COLLEGE OF ENGINEERING
MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

Accurate Acoustic 2D Mapping Apparatus

Final Report
December 8, 2020

University of Michigan - Mechanical Engineering

ME450 FA2020 Section 4 Team 11
Justin Campau, Josh Clark, Carl Johnson, Aaron Maas, Myles Siglin

Sponsor: Bogdan Popa

Table of Contents

Executive Summary

Acoustic Two-Dimensional (2D) mapping is a positioning system utilized to locate an object based on its effect on sound propagation. An object is placed inside a sound chamber and a microphone is placed at specific locations as a speaker emits a sound wave. The microphone detects the pressure changes due to the sound waves as they propagate throughout the chamber and interact with the object. The microphone is then moved to another position, repeating the process until pressure readings in the entire chamber are recorded. This data is then utilized to construct spatial maps of the chamber, highlighting the position of the object.

The 2D acoustic chamber consists of two 4' x 4' sheets of plexiglass, spaced 3cm apart vertically. Currently, a drive belt is looped around an arm outside the top sheet of plexiglass, and down around the outside edges of the plexiglass into the chamber. The problem with this setup is that the portion of the drive belt inside the chamber interferes with the sound wave propagation and subsequently the data collected. The purpose of this project was to design a new system to move the microphone within the acoustic chamber with a minimal amount of interference in the data.

The specifications the new system had to meet include consistent synchronous motion between the microphone and driving cart, the minimization of material inside the chamber, easily removable components, and the ability for the cart to clear the rails on top of the upper sheet of plexiglass. The concept chosen was a 3D printed housing for the microphone connected to the driving cart using magnetic coupling. It was chosen because it was the concept that required the least amount of material inside the chamber, enabled the cart to clear the rails easily, maintained synchronous motion, and allowed for components to be easily swapped.

The final design consisted of a 3D printed, ABS, square prism housing that held the magnets and microphone in slots for easy swapping, three ball casters on the top of the housing to reduce friction between it and the plexiglass, and three neodymium magnets to provide enough magnetic force to couple the housing with the cart. This design was verified using both empirical testing and engineering analyses, although only the magnets were empirically tested due to limitations stemming from COVID-19. Verification proved that the design could work, given that it is able to be empirically tested and modified as needed.

In conclusion, although the system wasn't able to be tested empirically in whole, the testing that was able to be completed proved to be promising, and indicated that the system would work. However, the housing could stand to be modified in order to take the microphone's wiring into consideration, as it currently doesn't offer any convenient form of management for the wires.

Problem Description & Background

What is Acoustic Mapping?

Acoustic mapping is a real time spatial imaging technique where a microphone is used to measure pressure changes due to a sound source, creating maps of a designated location as described by interaction with the acoustic waves. Acoustic mapping allows for very accurate visualizations of spatial temporal attributes with minimal changes to the environment being investigated. One example of a relevant application of acoustic mapping is to detect leaks in large diameter pipes for fluids such as water or oil. Using a free swimming leak detecting method as investigated by David Kurtz [1], a device is inserted into a pipeline and measures the acoustic signal generated at the leak position as it passes by.

Figure 1. Inserting an Acoustic Device to Detect Leaks in a Pipe Line [1]

There are also marine applications as acoustic mapping can be used for underwater positioning systems where autonomous surface vehicles with acoustic detectors can automatically locate sound sources within the water [2]. A sound originating from underwater, is captured via three channels in the acoustic detector. The data is processed to determine the direction of propagation of the waves and estimate their point of origin.The diagram below illustrates this process.

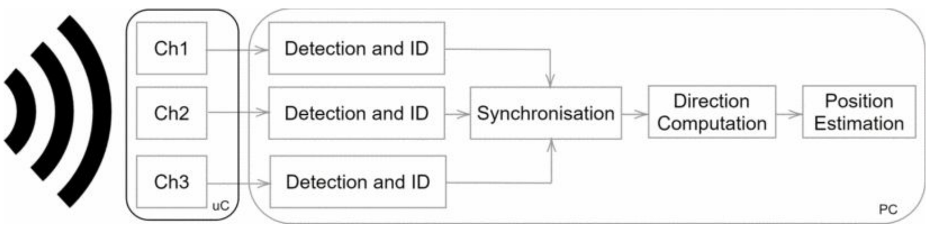

Figure 2. Illustration of How Acoustic Detectors Work for Underwater Mapping [2]

In both of these examples, the acoustic sensing method has minimal effects on the studied environment illustrating how suitable acoustic mapping is for non-invasive data collection.

Acoustic Mapping: Sponsor Research and the Current Method

Sponsor Research

Our project sponsor, Professor Bogdan Popa, is interested in measuring the propagation of sound waves in a given medium; recent research of his is focused on the use of Willis structures to affect sound propagation. Of particular interest is a panel of active Willis structures which detect incoming sound from one direction and cancel it out, preventing it from propagating outward from the speaker, as seen on page 5 in Figure 3 [3].

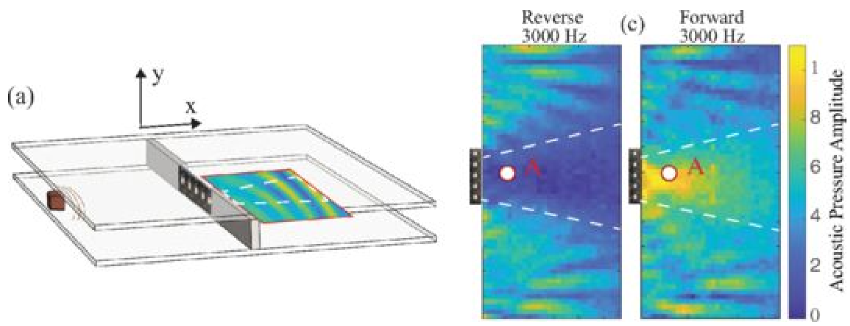

Figure 3. A diagram of the active Willis structure array cancelling out sound when oriented against the direction of wave propagation. [3]

The purpose of the Willis structure is to cancel out unwanted noise and other vibrations when installed in sonic mapping and signal processing devices. The ability to remove undesired sounds, a "sonic invisibility cloak" [3], would have further applications in a wide range of fields.

Experimental Setup

The Willis structures and other mechanisms of sonic interest are tested in Prof. Popa's lab using a raster scanning, moving microphone. The object being studied is placed in the mapping chamber. The mapping chamber consists of two square acrylic sheets, measuring 120 cm on each side. The sheets are mounted with 3 cm of air between them; the sheets are supported by aluminum braces to prevent sagging. The microphone moves to its initial position, then the tone of interest is played on the speaker. The sound is allowed to propagate and decay fully, then the microphone moves to a new position; the tone is played again, and the process is repeated until the entire area of interest is scanned. [4] A labeled photograph of the chamber is seen on the next page in Figure 4.

The microphone is contained in an internal caddy which is suspended on a toothed belt, driven by the experimental control system along the control arm. The positioning cart is located on the control arm. The cart moves along with the microphone, connecting it to the data acquisition card, as well as allowing for easy visual reference for the microphone position. The use of the belt allows for the microphone to be easily and precisely moved along the horizontal axis, and the control arm's motion in the vertical direction allows for the microphone to accurately scan much of the mapping chamber. Of note is that while concrete positioning along the plane of the acrylic sheet is important for data acquisition, the height of the microphone within the air gap is insignificant. The control arm's height above the top sheet, however, must be sufficient to clear the aluminum support braces. A cross-sectional diagram of the microphone positioning system within the mapping chamber can be seen in Figure 5, located on the next page. The belt profile and internal caddy increase the amount of material in the chamber, which can negatively affect the propagation of the sounds being studied due to additional absorption and reflection. The belt's need to completely move from side to side prevents mapping in the line of any objects within the chamber. This is demonstrated in Figure 6, which will be introduced later.

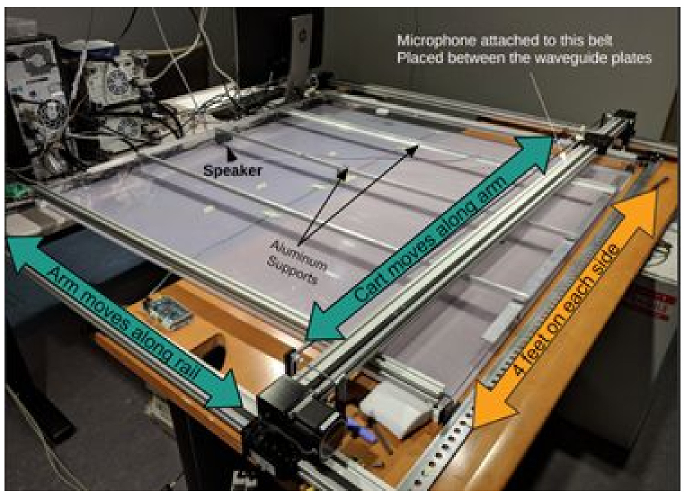

Figure 4. A labeled photograph of the mapping chamber and the microphone's pathing. The microphone moves along an arm in the horizontal direction, while the arm moves up and down the vertical axis of the chamber. Also seen are the speaker and the aluminum braces used to prevent sagging. [4]

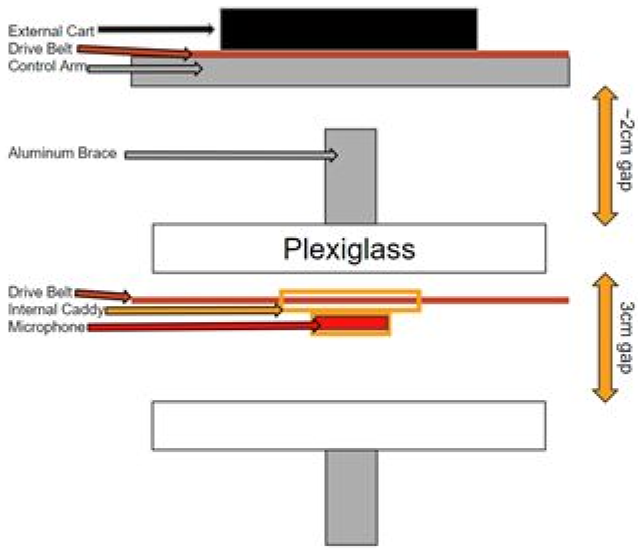

Figure 5. A cross sectional diagram of the microphone suspension system. The Plexiglass sheets form the boundaries of the mapping chamber; the support braces extend 0.75 inches (~2cm) vertically outward from the sheets. The control arm which contains the external positioning cart clears the upper brace. The cart locates the microphone; both are controlled by way of a toothed drive belt which moves the microphone in the horizontal direction, seen as from left to right in this image.

