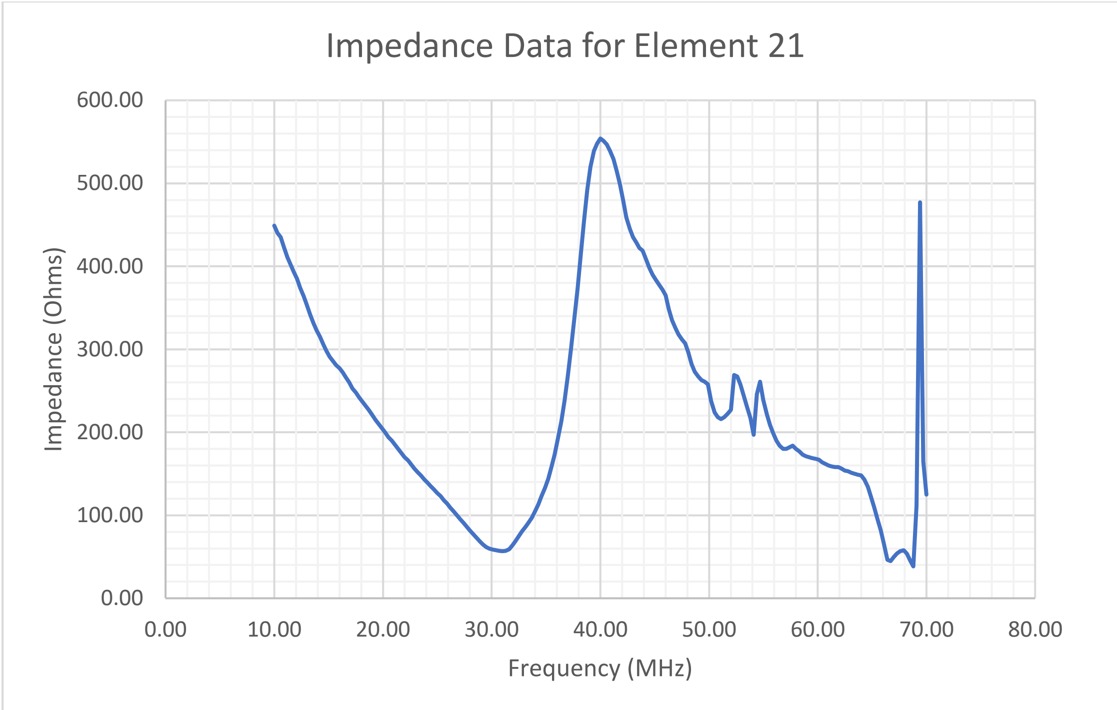

Figure 4.15 – Impedance data for element 21

From the plots, the resonant and anti-resonant frequencies were identified by the first trough and subsequent crest, respectively. Of highest interest, the resonant, or center, frequency of these five test array elements was noted to be roughly 30-32MHz, with impedances of approximately 60-70 ohms.

When the PCB was being designed, the goal was to have trace impedances of approximately 50-75 ohms, so these impedance values were exactly as expected. However, as was mentioned in the proposed solution section, the expected center frequency was 35.6MHz, which is higher than the measured 30-32MHz frequency from the impedance analyzers. Generally, however, the shapes of these impedance traces match quite well with the simulated impedance traces as shown in Figure 3.6. It should be noted that the simulations place the center frequency at roughly 45MHz, which was consistent with the old design, however it did not show a center frequency of the proposed 35.6MHz center frequency. Additionally, the frequency difference between the resonant and anti-resonant frequencies in the simulations is larger than in the measured results. Aside from these discrepancies, however, the results agree quite well with the simulations – the plots are generally shifted and frequency-scaled versions of one another.

The impedance plots for elements 5, 8, 12, and 16 have very smooth and defined shapes, yet for element 21, there are a few extra bumps that are not seen in the other elements. This can be attributed to the fact that the impedance measurement for element 21 was done at a different time than the other four test elements – specifically, after the transducer elements were re-poled, which could account for the noted variations in electrical acoustic performance.

4.4 Image Testing

Ultimately, the goal of this project was to produce a working, high-frequency ultrasound transducer, which can produce high quality images. Towards the end of the term, the transducer was fully assembled and capable of producing ultrasound images for analysis.

The new probe was used to image a wrist in movement, where the blood flow can easily be seen. A test image is shown below, in Figure 4.16.