The measurements taken by the microphone are organized by position of recording and time during a propagation; these organized measurements are then used to produce a colored graph which illustrates the propagation of the sound. An animation is commonly produced to map the sound as it propagates in space and time. A still from one of these animations is included below, in Figure 6. The previously mentioned inability to map in the line of a studied object can be seen as the dark blue horizontal line in the image.

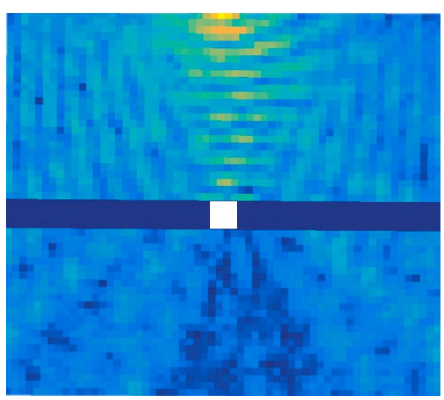

Figure 6. Still frame from animation demonstrating sound propagation in the mapping chamber as a function of time. The wave-like patterns in yellow seen at the top represent the sound from the speaker entering the chamber. The dark horizontal line represents the lack of measurements in the line of the white object in the center. The inability to map in that region is a key problem with the current recording method.

The Problem

The problem with the current setup can be seen above in Figure 6. The solid blue bar that spans the width of the image represents the position of the drive belt. This belt blocks the area it occupies from being scanned, while also deflecting the sound waves as they pass by it. This greatly reduces the quality of the scanning process and does not produce acceptable results.

Professor Bogdan Popa has asked us to come up with a new apparatus that eliminates the need for the drive belt. This apparatus must be able to house the microphone that is used inside the chamber, while consisting of as little material as possible. This will reduce the area of the chamber that cannot be scanned, while also reducing the deflection of sound waves as it passes by the microphone. This new mechanism must be able to relocate anywhere inside the chamber in order to produce a full range scan.

Requirements and Engineering Specifications

Our requirements and specifications were determined from meeting with our sponsor Dr. B Popa and looking into literature resources on research pertaining to acoustic mapping. Table 1 illustrates the requirements and specifications which are discussed further below.

Table 1. Requirements and Engineering Specifications

Requirement	Specification
Consistent synchronous motion between microphone and driving cart.	Final displacement for cart and microphone are within +/- 1% total displacement in X and Y Final displacement is in tolerance for a repeatability of > 10 times
Minimize material in chamber	Eliminate belt profile, reduce material by 90%
Components are easily removable and replaced	Microphone housing and mechanism can be swapped in < 1 min Mechanism can withstand part replacement > 15 times
Mechanism can clear rails (Bonus)	Mechanism can function with an extra space of 0.75” between driver and microphone

Consistent Synchronous Motion Between Microphone and Driving Cart

Since the acoustic mapping experiments require the microphone to be at a precise location as determined by the automated start-stop motion, it is imperative that the driving cart and the microphone move in sync. This will allow for controlled experiments with minimal variability in the data collection methods which is necessary to obtain accurate results. Since data is only collected once the microphone reaches a designated position, a tolerance was set such that the final displacements for both the driving cart and the microphone are within ± 1% of each other to ensure the design meets this requirement. A repeatability specification was introduced to ensure that while subjected to the start-stop motion, the mechanism will maintain synchronous motion between the moving parts.

Minimize Material in Chamber

The less material in the chamber the better it is for data collection. Reducing the material in the chamber will allow for less interference to the propagating sound waves. Additionally, the belt profile is invasive as it inhibits data collection along the obstacle under investigation. The specification to remove the belt, reducing the material by 90% was set to minimize the material and improve data collection near obstacles by removing the source of interference. Accordingly, this specification was developed after looking at investigations conducted by Van Dyke and his team [5] in which they determined that testing procedures can cause interference in acoustic experiments. Additionally, Lin, Wang-Sheng [6] illustrates that moving targets also result in acoustic field interference. Thus in setting this specification, we aim to ensure that the integrity of experimental data is maintained.

Components Are Easily Removable and Replaced

Professor Popa also conducts other experiments in the sound chamber so it is important that the mechanism has components that are easy to take apart and reassemble as needed. From this we determined that a specification allowing for a mechanism teardown under one minute is necessary. Since reassembly is important, an additional specification was introduced to ensure the mechanism can maintain its integrity after repeated disassembly and reassembly. According to research conducted by Ginzburg [7], moving parts wear and tear over use so it is imperative that the mechanism can consistently work over time as components are removed and replaced as necessary.

Mechanism Can Clear Rails

Because the top layer of plexiglass is supported by 0.75” aluminum rails, it is required that the mechanism be able to clear these supports to allow for continuous data collection. The specification was set accordingly such that the mechanism can function with an extra space of 0.75” between the driving cart and the microphone. It is noted that this is a bonus requirement which whether satisfied or not, has no bearing on the quality of the end product.

Benchmarking

Throughout the problem definition phase of the project, research was conducted into other Acoustic 2D Mapping setups in order to compare them to the current setup in our sponsor's lab. Five different experimental setups found through research were compared to the stakeholder requirements described previously. This is shown in Table 2.

Table 2: Comparison of different researched methods and how well they meet the stakeholder requirements.

Benchmarking: How Well are the Requirements Met?		
Technique	Method	Requirements Met
Zheng *et al.* [8]	Hydrophone controlled with a step motor	Consistent synchronous motion between microphone and driving caddy, minimizes material in chamber
Lindner *et al.* [9]	Transducers fixed to acoustic chamber walls	Minimizes material in chamber, components are easily removable
Liu *et al.* [10]	Microphones fixed in specific regions of the chamber	Minimizes material in chamber, components are easily removable, mechanism can clear rails
Vatul'yan & Morgunova [11]	Mathematical method	None
Lee and Gilbert [12]	Intersection canonical body approximation	None

The first setup in Table 2, from Zheng, Chen, Liu, and Hu [8], is a 2D acoustic waveguide with water in the empty space as opposed to air in our sponsor's setup. Their microphone (or a hydrophone in this case) is connected to a step motor, which moves the hydrophone to each measurement location. This step motor/hydrophone combination results in less material in the chamber when compared to Professor Popa's current setup, as well as synchronous motion between the microphone and its driving caddy. The components are not easily removable, however, and the mechanism also could not clear the rails present in our sponsor's setup. The setup is shown below in Figure 7.

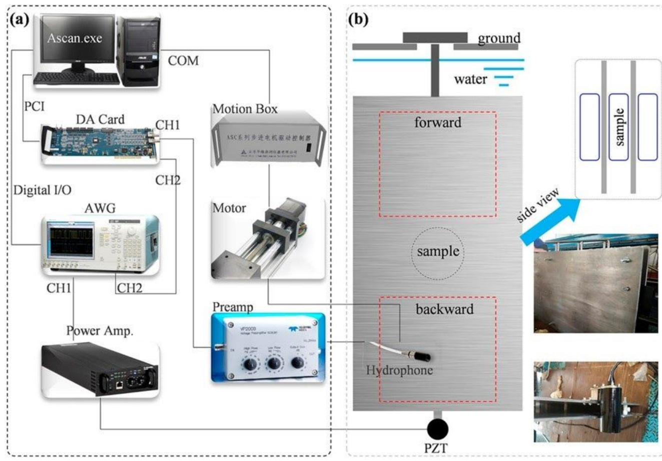

Figure 7: The hydrophone - step motor setup used by Zheng, Chen, Liu, and Hu. [8]

The second setup in Table 2 is from Lindner, Faustmann, Krempel, Munch, Rothballer, and Singer [9]. This setup uses piezoelectric transducers to measure sound waves created by ultrasonic liquid sensors in an acoustic chamber. Like the previous setup, liquid is used instead of air in between the two upper and lower layers of material. Instead of a microphone/hydrophone mechanism inside the waveguide, however, transducers are placed on top of the upper layer of material and on the bottom of the lower layer of material. The acoustic wave is generated by the lower transducer and is received by the upper transducer. The absence of a microphone and microphone support inside the waveguide results in a reduction of material when compared to Professor Popa's setup, and also enables the components to be easily removed. Since the transducers are in fixed locations there is no synchronous motion between a microphone and driving cart. As the transducers must be touching the upper and lower layers of material, they also could not clear the supporting rails in our sponsor's setup. The setup is shown on page 12 in Figure 8.

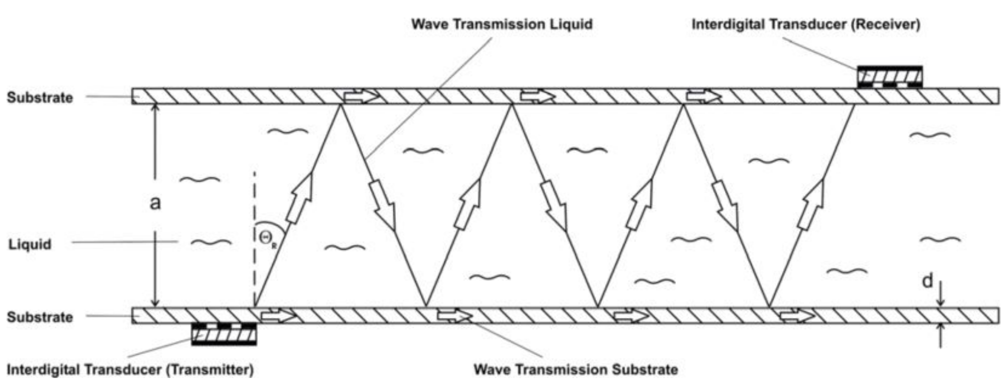

Figure 8: The acoustic chamber utilizing transducers as transmitters and receivers. [10]

The third setup in Table 2 utilizes microphones in fixed locations within a waveguide. This method is from Liu (Guang-Sheng), Zhou, Liu (Ming-Hao), Yuan, Zou, and Cheng [10]. As with the previous setups, the waveguide is two sheets of material with space between them. In this case, the space is filled with air. A microphone emits sound into the chamber, which is then recorded by microphones placed in different areas of the waveguide. This allows for measurement in many sections of the waveguide but does not allow for synchronized movement between a cart and the microphone(s), as they are stationary. This reduces the material inside the chamber when compared to the project sponsor's setup, but not by a large amount. Since there is no external cart mechanism, though, the support rails are not an issue. Lastly, the microphones are easy to swap. This setup meets most of the requirements, however it does not meet one of the most important ones. The setup is displayed in Figure 9 below.

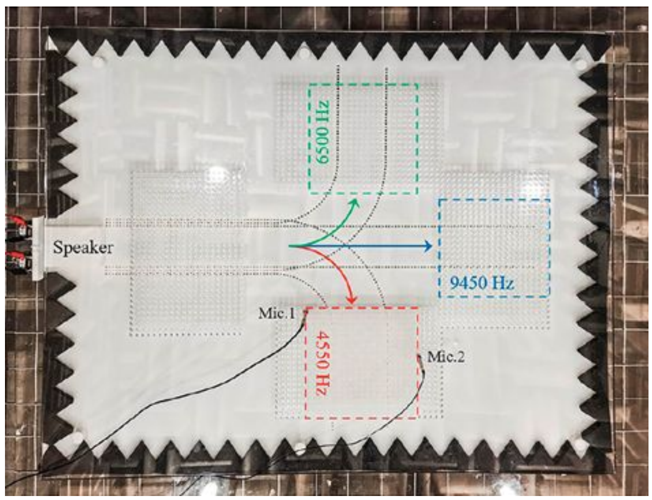

Figure 9: The positioning of the microphones in the stationary microphone setup. The mics are in similar positions on the other two sections (6500 Hz and 9450 Hz). [10]

The fourth and fifth are not setups at all. Vatul'yan and Morgunova present a mathematical method of analyzing sound wave propagation in a cylindrical acoustic chamber [11]. This concept may be possible to translate to the rectangular prism shaped chamber Professor Popa uses, but it does not meet any of the requirements as it is not an experimental method. Lee and Gilbert, on the other hand, used the intersection canonical body approximation to analytically determine the shape of a 3D object in a hypothetical acoustic chamber [12]. Similar to the previous method described, this concept may be of use to Professor Popa, but it does not meet any of the requirements. Therefore, these two "setups" are not entirely useful in the scope of this project.

Concept Generation & Development

During the task of defining the problem and creating the stakeholder requirements and engineering specifications, potential solutions presented themselves. The two solutions that came up were recorded as preliminary concepts, to be included in the concept exploration and development stage alongside other design concepts generated. They are briefly described in the following paragraphs.

The first preliminary concept developed makes use of magnetic coupling to move the microphone inside the plexiglass chamber. This concept, recommended by Professor Popa, uses the same external cart system that the current design does. In this concept, the belt that is used to translate the microphone laterally inside the waveguide is removed. In its place, magnets will be attached to both the microphone (via a mounting mechanism) and the external cart. Using the attractive force between the two sets of magnets, the microphone and its holder will be held against the top sheet of plexiglass and will slide across it in synchronous motion with the external cart. This concept would be beneficial as it significantly reduces the amount of material between the plexiglass sheets and requires minimal modification to the existing system. Furthermore, depending on the holder created for the microphone, it would be easy to swap out parts. This concept is illustrated on page 14 in Figure 10.

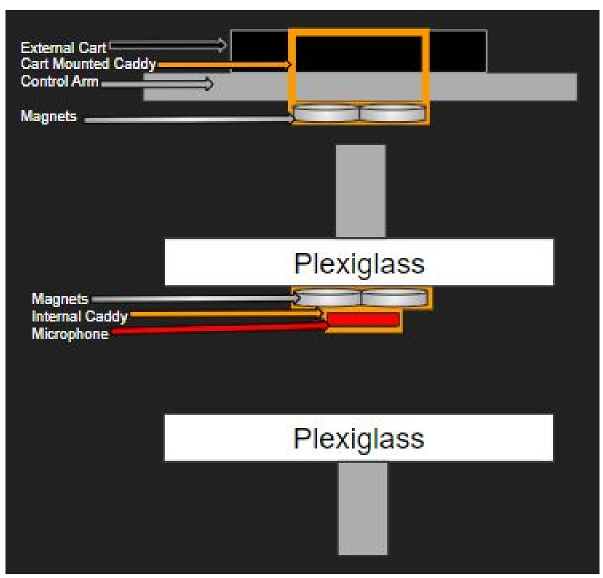

Figure 10: The preliminary design using magnetic coupling to synchronize the microphone and cart. The cart remains in the same position as it is in the current setup.

The second initial concept also uses magnets to synchronize movements between the cart and the microphone. Like the magnetic coupling idea, the microphone would be placed in a manufactured holder along with a few magnets. Furthermore, the existing external cart system would still be able to be used, albeit with some modifications. This is where the similarities end. Instead of magnetic coupling, this idea would utilize magnetic suspensions (also called magnetic levitation) to suspend the microphone in between the plexiglass sheets. This concept can be seen in use by maglev trains and is detailed in the textbook “Alternative Energy DeMYSTiFieD” [13]. In order for this concept to function, the cart system would need to be moved from overtop of the plexiglass sheets to under them. Magnets would then be placed on top of the cart. The opposing forces between the magnets on the cart and the magnets in the microphone holder would cause the microphone to be suspended above the bottom surface of the plexiglass and move along with the cart. This concept is more complex than the one involving magnetic coupling, but also reduces material inside the chamber, enables fast swapping of components, and as an added benefit it could eliminate friction between the microphone housing and the plexiglass sheets. This concept is illustrated in Figure 11.

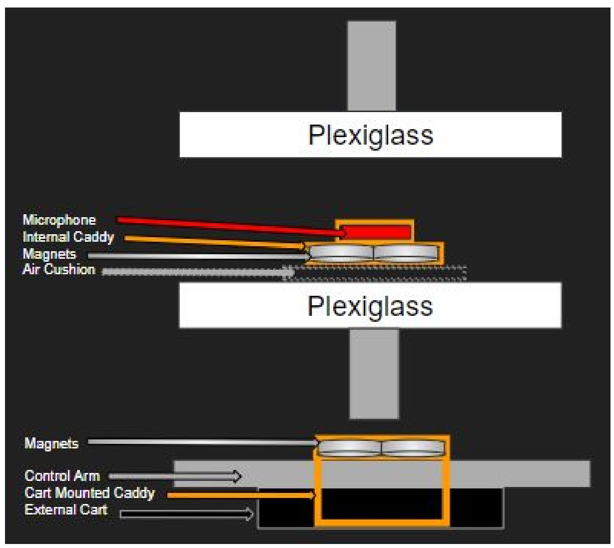

Figure 11: The preliminary design using magnetic suspension to synchronize the microphone and cart. The cart system would be moved underneath the plexiglass sheets and an air cushion would exist between the bottom sheet of plexiglass and the microphone.

Since our stakeholder Professor Popa already gave us a concept to go with, we incorporated divergent thinking to our concept generation to come up with ideas that would further explore the solution space. Doing so allowed us to come up with a wide range of ideas and to evaluate whether the proposed solution was in fact the best solution for the problem. For the concept generation our ideas were split into two categories: housing and locomotion. Housing concepts related to the proposed solution, and involved different ideas of shape, material properties, and features that could be incorporated to hold the microphone. Locomotive concepts explored motion beyond what was initially recommended. We used a combination of brainstorming, design heuristics and the SCAMPER technique to generate and develop concepts.

Locomotive Concepts

Electrostatic Coupling uses a material on the housing surface that is magnetically charged so that it is attracted to a magnet on the other side of the plexiglass. This induced charge is only applied at the surface in contact with the plexiglass and supports a housing with the microphone.

Microphone Array eliminates the need for motion by replacing the drive mechanism with systematically placed microphones in the acoustic chamber that record sound at different locations during the experiments. These concepts are shown in Figures 12 and 13 on page 16.

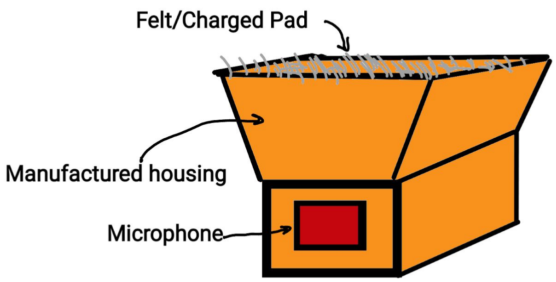

Figure 12. Electrostatic Charge

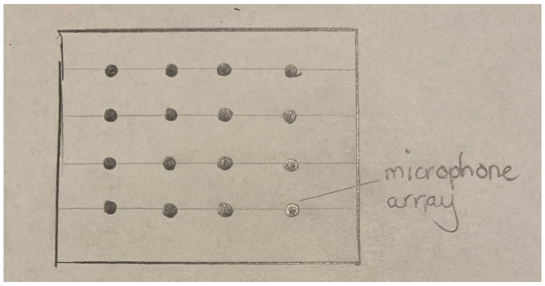

Figure 13. Microphone Array

Hoverboard was a creative approach that would use a floating housing in the acoustic chamber holding the microphone and moving it from one location to another. This contactless concept would also eliminate the current drive mechanism.

Robotic Arm was another creative concept which imitates the range motion of a human arm. The robotic arm would be programmed to pick up and move the microphone to predetermined positions during the experiment. This concept would combine the function of the drive belt and the sensing microphone while allowing for a wider range of motion to reach every point in the acoustic chamber. These concepts are illustrated below.