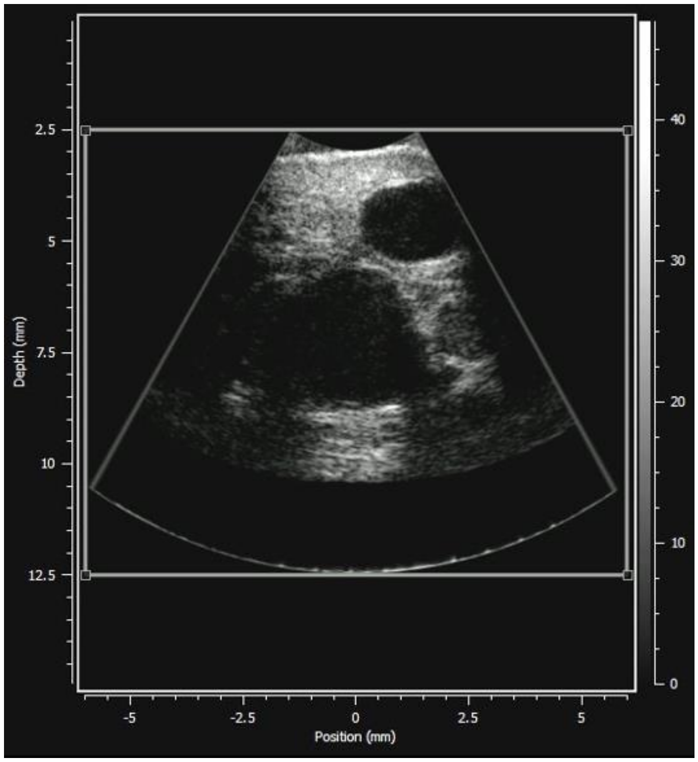

Figure 4.16 – New probe imaging a human wrist in motion

Creating a clear ultrasound image was considered to be a success for this project, and the fact that the probe was able to produce a relatively high-quality image was an excellent sign. It is evident that there is contrast between different tissues, however this contrast may not be as significant as desired. However, as a first iteration for the new transducer designed by Group 11, this should be considered a success that can be built upon in the future.

5.0 Project Management

5.1 Task Distribution

The team decided to split the biggest tasks, excluding all lab work, into four major categories and assign subtasks on a case-by-case basis. The four main tasks for this project were as follows: PCB modification, fixture design, simulations and analysis, and cost reduction. These categories were presented to the group as being the most significant for this project, and therefore had high priority.

For the task distribution of the four main tasks, the PCB modification was done mostly by Megan and Graeme. Fixture design was completed by Alexa, simulations and analysis was led by Sierra. Finally, the cost reduction was taken on predominantly by Megan, which entailed emailing PCB manufacturing companies.

All the tasks involving hardware, fabrication and assembly were completed together, with every member of the group being present in the lab at the same time. It was decided early into the Fall 2020 semester that each of the group members could benefit from lab time, and everyone was interested in being part of the build process with Dr. Brown. The tasks in the lab were shared evenly, with each group member contributing to each step of the probe assembly.

5.2 Kanban Board

One of the biggest tools that was used by the team in scheduling and assigning tasks was the use of a *Kanban* board. A Kanban board is one of the tools used in Agile project management, said to "help visualize work, limit work-in-progress, and maximize efficiency" [10]. In a Kanban board, individual tasks can be described and placed into different columns on the board, which describe the current status of the task. GitHub was chosen as the platform to host the Kanban board and related project tasks, as it is free, easy to use, and meets all requirements from the team.

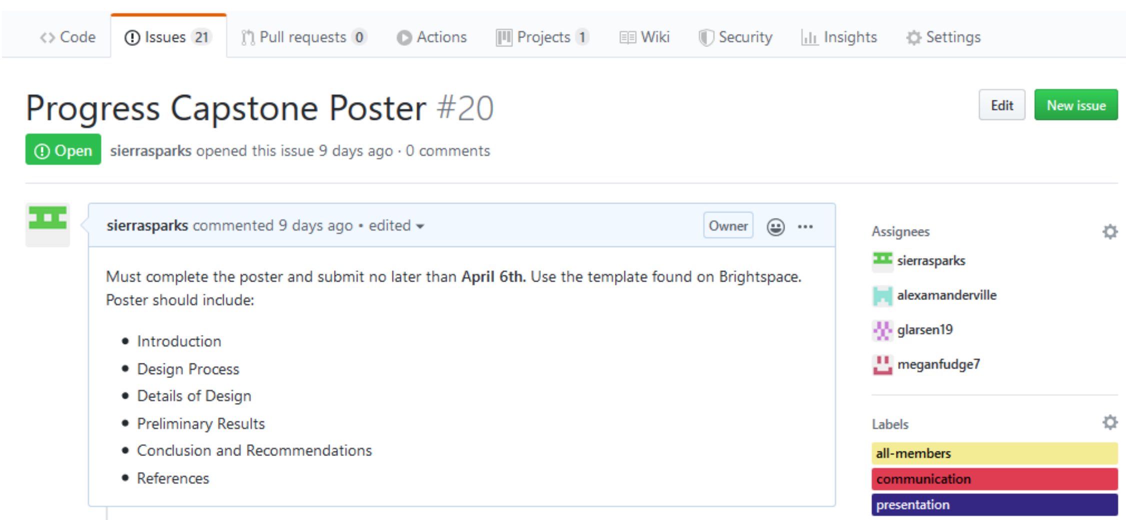

Figure 5.1 – Sample entry for a new issue on the project Kanban Board

Each task is initially created in the 'Issues' section of the GitHub repository. Figure 5.1 above shows a sample entry for a new issue. As can be seen, each issue has space to assign the task to any user, can be grouped with labels that pertain to the nature of the task, and can have comments that provide a brief description of the task. These issues can then be assigned to the Capstone Kanban Board, and placed into one of four categories, or columns: *To Do, In Progress, Under Review,* and *Done.* A photo of the Kanban board shown in more detail can be viewed in Appendix D.