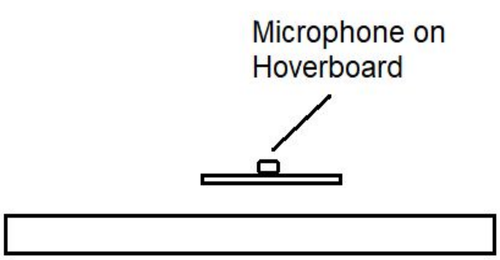

Figure 14. Hoverboard Microphone

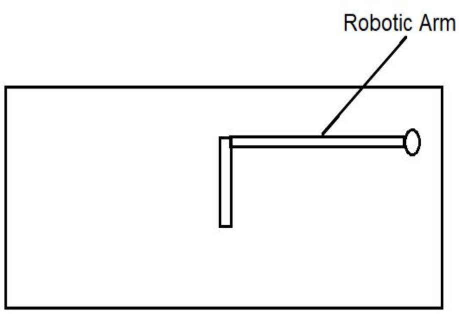

Figure 15. Robotic Arm Concept

Some other concepts that were explored were placing a thin film on the plexiglass for reduced friction, using a wireless microphone as well as a small remote controlled vehicle that can be manually driven to different locations in the chamber. The sketch for this concept is shown in Figure 16 on the next page.

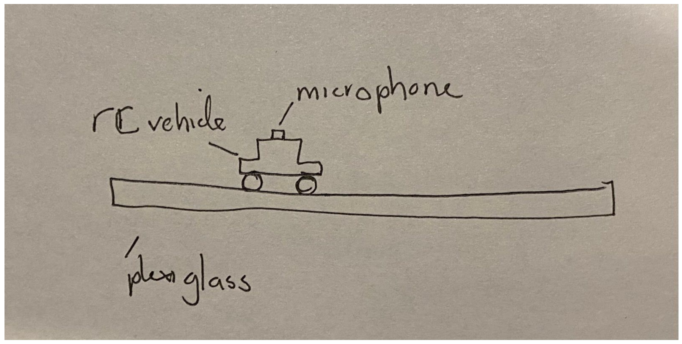

Figure 16. RC Vehicle

Housing Concepts

Tapered Housing is a microphone holding concept that would allow for minimal material while providing a large enough area at the top surface to place magnets. The microphone would sit at the bottom with a clip holding it in place.

Spring Loaded Enclosure is a housing idea that uses two springs in tension to clamp the microphone in place. These concepts are in Figures 17 and 18 respectively. .

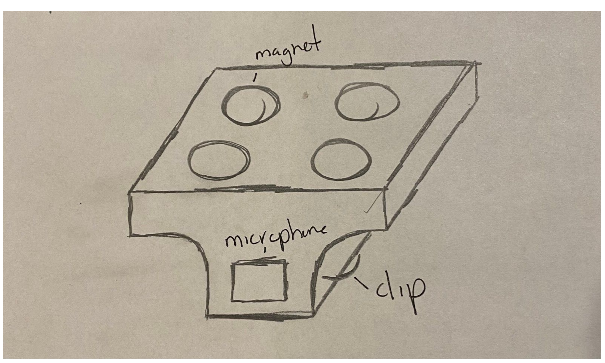

Figure 17. Tapered Housing

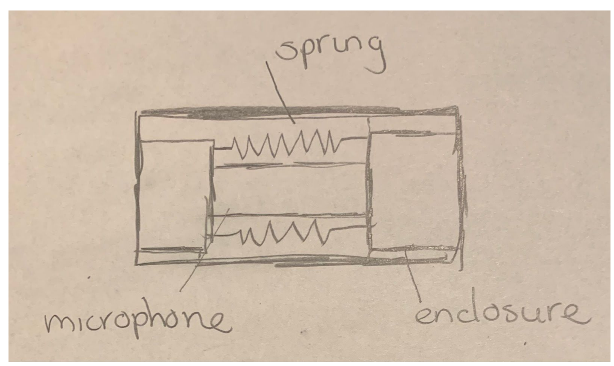

Figure 18. Spring Loaded Enclosure

Ball Bearings/Ball Transfer are similar concepts which combine both housing and locomotion. Both of these concepts hold the microphone on a plate and utilize ball bearings at the point of contact with the plexiglass with the difference being in the ball transfer, the ball bearings are magnetized while in the other, a magnetic is placed between the ball bearings on the housing. The ball bearings would help make motion smooth by reducing friction. The ball bearing (left) and ball transfer (right) are shown in the figure which follows.

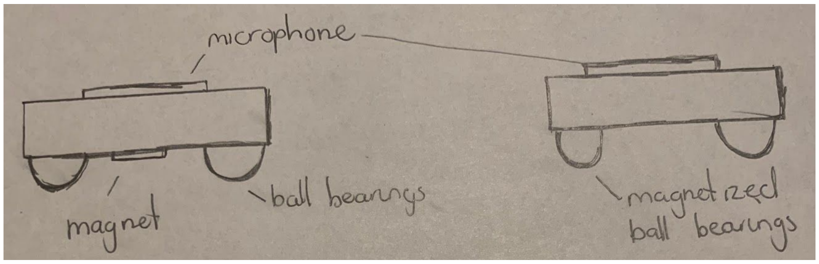

Figure 19. Rolling Contact Ideas

Other ideas included adding a lubricated surface for sliding or utilizing a metal for the ideas discussed above to eliminate the need for a magnet inside the chamber if using a magnetic coupling mechanism.

Brainstorming

Unable to meet in person due to pandemic restrictions, our initial team brainstorming session was conducted remotely over Zoom. A shared document was created where we wrote down any ideas that came to mind during the brainstorming session. Despite the circumstances, we were able to discuss and share ideas - avoiding any bias regardless of how outlandish an idea was.

Several ideas were generated from brainstorming which encompassed both housing and locomotion. The locomotive concepts included the robotic arm, hovercraft, and oppositely statically charged surfaces that would repel each other while the housing concepts were the spring loaded enclosure, and a lubricated housing to reduce friction.

Design Heuristics

The second method we used to facilitate the concept generation/development is design heuristics. Design heuristics is “an empirically driven design ideation tool intended to support variation and novelty in concept generation” [14]. In order to utilize this method, we took the ideas we already had and applied different design heuristics from the list of 77 in the concept development canvas module (which in turn was from Christian 2012 [14]). This list of 77 heuristics is shown below in Figure 20.

1. Add levels
2. Add motion
3. Add natural features
4. Add to existing product
5. Adjust function through movement
6. Adjust functions for specific users
7. Align components around center
8. Allow user to assemble
9. Allow user to customize
10. Allow user to rearrange
11. Allow user to reorient
12. Animate
13. Apply existing mechanism in new way
14. Attach independent functional components
15. Attach product to user
16. Bend
17. Build user community
18. Change direction of access
19. Change flexibility
20. Change geometry
21. Change product lifetime
22. Change surface properties
23. Compartmentalize
24. Contextualize
25. Convert 2D material to 3D object
26. Convert for second function
27. Cover or wrap
28. Create service
29. Create system
30. Divide continuous surface
31. Elevate or lower
32. Expand or collapse
33. Expose interior
34. Extend surface
35. Flatten
36. Fold
37. Hollow out
38. Impose hierarchy on functions
39. Incorporate environment
40. Incorporate user input
41. Layer
42. Make components attachable/ detachable
43. Make multifunctional
44. Make product recyclable
45. Merge surfaces
46. Mimic natural mechanisms
47. Mirror or array
48. Nest
49. Offer optional components
50. Provide sensory feedback
51. Reconfigure
52. Redefine joints
53. Reduce material
54. Repeat
55. Repurpose packaging
56. Roll
57. Rotate
58. Scale up or down
59. Separate functions
60. Simplify
61. Slide
62. Stack
63. Substitute way of achieving function
64. Synthesize functions
65. Telescope
66. Twist
67. Unify
68. Use common base to hold components
69. Use continuous material
70. Use different energy source
71. Use human-generated power
72. Use multiple components for one function
73. Use packaging as functional component
74. Use repurposed or recycled materials
75. Utilize inner space
76. Utilize opposite surface
77. Visually distinguish functions

Figure 20: The 77 design heuristics from Christian 2012 [14].

The thin film plexiglass cover was developed using Heuristics 22 and 27 (change surface properties and cover or wrap). Heuristic 20 (change geometry) inspired the tapered housing, while heuristic 47 (mirror or array) inspired the idea to place the microphones in an array. Lastly, heuristic 56 (roll) led to the development of the idea to use ball bearings. Each of these either improved on a previous concept or was a new concept that could potentially solve the problem to some varying degree.

SCAMPER

The third concept generation and development method we employed was SCAMPER which stands for substitute, combine, adapt, magnify or modify, put to other uses, and eliminate. This technique "uses a set of directed, idea-spurring questions to suggest some addition to, or modification of, something that already exists" [15]. For our concept generation, substitute, adapt, and eliminate were utilized. To incorporate substitute we replaced attractive forces used in the magnetic coupling with repulsion leading to the idea of using magnetic suspension (or levitation). Adapt was incorporated by referring to our past ME250 project on remote controlled vehicles. This generated the idea to place the microphone on a small remote control vehicle that could be driven inside the chamber. From eliminate we developed ideas that focus on minimizing certain aspects. The two concepts that came from this are the use of a wireless microphone which eliminates the wires present in the current system, and using magnetic material for the microphone holder instead of magnets to further reduce the amount of material in the chamber. Each of the concepts developed using SCAMPER provided us with good options to consider.

Screening

To decide on a final concept, the generated ideas were screened using a Pugh chart with a 3-point ranking system to judge how well they meet design requirements. The criteria used were the requirements listed in Table 1 (pg. 8-9) and manufacturability. Each criteria scored 1, 2, or 3 depending on how well the concept satisfies the requirement; 3 being the best and 1 being the worst. Based on our understanding of the current system, the current setup was given a score of an 11. Once every concept was scored, we then compared their performance against the current setup. Table 3 below shows the Pugh chart highlighting scores for each concept relative to the current setup.

Table 3: Pugh chart ranking our concepts based on how well they met our requirements.

	Criteria					
Concepts	Synchronous Motion	Minimize Material	Easily Removable Components	Mechanism Clears Rails	Manufacturability	**Total**
Drive Belt (current)	3	1	1	3	3	**11**
Magnetic Coupling	2	3	3	1	3	**12**
Magnetic Suspension	1	3	3	3	2	**12**
Robotic Arm	2	3	1	2	1	**9**
Electrostatic Charge	2	3	2	1	1	**9**
Magnetic Coupling: Ball bearings	3	3	3	2	2	**13**
Magnetic Suspension w/ magnetic housing	2	3	3	3	2	**13**
Microphone Hovercraft	1	1	2	2	1	**7**
Microphone Array	1	1	1	2	3	**8**
Microphone RC Vehicle	1	1	3	2	1	**8**

Manufacturability and removability are scored depending on how many subcomponents would need to be manufactured and installed thus concepts with less components scored better. This explains why concepts such as magnetic coupling scored better. Material reduction was scored on how many components or material would be utilized relative to the current system which is what the majority of the concepts would do well. For clearing the rails, designs that required close contact to the cart gantry to function were scored poorly. Some designs required additional research on similar mechanisms to better understand how to score them. From this research we discovered that the magnetic suspension concept which utilizes repulsive magnetic forces can be highly unstable[16] therefore this design would require a closed-loop feedback system to maintain stability and synchronous motion[17]. The RC vehicle concept introduces human error to the final displacement which is why it scored poorly for synchronous motion.[18] We have also found that ball bearings can be used to reduce friction[19] and so we scored concepts with bearings well for synchronous motion.

To help narrow down to a final design, constraints and barriers to the project were also considered. The first constraint is limited accessibility to manufacturing resources due to the COVID-19 restrictions and our lack of experience making a functioning prototype. The second is the time constraint to complete our prototype, as outlined in our project plan. Lastly, our sponsor, Professor Popa, prefers that our design does not radically alter the current experimental space. These constraints limit our design choice to be the simpler option.

Final Design Concept

From the pugh chart, the concepts that scored the highest were the magnetic coupling with ball bearings and magnetic suspension with magnetic housing. Keeping in mind that repulsive magnetic forces can be unstable and our design constraints, we have selected the magnetic coupling with ball bearings to be our final design concept. Going forward, we will be conducting engineering analysis and experiments to finalize more details of the design.

Engineering Analysis

Engineering Analysis

The use of engineering analysis will allow us to determine the specifics of our design, within the constraints of the design space set by our concept screening. A discussion of the factors to consider in designing the magnetic coupling and spring retention systems will follow the analysis of each.

Material Selection

Selecting a material for our solution is key to ensuring that our design is lightweight enough to support synchronous motion with the chosen magnets and that it is cheap and manufacturable. We have decided that in order to meet these constraints, our solution will be 3D printed. This ensures that it will be light weight, and it will be easy to both modify and manufacture. Based on several factors including density, cost, strength, and friction coefficient, the material best suited for our purpose is ABS. The material properties that were compared to come to our material decision are organized below in Table 4.

Table 4. Comparison of 3D printing materials for our solution.

	Density (g/cm^3) [22][23]	Friction Coefficient [24]	Cost ($/kg) [26]	Yield Strength (MPa) [22]	Tensile Strength (MPa) [22]
ABS	1.02 - 1.21	0.256	20 - 30	29.6 - 48.0	29.8 - 43.0
PC/ABS	1.10 - 1.15	0.357	75 - 90	45.0 - 55.0	40.0 - 50.0
PLA	1.23 - 1.25	0.266	20 - 30	59.0 - 61.0	52.0 - 54.0

CAD Model

Our CAD model of our solution provided us with necessary information that was used in our analysis, including the total volume and mass of the assembled components. As seen below in Figure 21, the dimensions of our solution result in a volume of 1.125 in^3. Adding the ball casters to the housing adds ⅜" to the total height of the housing, which results in a final volume of 1.97 in^3.

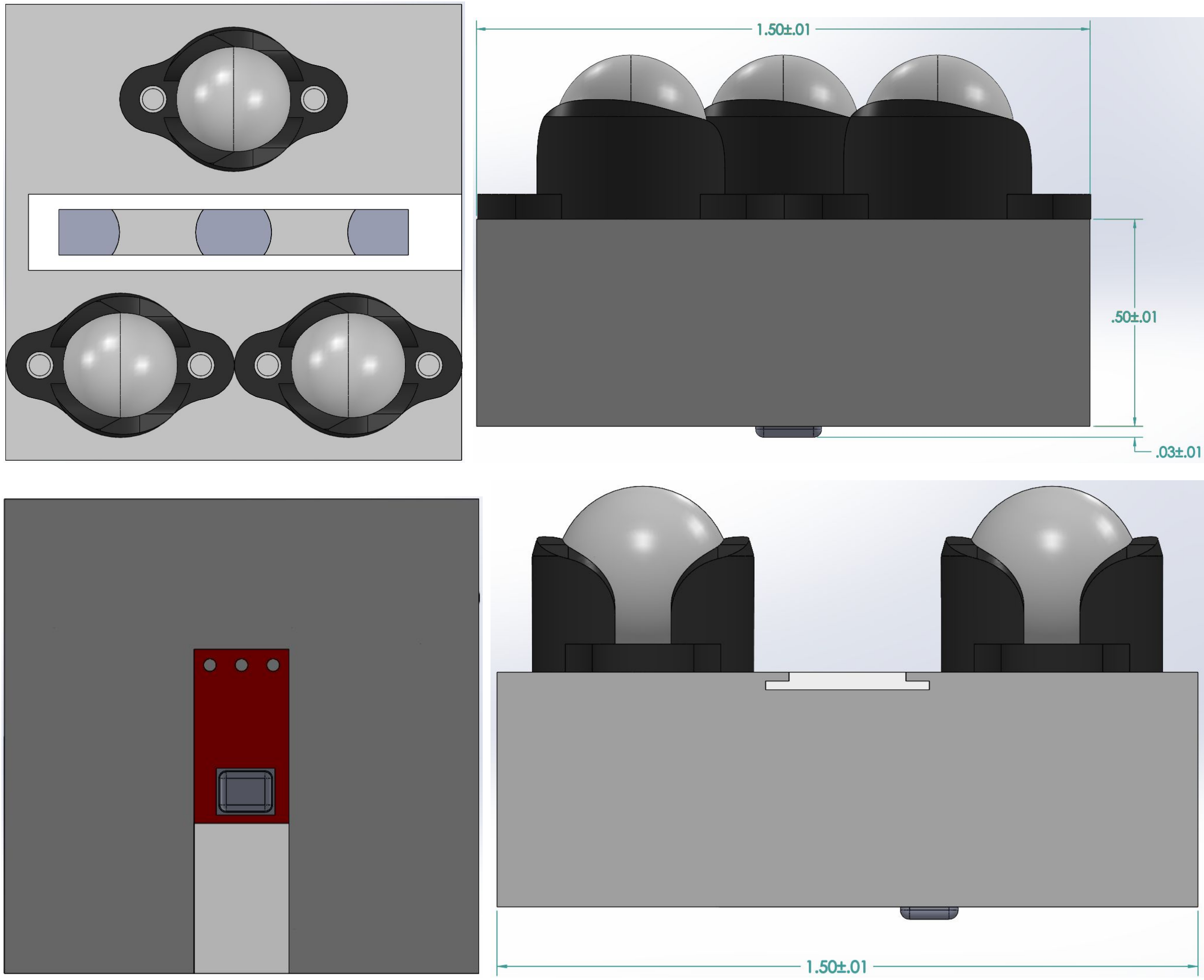

Figure 21: The Solidworks model of the final design, complete with dimension. The views from left to right, top to bottom are the top, front, bottom, and right side.

The CAD model was also used to determine the mass of the overall microphone housing assembly for use in further analyses. The mass of the housing, assuming it's solid ABS, comes out to be about 17.80 grams. The magnets are known to be about 0.187 grams each for a total of 0.562 grams of magnets. Furthermore, the microphone is about 2-3 grams and the ball casters are known to be about 0.8 grams each (without screws or spacers) for a total of 2.4 grams from the casters. This puts the total mass of the housing assembly at about 23.26 grams.

Free Body Diagram – Magnetic Coupling

As discussed previously, the magnetic coupling will be used because of its ability to deliver a force without direct contact of any sort between input and output. Our initial research explains that magnetic force can be modeled with reasonable accuracy through an inverse quartic relationship [20]. This relationship can be described explicitly by Equation 1 below.

$$F_M = \frac{3\mu m_1 m_2}{2\pi r^4} \tag{1}$$

Where μ is the permeability of the medium, m_1 is the magnetic strength of the top magnet, m_2 is the bottom magnet, and r is the distance between the magnets. The equation is derived from Ampere's law using vector analysis while assuming the magnets are small enough to be approximated as magnetic dipoles of strength m.

We drew a free body diagram to determine the relationship between magnetic force, gravitational force, and frictional force, seen in Figure 22, below.

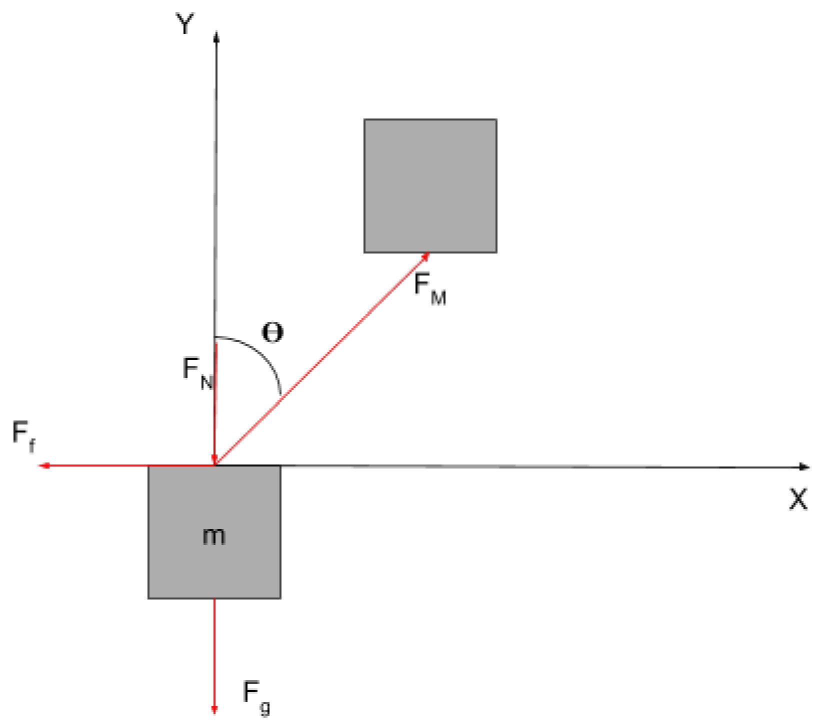

Figure 22. Free body diagram analysis of the system using a lumped parameter method. The upper square is the magnets that will be on the cart controlled by the experimentalist. Moving the cart causes the attractive force, F_M, to change direction and create a force in the X direction to accelerate the bottom mass. This bottom mass represents the entire housing we are prototyping and we assume that it rolls along the plexiglass (shown by the X-axis) via caster with no slipping.