5.3 Work Breakdown Structure

To further explain how the project was categorized, a Work Breakdown Structure was created at the beginning of the project, to aid in visualization of all the tasks that were required. This included the four main categories:

- Communications,
- Hardware and Testing,
- Simulations, and
- Project Management.

The tasks in the Work Breakdown Structure were then further categorized by grouping tasks that pertain to each other together, using a colour-coded scheme – tasks that were grouped together are boxed together using the same colour. The full Work Breakdown Structure can be found in Appendix E.

5.4 Project Schedule

This section of the report will discuss the project's schedule as it has been completed by Group 11. Gantt charts for the Winter and Fall academic semesters will be provided and discussed, along with a cumulative list of all we have accomplished throughout the year.

5.4.1 Gantt Charts

Gantt charts have been created in order to maintain a schedule throughout the 12-month period that the project will be completed in. For clarity, the Gantt charts have been divided into two main sections corresponding to the two academic semesters, Winter and Fall 2020. Throughout the year, these Gantt charts were maintained by the team and updated when changes occurred.

To negate the issue of readability one might have by copy/pasting the Gantt charts into this document, they are provided below in a tabulated format. This is both easier to read and comment upon for the purposes of this report. The Gantt charts in their graphical form will be provided in Appendix F.

Table 5.1 – Tasks for Winter 2020

Task	Start Date	End Date	Lead
Assignment 1	1/20/2020	2/11/2020	All
Assignment 2	2/12/2020	3/10/2020	All
Identify new angle	3/1/2020	3/20/2020	Sierra
Design PCB V2	3/6/2020	4/1/2020	Megan, Graeme
Cost reduction	3/10/2020	3/24/2020	Megan
Wire bonding fixture	3/13/2020	4/6/2020	All
Silicone mold	3/20/2020	3/27/2020	Graeme
Progress presentation	3/17/2020	3/26/2020	All
Capstone poster	3/15/2020	3/29/2020	All
Epoxy cure fixture	3/20/2020	3/31/2020	Alexa

We can do the same for the Fall 2020 task list, shown below. It may be noted that the scope of the project had changed due to the limitations brought on by COVID-19, and the PCBs that we designed were not to be ordered during the term. Dr. Brown and Dr. Landry proposed that a probe build be completed in-house and be modified to meet the requirements of this project in their own lab; negating the need to place an order for PCBs. The PCB design is theirs to order in the future.

Table 5.2 – Tasks for Fall 2020

Task	Start Date	End Date	Lead
Develop plan	9/1/2020	9/10/2020	All
Term scheduling	9/11/2020	9/15/2020	All
Design PCB	9/15/2020	9/30/2020	Megan and Graeme
Price new PCB	10/1/2020	10/22/2020	Megan
Build ultrasound probe in lab	10/23/2020	11/28/2020	All
Seminar presentation	10/26/2020	10/27/2020	All
Order PCB and wait	N/A	N/A	All
Finish probe assembly	11/28/2020	11/28/2020	Sierra and Alexa
Test new probe	12/03/2020	12/05/2020	Dr. Brown and Dr. Landry
Final presentation and report	12/01/2020	12/16/2020	All

5.4.2 Discrepancies

Originally, the team had hoped to start their in-person lab training to start working on the physical transducer model in the Summer of 2020. This would allow members who were in Halifax to work in the lab on hardware assembly and design. However, with the COVID-19 pandemic, this introduced several challenges for allowing this to happen. Due to the outbreak, in-lab training was unable to be completed during the summer and was moved to begin in the Fall 2020 semester, when regulations eased, and physical work could continue under socially distanced conditions.

Ultimately, it was decided that a contingency plan be developed for these special circumstances. With the guidance of Dr. Brown, Dr. Landry and Debbie, a Project Manager at the NSHA, a realistic plan was developed in September 2020 while accounting for the pandemic. This plan was focused more on hardware modifications in-person than ordering a new probe. While the probe design was completed this Fall, it has not been ordered and will be up to Dr. Brown and Dr. Landry to obtain due to the long delivery time estimates.

5.5 Project Budget

The project's anticipated economic budget is to be discussed in this subsection.

5.5.1 Overall

A preliminary budget has been developed with the help from Dr. Brown and others involved in the project. This budget details what the project is expected to cost the External Supervisor and sponsor throughout the duration of this project.

It may be noted that while this budget is a goal for Group 11, each of the costs have been overestimated for the purpose of this report. To maintain the budget, it was important that we overestimate the materials to be used rather than underestimate. This allows for possible mistakes to occur and extensive testing on the materials to be conducted. The budget for this probe is shown below in Table 5.3.