Equations 2 and 3 below are what we used to describe the frictional force, F_f, and the gravitational force, F_g.

$$F_f = \mu F_N \tag{2}$$

$$F_g = mg \tag{3}$$

Here μ is the coefficient of friction, m is the mass of the housing, and F_N is the normal force exerted by the plexiglass. In order to determine the normal force, we use Newton's second law of motion for the forces along the Y-axis. For this we assume that the vertical distance between the magnets will remain constant at $20\ mm$ and thus the acceleration along the Y-axis must be zero. Equation 4 shows the results of the force balance along the Y-axis.

$$F_N = F_M \cos\theta - mg \tag{4}$$

The angle θ represents the separation between the centers of the two masses in the diagram and is a critical parameter in the relationships between all of the forces. From Equation 4, we can see if $F_N \leq 0$, then $F_M cos\theta < mg$ and the coupling fails.

Using Newton's second law for the forces in the X-axis, we can find the acceleration of the housing in terms of the forces acting on it, shown by Equation 5 below.

$$\ddot{x} = \frac{1}{m}[F_M \sin\theta - \mu(F_M \cos\theta - mg)] \tag{5}$$

Here we see that the acceleration is a function of all three forces acting on the housing. Also if $F_M sin\theta \leq \mu(F_M cos\theta - mg)$, then the coupling fails because the frictional force is too strong. Further analysis was conducted using Equations 4 and 5 to find out how many magnets we would need to keep the separation angle small but yet be able to overcome the frictional force.

Sliding versus Rolling

The first step for analysis included evaluating whether sliding or rolling with 2 rollers would be better suited for this project. This involved evaluating the two points of failure where the magnetic force cannot overcome friction or carry the weight of the mechanism. The minimum and maximum angles correspond to each point of failure respectively. This is illustrated in Table 5 below.

Table 5. Comparison of free body analysis results for sliding and rolling

	Sliding	Rolling
Coefficient of Friction μ_k	0.256	0.025
Force to Overcome Friction (N)	0.8294	0.0804
Minimum Angle (Degrees)	13.5	1.2947
Force to Hold Weight	0.3485	0.3425
Maximum Angle	84.858	84.4775
Range of Operation (Degrees)	71.358	83.1828

From this analysis we determined that using rollers which increase the mechanism weight, greatly reduce the effects of friction lowering the minimal angle of separation, θ-separation, required between the top and bottom magnets to move the mechanism. The change in friction coefficient is the cause of this change and its irrelevance in determining the force to hold the weight explains the small difference at upper limits. Thus, the high coefficient of friction for sliding outweighs the effect of increased weight on using rollers. The smaller minimum θ-separation for rolling also shows that a smaller separation between top and bottom magnets would be required for motion which improves the synchronous motion.

Detailed Friction Analysis for Failure

Having determined that rolling is better suited for this project, we then studied the friction effect of using different roller combinations for the mechanism. Using Equations 3 and 4, the normal force was calculated from the weight and force of a single magnet and which was then used to determine the minimum force required to overcome friction. The plots below illustrate how varied roller combinations affect the minimal force required to overcome friction as well as the corresponding θ-separation.

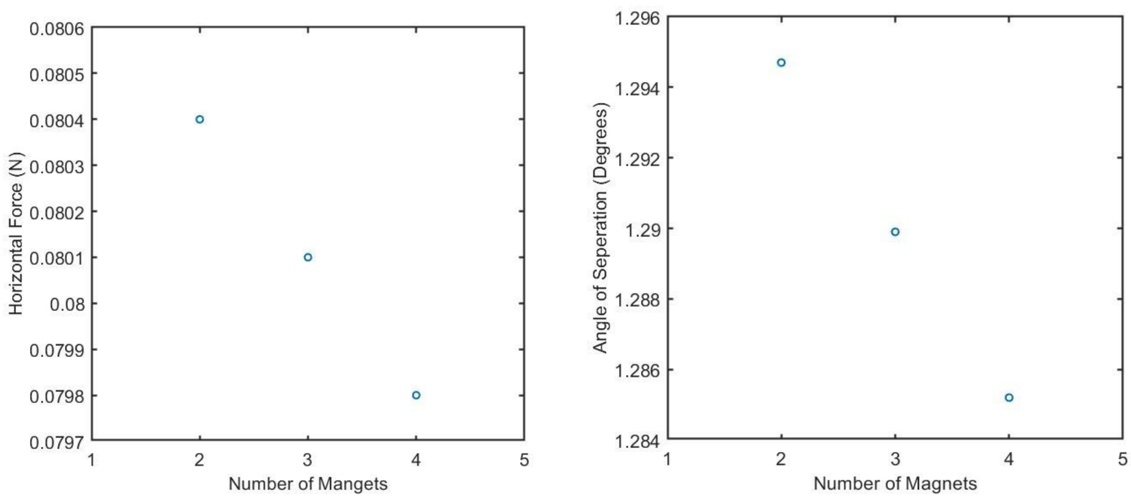

Figure 23. Plots for Minimum Horizontal Force Required to Overcome Friction as Well as The Corresponding θ-Separation

By holding the magnetic force constant, we determined that increasing the weight reduces the resulting normal force which in turn minimizes the minimum force required to overcome friction. Since the reduced force corresponds with a smaller θ-separation, we concluded that minimizing friction improves on the synchronous motion. Making accommodations for friction does have an effect on the other point of failure from weight which is discussed further in the following section.

Analysis for Failure from Weight

The minimum vertical force and necessary angle of separation from the single magnet required to hold the mechanism was determined for each combination and are presented in the plots below.

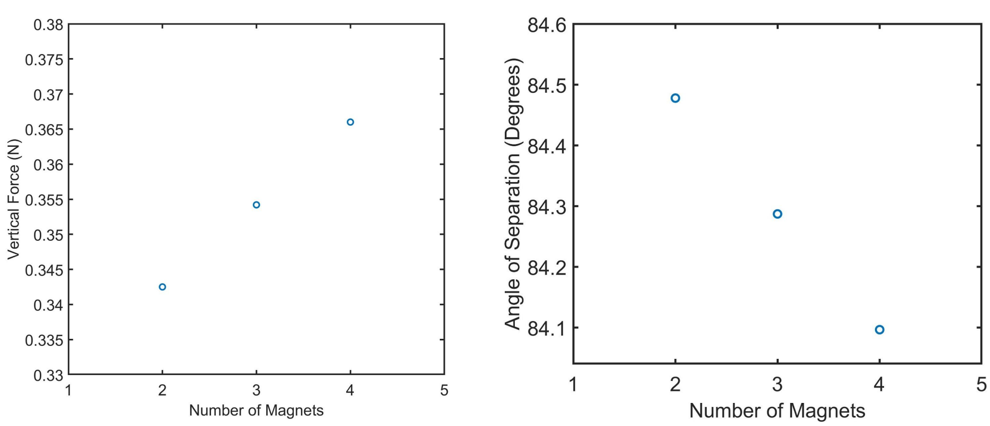

Figure 24. Plots for Minimum Vertical Force Required to Hold Mechanism Weight as Well as The Corresponding θ-Separation

From this analysis we determined that while improving friction by increasing weight improves on synchronous motion, it comes at a cost as a larger force would be required to hold the mechanism and prevent it from falling in the chamber. This reduces the maximum possible angle of separation between caddy and mechanism. Thus while including more rollers improves friction behavior, it reduces the effective range of operation for the mechanism. From this analysis we determined that using 3 rollers would offer the best compromise between the better conditions for failure from weight for using 2 rollers and the improved synchronous motion from using 4 instead.

3 Rollers: Varied Magnetic Force

Once the use of 3 rollers was established, we then evaluated the performance of 2, 3, 4, and 5 magnet couplings. Using Equation 1, which was solved for the manufacturer's listed 0.8 pounds pulling force at a separation of 1 inch, we then determined the magnitude of the magnetic force for a constant y-separation of 32 mm and an x-separation which varied from 0 to 100 mm. This magnetic force magnitude was then resolved into x and y-components; these components were plugged into Equations 2, 3, and 4 in order to determine the behavior of the housing as the cart moved further away and as more magnets were added. Representative plots of the behavior are included below.

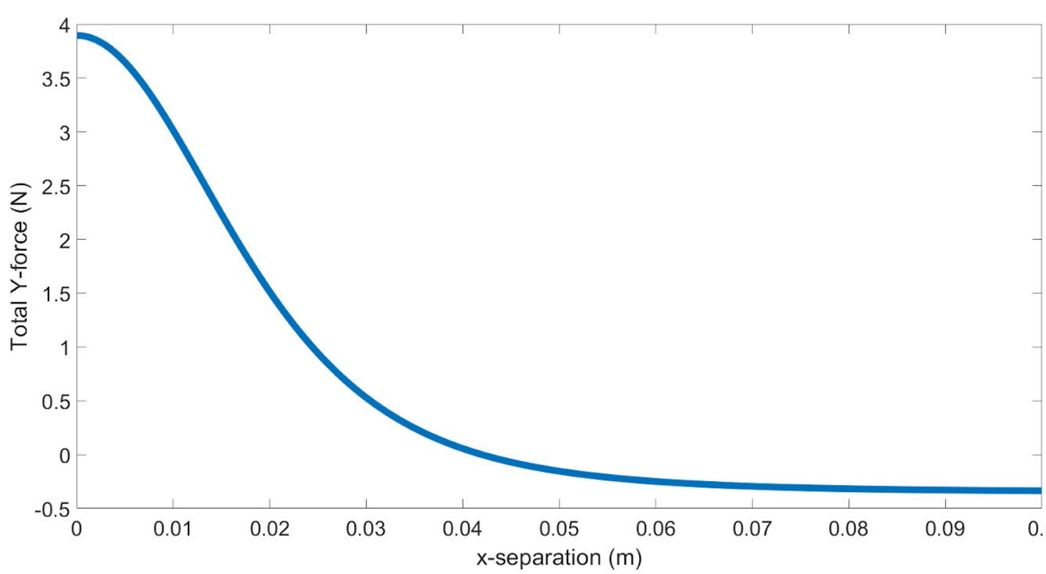

Figure 25. Plot of total y-force versus x-separation for a three magnet configuration. The y-force varies with the x-separation from the positioning cart for a given magnet configuration. The coupling fails when this force, the sum of the upward component of magnetic force up and the weight down, is less than or equal to zero. For this plot, the corresponding x-separation is 42 mm (~1 ⅝ inches)