Table 5.3 – Budget allocation

Item	Quantity	Unit Cost	Total Cost
PCB Fabrication*	5	\$300 - \$1000	\$1500 - \$5000
Teflon Mold	1	\$200	\$200
Piezoelectric Wafer	1	\$120	\$120
Resin	1 bucket	\$50	\$50
Booking 3D Printer	1	\$80	\$80
TOTAL			**\$1950 - \$5450**

A range of possible values has been used in this budget based on current cost and the cost reduction goals. At this time, online quotes have been used as no detailed quotes have been returned by manufacturers. It is expected that the budget will narrow down as PCB companies become available to quote the design in question. However, this was a good estimate of values and all numerical results have been discussed with the External Supervisor.

5.5.2 PCB Cost Reduction

The largest expense of the project comes from the manufacturing of the flex PCBs. Alternative design and fabrication methods were identified as a secondary goal for the project in order to reduce the total cost. The design with inner trace spacing of 3 mil, with 1.5 oz copper thickness, is the driver of the high cost. This positive impact of these modifications could be seen not just in this project, but the lab overall because more PCBs can be ordered for the same cost, increasing the number of tests and trials that can be done.

The company ALLPCB was the manufacturer selected for the 4-layer design as explained in section 4.1.2. The cost breakdown is shown in Table 5.4 below, including the total cost, the cost per board, and the cost for the amount required to manufacture the probe.

Table 5.4 – Cost breakdown for PCB

Quantity	Total Cost (USD)	Cost per Board (USD)	Cost for Probe Quantity (USD)
20	510	25.5	51
40	600	15	30
500	1500	3	6

The total the cost per board did not increase much from a quantity of 20 boards to 40 boards, this quantity was selected. The 500-piece option was not selected, although it provides the least expensive cost per board, as this is a new design and manufacturer so the results would need to be tested before a large order was placed. This quantity gives an indication of cost for high production volumes in the future. The final order when placed through ALLPCB came to 585 USD, plus 19 USD for shipping from China to Nova Scotia. The lead time was quoted at 25 days.

6.0 Discussion

6.1 Discrepancies and Challenges

Two days before the submission date of this report, the company ALLPCB contacted us with regrets that they could not manufacture the 4-layer design. Although we had been skeptical of their promises throughout the process as the design requirements for this PCB are often very difficult for manufacturers to meet, the ALLPCB had confirmed in various conversations and review processes that they would be able to able to produce the design. After the order had been finalized and placed, during actual manufacturing, the engineers discovered the 1.5oz inner layer copper thickness with the given trace spacing was not possible. For this reason, the objective of the project to decrease the PCB cost has not been fully met at this time. However, there is a contingency plan in place with the other design alternatives and companies available. Also, the probes can still be fabricated using the old model of the PCB, meaning the other objectives are still met. The fabrication process used to create the probe explained in the testing section of this report utilized one of the straight probes from the original manufacturer, Microconnex.

Other options will continue to be explored by the team in the hopes of finding a possible solution before graduation, but results will not be known before the deadline of this report. ALLPCB has been sent the 2-layer design to see if they can manufacture that variation. Another company, Advanced Circuits, has been sent both the 2-layer and 4-layer designs. This company had not previously been contacted in the scope of this project, however they have been used in the past by Daxsonics and show strong capabilities on their website. Finally, Microconnex, the original company, will be sent the 2-layer design to check the pricing against the original 4-layer design quote.

6.2 Successes

The results from this project have resulted in several improvements to the existing probe that make it ideal for not only the new spinal applications, but also several, more general applications. The most significant change was found in the new PCB design, as the different trace spacing along its length allow the same board to be cut in multiple locations depending on its desired function. This improvement also simplifies documentation, as there is now only a single design to keep track of rather than individual ones for each application. Finally, even if the proposed cost-saving production methods are not possible, having a single PCB that can be used for every application allows for bulk ordering, which in itself will reduce the overall cost of the probe.

Novel production methods were also identified over the course of this project. In terms of the probe itself, the use of multiple 2-layer boards was found to work equally as well as a 4-layer board, although they take slightly more time to assemble. This produces more options for PCB manufacturing, as it removes requirements for the inner layers that have proven to be difficult to meet. A new method for applying the silicone coating was also tested and validated. This will allow for more uniform coverage of the probe, and less work trying to modify existing molds to accommodate different probe shapes.

A final notable success is that of the electrical impedance results. True, the center frequency was not the expected value, however when looking at the impedance values at the resonant frequency, they agreed exactly with the desired trace impedances of 50-75 ohms that were incorporated into the design of the PCB in OrCAD.

6.3 Limitations

Although the improvements to the PCB produce significant benefits, they also have some drawbacks. One such drawback is the fact that the ground planes need to be manually cut back for the straight 44 and 48 um cases, because they need to continue to the end of the probe if the 38 um case is to still be available. Another drawback is that although several new production techniques were tried, they have still proven to be difficult to manufacture, and are still relatively expensive. Even with the 2-layer design, the lower manufacturing cost is somewhat offset by the extra time required during assembly to bond the two sides together. This may still result in a net decrease in cost, but staff will need to be able to accommodate the extra workload.

As well, the grating lobe simulations only focused on the center frequency of the transducer and did not account for the possibility of different pitches, as the PCB has been designed for. More sophisticated modelling is possible that accounts for the grating lobes across the full bandwidth and not just at the center frequency. Newer models for the grating lobe profiles could be modelled using a MATLAB add-on, *Field II*, which accounts for more specific aspects of the transducer including the bandwidth. These aspects, however, were not considered in this project.

Finally, the overall design of the probe was not exactly as expected. The results of the impedance tests showed that the actual resonant or center frequency of the probe was closed to 30-32MHz as opposed to the expected 35.6MHz. Although this is still a relatively high frequency, it what was desired by the client. This reduced frequency could be due in part by inaccuracies in the in-lab fabrication processes, such as overlapping the piezo samples, not slicing the probe at exactly 37.7 degrees, or in faulty connections or wirebonds. Furthermore, the impedance simulations were modelled with the original design's 45MHz center frequency, which made comparison between the simulated and actual center frequencies more difficult. As COVID-19 placed the team on a very tight timeline in terms of fitting in lab and fabrication times, the final assembly and testing were done in a bit of a rush. In the future, it would be desired to fabricate multiple transducers with more fabrication time, to reduce some of these errors and hopefully compensate for the lower-than-expected frequency of operation.

7.0 Conclusion

Group 11 has worked hard to maintain a tight schedule throughout the Winter and Fall semesters of 2020, despite the challenges and limitations brought on by COVID-19. The schedule originally put in place by the team had to be adjusted multiple times as the circumstances concerning the pandemic changed, and fortunately, each time the schedule changed the new deadlines were met.

Design specifications for the new flex circuit board had been determined in the first semester of Capstone. The target angle for the new PCB end was found to be 37.7 degrees. The operating frequency for the probe was determined to be 36MHz. Excellent simulations were completed initially, providing the team with a grasp on the concept of designing an ultrasound along with what one should expect from the design.

In Fall 2020, the new ultrasound PCB was designed with *four* different possible applications, as suggested by Dr. Brown. This new development will save the Dalhousie Ultrasound Group the trouble of having to order four different types of PCBs for their different uses. The supporting fixtures for the new design were modelled in SolidWorks to accommodate the angled design, and they are going to be fabricated later by Dr. Brown and Dr. Landry.

A working prototype for the angled ultrasound probe was successfully assembled by the group, and after testing it was found that the probe was capable of imaging a human wrist. Upon further analysis, the probe was found to have a good impedance test.

Developing the ultrasound probe for guided spine surgery has proven to be both a challenging and fascinating project. Prior to this design project, the team had very little knowledge of imaging technologies. In this regard, the learning curve has been steep. However, the motivation for this project has not been difficult to find as this new technology is extremely compelling for the application of spinal surgery as a safer, less invasive approach.

8.0 Recommendations

This section of the report will discuss the recommendations that Group 11 has for the remaining tasks concerning this project. For simplicity, this will be broken into two subsections for cost reduction & PCB orders, and fixture design & fabrication.

8.1 Cost Reduction and PCB Orders

The remaining work for the PCB involves contacting PCB manufacturing companies and obtaining quotes for the work that still needs to be done. Unfortunately, as mentioned earlier in this report, ALLPCB (the prospect manufacturer for the newly designed PCB) backed out of production after initially telling the group they could make the new PCB.

If it becomes impossible to find a PCB manufacturer who can make the 4-layer design, a 2-layer one can be manufactured and used just as effectively. As a final resort, Microconnex, the original manufacturer, can certainly do the 4-layer design with the updated four-cases that the new PCB accommodates. Once a design and company are selected, the Dalhousie Ultrasound Group can order the PCB in bulk and test them in the lab.

8.2 Fixture Design and Fabrication

Due to the makeshift prototyping completed by Group 11 and Dr. Brown, many of the fixtures that were designed were not actually required for the assembly of the test probe. It is recommended that the fixtures be fabricated and used for the newly ordered PCBs; they will surely help in the probe assembly process.