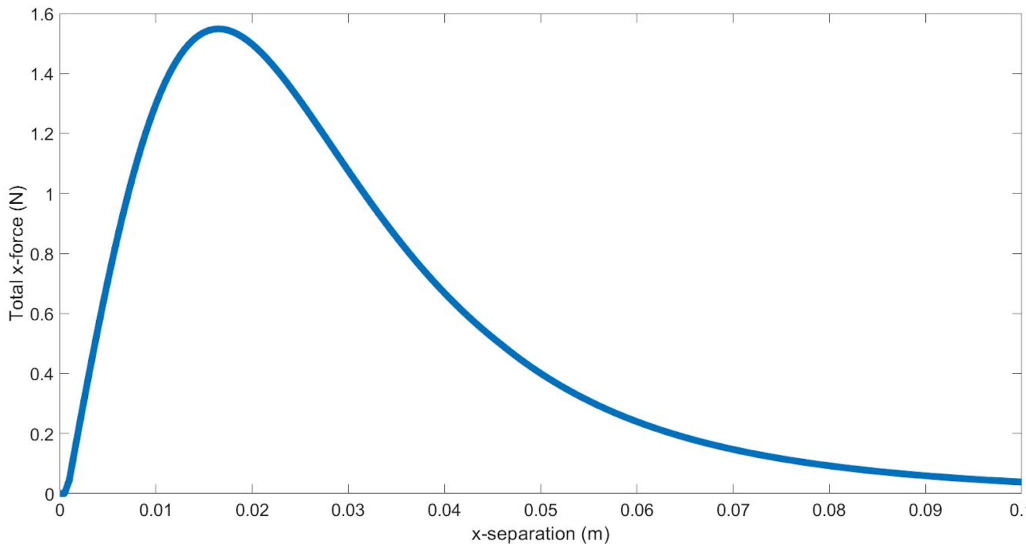

Figure 26. Total x-force versus x-separation for a four magnet configuration. The x-force varies with the x-separation; The coupling will fail to move when this force, the sum of the horizontal component of magnetic force and the friction force, is zero. The highest net force occurs as a tradeoff between the angle of the magnetic force and the distance from the positioning cart, and for this plot occurs at 16.5 mm (~⅝ inches).

From these plots we determined the following x-separations: the maximum x-separation at which the coupling would fail due to the vertical magnetic force failing to counteract the housing's weight, called x_{weight}; the minimum x-separation at which the coupling would fail due to not being able to overcome the friction force, called $x_{friction}$; and the x-separation at which the coupling would have a maximum x-acceleration due to the best balance of x-separation and angle, called $x_{max\ a}$. This data is summarized in Table 6, below. Of note is that the largest gain comes from the jump from 2 to 3 magnets; the friction force with the rollers is generally low enough that the smallest meaningful displacement in our calculations, 1 mm, is enough to overcome it, and that the different magnet numbers all have the same displacement for maximum acceleration. The friction force is similar for all magnets, as the additional mass of around 0.2 g per magnet does not make much of a difference, and the additional upward force does not add much to friction due to the low effective coefficient of friction for our rollers.

Table 6. Break points for displacement for each magnet configuration

Number of Magnets	x_{weight} (mm) [inches]	$X_{friction}$ (mm) [inches]	$X_{max\ a}$ (mm) [inches]
2	37 [1.5]	1.0 [0.025]	16.5 [0.650]
3	42 [1.7]	1.0 [0.025]	16.5 [0.650]
4	46 [1.8]	1.0 [0.025]	16.5 [0.650]
5	49 [1.9]	1.0 [0.025]	16.5 [0.650]

From this, we determined that using 3 magnets would be the best choice, as it provides the largest boost to x_{weight} before diminishing returns kick in. In practical terms, this means that the positioning cart could be up to 1.7 inches ahead of the microphone housing and still keep it pressed against the upper plexiglass. The 3 magnets will satisfy the preliminary analysis result of a force 1.5 times that of our housing's weight for x-separations less than 30 mm (~1 ⅛ inches). For a given experiment, the distance between sampling locations can vary, but 30 mm is a solid baseline; if needed, the force can be adjusted by adding magnets should later testing require a larger displacement between samples.

Analysis Summary

The analysis performed above led us to the use of 3 magnets and 3 rollers on our housing to provide good coupling within the testing conditions. The choice of 3 magnets comes down to the best compromise between effectiveness and adding magnets; the choice of 3 rollers results from good frictional behavior without additional mass.

Risk Assessment

We conducted a failure mode and effects analysis (FMEA) to highlight any possible issues that may be incurred from the design and how to best alleviate them. The table below goes over the possible risks from this design

Table 7. Failure mode and effects analysis table

Process	Failure Mode	Failure Effect	SEV	Potential Cause	OCC	Controls	DET	RPN (OCC*SEV*DET)	Recommended Action
Coupling Failure	Magnets losing strength	Experiment halted	6	Magnets lose strength over time	2	Test run to check magnetic strength before experiment	4	48	Replace magnets. Check for proper orientation
	Ball caster not rotating increasing friction which causes coupling to fail	Experiment halted	4	Ball caster might get stuck	4	Check for ball caster rotation before placing into chamber	1	16	Check ball casters to ensure they rotate freely
Housing Failure	Magnet and microphone slot breaking	Experiment cannot start	3	Improper handling	2	Gentle handling of parts	1	6	3D print extra parts in case of failure
	Housing breaking	Experiment cannot	3	Improper handling	2	Gentle handling of	1	6	3D print extra part in case of

		start				parts			failure.

The process column details the processes that would result in failure while the failure mode gives more detail on what the possible sources for that process could be. Failure Effect explains the impact such a failure would cause and SEV rates the severity of failure from 1 - 10 with 10 being the most severe. Potential cause explains what might cause the part failure and OCC rates how frequently the failure could possibly occur (lower rating means failure is less likely to occur). Controls detail the systems in place to ensure failure does not occur and DET rates how easily the failure can be detected. A lower value for this rating means this kind of failure is less likely to occur. The recommended action column highlights possible solutions to rectify the situation should failure occur. The part of our design with the highest risk is the magnetic coupling as it is the most significant part. We assessed that failure could come from an increase in friction, which could be caused by ball casters failing to roll or magnets losing strength, leading to the magnets failing to hold the mechanism. We attempted to account for these failures by making sure we had 3 magnets and 3 ball casters to ensure a good balance between reducing friction and maintaining the coupling. We believe that the current risk levels from our design should be low enough to not be an issue, however it is difficult to be certain of this as we were not able to construct the design and test it ourselves. We have included possible solutions that may help alleviate these failure modes should they occur and some suggestions on how to minimize risks.

Design Solution

The final design solution used magnetic coupling along with ball casters to meet the requirements and specifications, as described in the Concept Generation and Development and Final Design Concept sections. The key attributes of the design include the housing, the ball casters, the slots and slot fittings, and the magnets. As can be seen below in Figure 27, the solution used a square prism-shaped housing to mate the ball casters, magnets, and microphone.

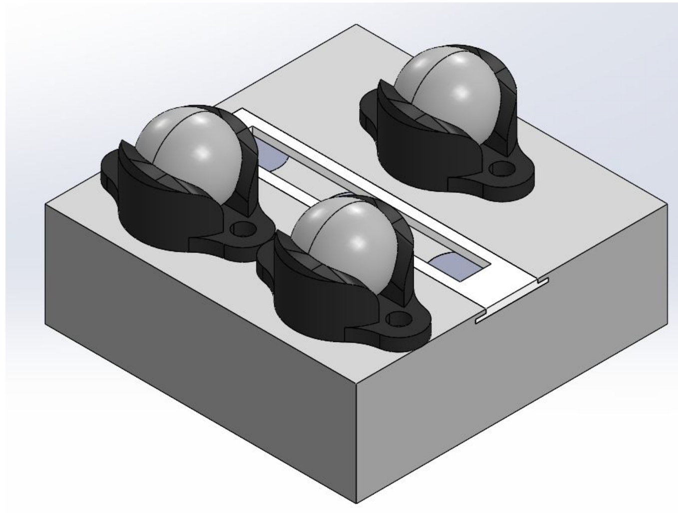

Figure 27: The CAD model of the final microphone housing assembly as seen from an isometric view

The housing was designed as a square prism for one main reason, manufacturability. The positioning of the three ball casters on the top surface of the housing, as seen above in Figure 27, enabled multiple possible shapes for the housing to be considered. One of the alternatives considered involved tapering the housing from the side with two ball casters to the side with one ball caster. This taper, however, would've added unnecessary complexity to the design, as the amount of material saved would have been minimal in terms of both cost savings and a reduction in interference with microphone measurements. The original design of the housing did have a taper, however, but instead of from the side with two ball casters to the side with one it was inwards from the top of the housing to the bottom of the housing where the microphone was mounted. The removal of this taper was a change made early in the solution development process, as it was noted that housing wouldn't fit between the two sheets of plexiglass at its then height. The final, square design for the housing ended up with a volume of 1.06 in^3. This greatly reduced the amount of material inside the acoustic testing chamber, which helped our solution meet the "Minimize material in chamber" requirement and corresponding engineering specification.