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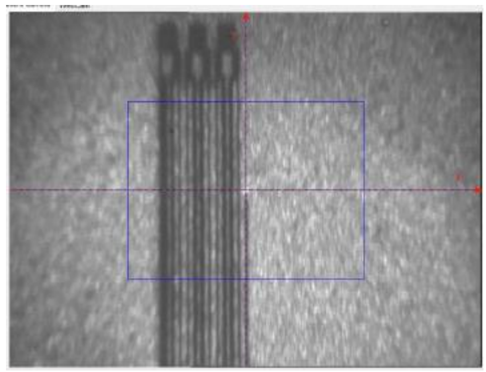
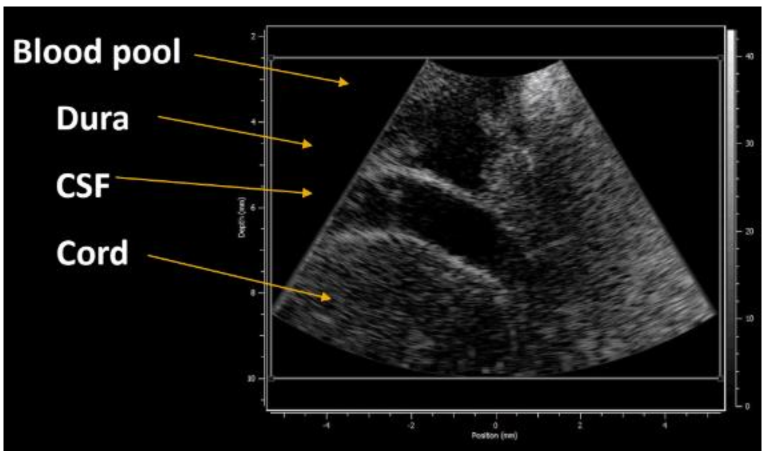
Appendix A: Ultrasound Images from Previous Design

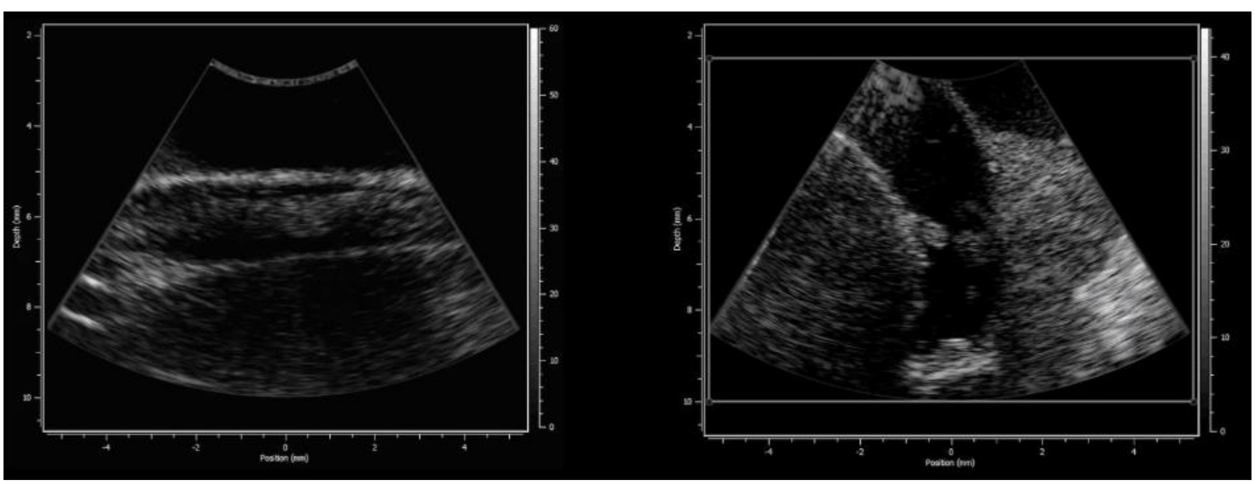
Note: All images retrieved from J.A. Brown [11].



Laser micro-machining



In vivo porcine imaging

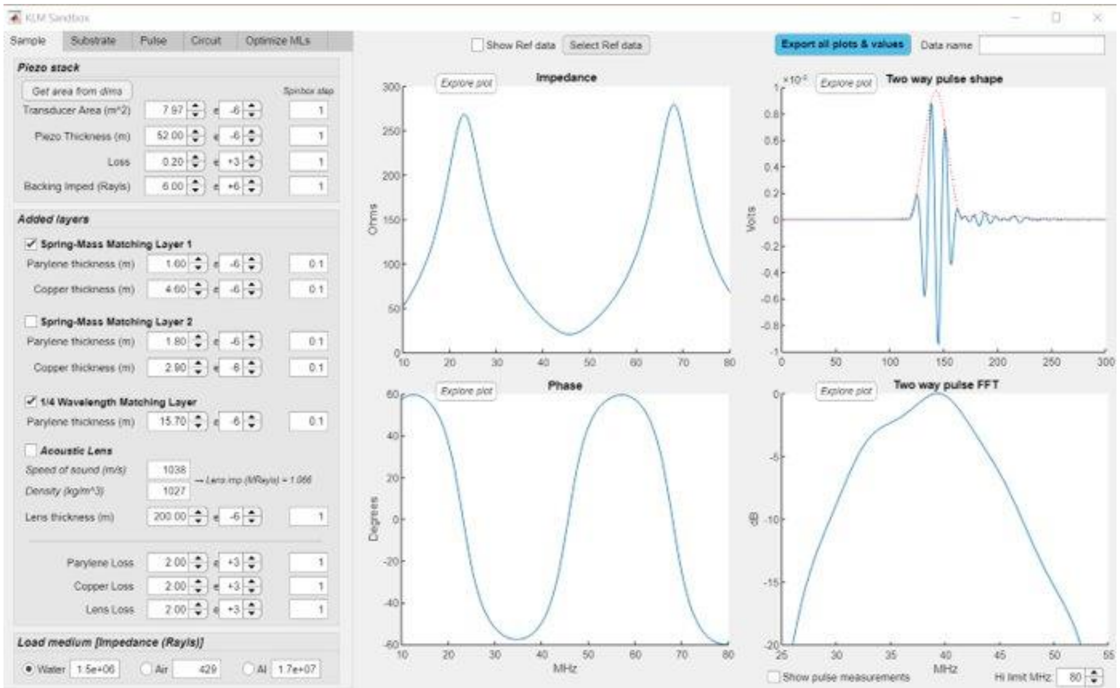


Nerve rootlets

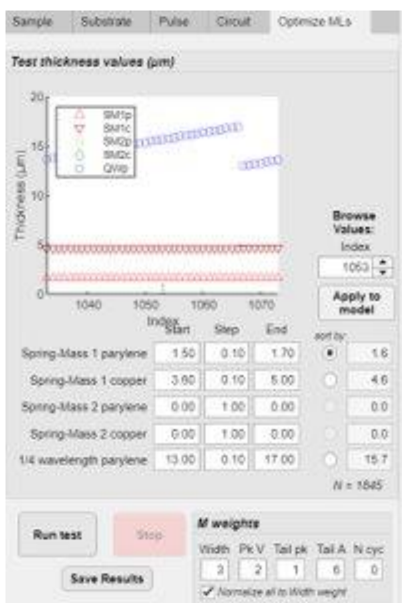
Appendix B: MATLAB Code for Grating Lobe Simulations

```
% grating_lobes_v4.m
% Plots the grating lobes in polar and cartesian coordinates.
theta = 0:0.01:2*pi; % plots from 0 to 2pi
d = input('Enter a value for the pitch, in um: ')*1e-6;
lambda = input('Enter a value for the wavelength, in um: ')*1e-6;
% Below equation was retrieved from:
%
http://www.personal.psu.edu/faculty/m/x/mxm14/sonar/beamforming.
pdf
amplitude = (cos((pi*d*sin(theta))/(lambda))).* …
     (cos((pi*d*sin(theta))/(lambda)));
figure(1)
polarplot(theta,amplitude);
title(['Polar  Plot  of  Grating  Lobes  for  a  Pitch  of  ',
num2str(d*1e6),…
     ' microns, ', num2str(1500/(lambda*1e6)), ' MHz']);
figure(2)
plot((theta*180/pi),amplitude);
xlabel('Angle (deg)');
ylabel('Relative Magnitude');
title(['Grating Lobe Magnitudes for a Pitch of ', num2str(d*1e6),
'…
     microns, ', num2str(1500/(lambda*1e6)), ' MHz']);
```

Appendix C: GUI for ML and Two-Way Pulse/Impedance Simulations

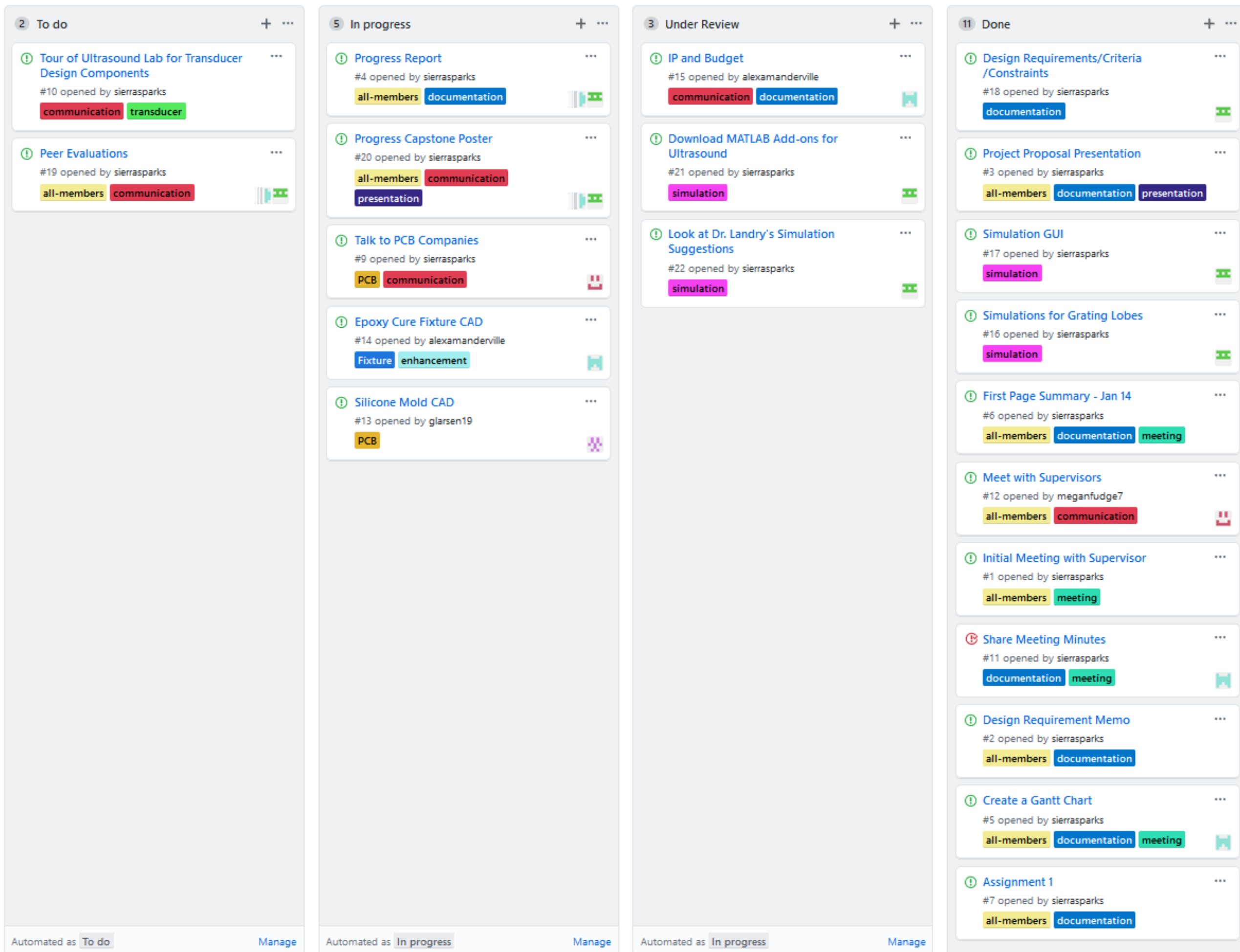


GUI for impedance and two-way pulse simulations

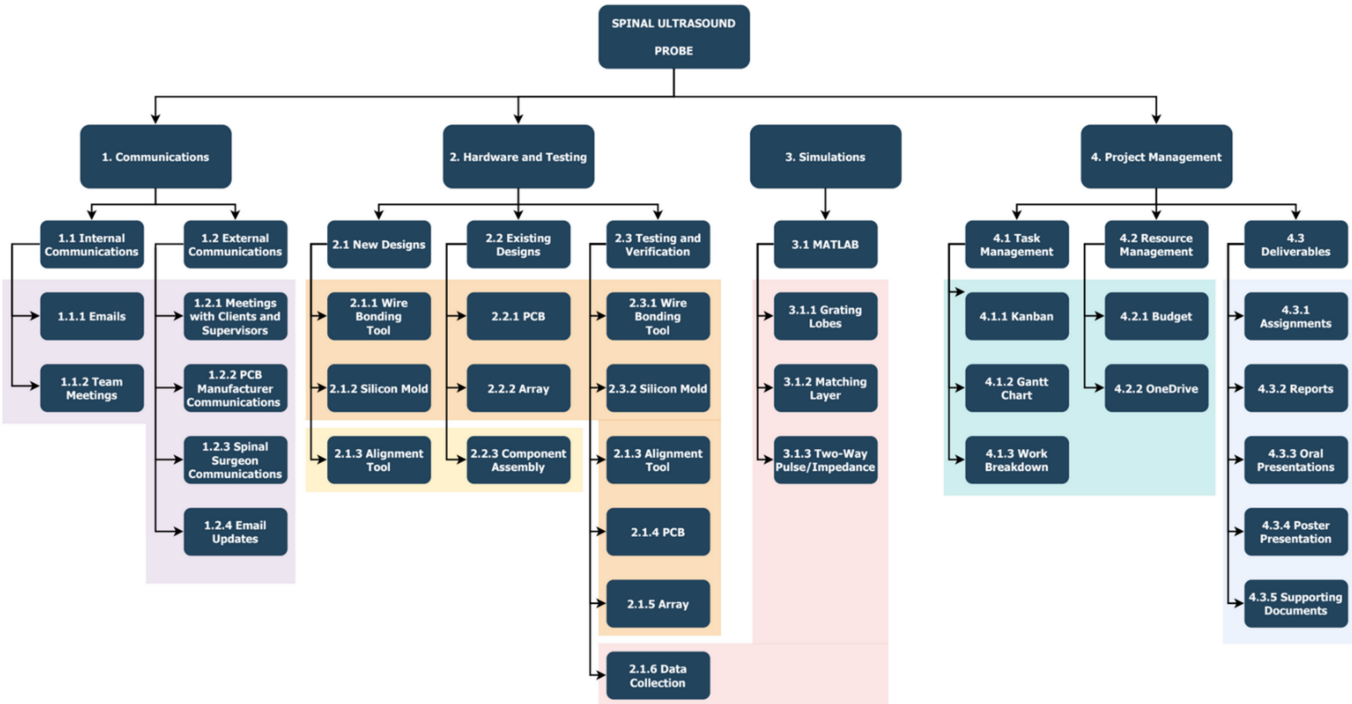


ML test thickness simulation inputs

Appendix D: Kanban Board



Appendix E: Work Breakdown Structure



Appendix F: Gantt Charts