The ball casters are located on the top surface of the microphone housing, on either side of the magnets. As shown in Figure 27 above, two are mounted on one side of the magnets, while one is mounted on the other side. This is the optimal configuration, as described in the Engineering Analyses section. They are held in place by screws and screwed into holes in the housing specifically added for this purpose. The specific ball casters were chosen as they were the smallest model found that were both within the budget and easily accessible. As can be seen in Figure 28 below, the casters extend above the housing about 0.4 inches. This distance doesn't significantly impact the performance of the magnets, also described in the Engineering Analyses section. The addition of the ball casters reduced friction between the plexiglass and housing, assisting in the solution keeping “consistent synchronous motion between the microphone and driving cart” and the related engineering specifications.

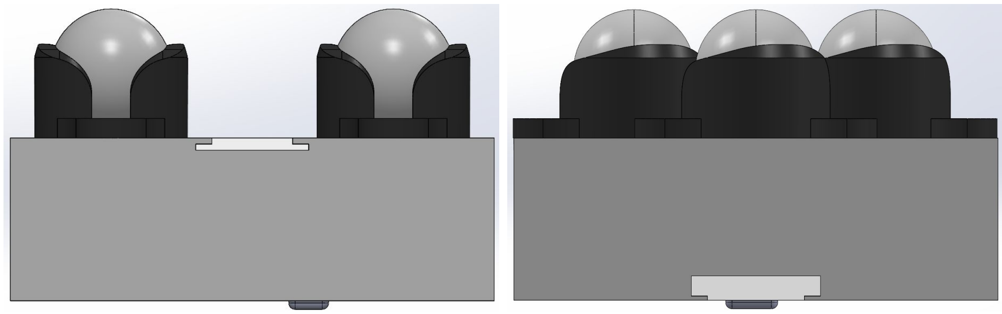

Figure 28: The CAD model of the microphone housing assembly as seen from the right side (left) and back side (right)

In order to connect the magnets and microphone to the housing, slots were used. These can be seen in both the right and back side views in Figure 28 above. The method of connection was changed multiple times throughout the development of the solution. Spring loaded enclosures were originally planned to be used, but once those proved difficult to design, snap fits were designed for use. However, like for the spring loaded enclosures, the small size of the housing made it difficult to ensure that functioning snap fits could be easily manufactured. Therefore, the design shifted to slots as they were easier to manufacture. The top slot allows for a piece of plastic to slide overtop of the magnets and hold them in, while the bottom slot allows for the microphone to slide in and then a second piece of plastic “plugs” the rest of the slot. The top slot can be seen clearer in Figure 27, while the bottom slot can be seen clearly in Figure 29. Both pieces of plastic are held in place by friction. These slots are significant in the fact that they allow for easy removal of the components and enable the solution to meet the corresponding engineering specifications. Once the plastic parts are slid out of the housing, then the magnets and microphone can both be easily accessed.

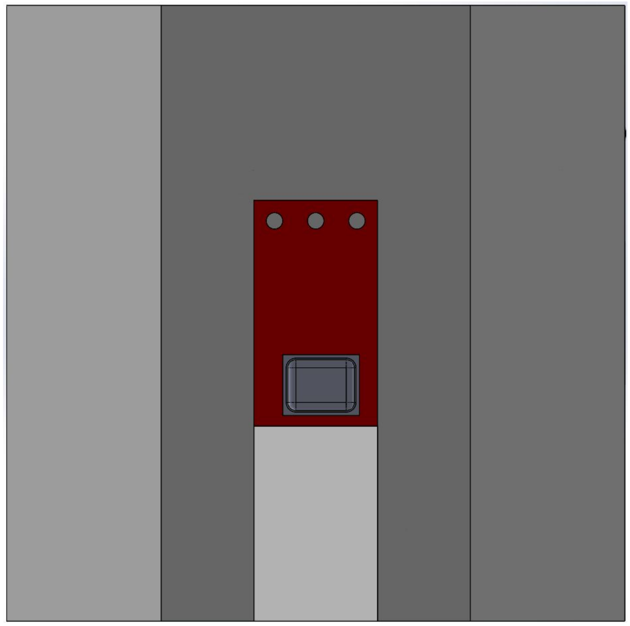

Figure 29: The CAD model of the microphone housing assembly as seen from the bottom

The last significant feature of the design solution is the magnets themselves. As originally recommended by the sponsor, the magnets used are grade N42 neodymium disc magnets, with a size of ¼ inch by 1/32 inch. These magnets are strong enough to ensure the setup works as intended while still being small enough to avoid any excess material in the chamber. As shown in the Engineering Analyses section, the optimal number of magnets for the solution to work as intended is three. Each magnet is placed in the top of the housing, held in by the slotted plastic "lid" as described previously. These magnets ensure that the design can both clear the rails and maintain synchronous motion with the cart outside the chamber, as well as that the design meets the relevant engineering specifications.

Together, each key attribute of the design came together to fulfill each requirement and engineering specification. Unfortunately, however, the housing was unable to be printed and tested due to COVID-19 restrictions. Therefore, while the design works in theory, it should also be further verified in empirical testing.

Verification

Verification Methods

In order to verify that our solution will perform to our engineering requirements and specifications, we are going to employ two main methods. One of these methods involves our 3D CAD model, which will ensure we are minimizing the amount of material that is in the chamber and making sure the different components are easy to remove and replace. The second method we will employ will be to set up a clone of the experiment that is in the lab, and empirically test the movement of the mechanism by hand.

CAD Model

As previously mentioned, the CAD model shows the small volume of material that the solution consists of. This is consistent with the minimizing material requirement, as it only takes up a 1.5” x 1.5” space, rather than spanning the entire width of the chamber. The CAD model was also used to verify whether or not our components were able to be easily removed and replaced. Using our model, we were able to design certain aspects and geometries of the housing that met this requirement. This included the sliding cover to keep the magnets in place and the extrusion where the microphone is able to be slid in and out in seconds. This was the best method to verify these requirements, as we were able to strictly control the dimensions and geometry to meet the criteria while being able to visualize the parts coming together.

Empirical Testing

Due to the COVID-19 pandemic, our team was unable to access Professor Popa’s Lab. This barred our team from observing and using the existing experimental setup, forcing us to try and clone the experiment on our own. This was done by purchasing a plexiglass sheet, magnets, and the microphone that is used in the actual experiment. While this was the closest we can get to the actual experiment, it is important to note that the actual setup is controlled electronically and uses a motor to move the microphone around. Our team was forced to move the solution by hand but we were able to mimic the movements of the experiment and with enough testing and confirmed the performance of our solution to the synchronous motion requirement.

To perform this method, we used magnets above the plexiglass glass to mimic the cart mechanism of the experiment. This pulled the ball casters and housing into contact with the underside of the plexiglass. From here, several iterations of moving the magnets in the X and Y directions were performed. The final location of the magnets and the housing were then measured. The displacement of the housing mechanism and the magnets mimicking the cart were within a few millimeters on most tests, so we believe our solution will fulfill our synchronous motion requirement.

While we do not believe this to be the best solution overall, it was the best solution available to us and was recommended by our sponsor. Ideally, we would be able to attach our solution to the existing experiment and test it that way, but that was out of the question as previously mentioned. The limitations of this method included the inability to exactly mimic the motion of the existing cart. We do not know exactly how fast the cart accelerates in the actual experiment, so we had to estimate this speed in our own testing.

Discussion and Recommendations

Having completed the project, we believe our design does well having simple parts that can be easily set up and replaced with similar equally inexpensive components. It is very simplistic, and attempts to meet the requirements we established. The main weakness for this project stems from our inability to manufacture a working prototype and figure out any issues that may be incurred from practical use. Not being able to make a prototype also prevented us from testing how well the design works from repeated use. However, using our limited empirical tests, we were able to confirm results from the engineering analysis shown earlier. We learned that the orientation of the magnets can greatly improve the stability and synchronization of motion. Shown in the CAD model of our final design, we have the magnets arranged in a line. This allows for the magnet force to be more evenly distributed and prevents the coupling from being completely interrupted when passing over the aluminum braces. The magnets will be mounted in alternating poles, either north-south-north or south-north-south. The magnets mounted on the gantry cart should be mounted in the configuration opposite on the housing. This provides a lot more stability than stacking the magnets. Also the difference in position between the cart and the housing is nearly identical, fulfilling the requirement of consistent synchronous motion. Learning these insights was possible because we had the ability to fabricate an experimental rig that mimicked Professor Popa's setup as much as possible.

Beyond the magnets, there are a few redesigns that should be considered for the housing. The current model of the housing does not provide any support/management for the wires that would protrude from the microphone in the lab setup. An additional clip on the side of the housing or a path up through the housing for the wires could provide added convenience. Furthermore, the slot method for the microphone and magnets was unable to be tested. This should be tested empirically and may require some redesign if it is found to be unreliable.

Conclusion

Professor Bogdan Popa is conducting research on metamaterials using a 2D acoustic sound mapping chamber made of two separated sheets of plexiglass. Currently, he uses a microphone attached to a drive belt to move the microphone to discrete locations inside the chamber. This drive belt interferes with sound waves played by the speaker, ultimately destroying any quality results in the space it takes up and within the space behind it. In order to come up with a solution to this problem, we had to remove the drive belt and come up with a solution to move the microphone around the chamber while minimizing the material in the chamber overall.

Our solution involves a 3D printed housing made of ABS plastic coupled with ball casters and magnets to move the microphone inside the chamber. Outside the chamber, and driving caddy containing magnets moves above the chamber, and through magnetic force, drags the microphone to the necessary position. The housing is very small (1.5” x 1.5” x 0.5”) in order to minimize the material in the chamber, and lightweight enough that small magnets will be strong enough to synchronously move the housing with the driving cart. The ball casters were added to eliminate friction of the housing sliding against the plexiglass, to ensure the magnets would be able to keep the housing moving synchronously with the driving cart.

Due to COVID-19 restrictions and 3D printer hardware malfunctions, we were unable to fully test this solution with the actual experimental setup. However, we were able to build a smaller testing setup similar to the actual one, and test magnets sliding along the surface of plexiglass. The magnets were able to slide across the plexiglass with ease, so we believe that our final design would be able to accomplish synchronous motion as we eliminated friction with ball casters and by use of very lightweight materials.

Authors

Aaron Maas: Aaron was born and raised in Menominee, MI, a small town in the upper peninsula. He is a fifth year senior in Mechanical Engineering and will graduate in December of 2020. At Michigan, he spent 3 years on the Division 3 Club Hockey Team that made multiple National tournament appearances. Outside of school and hockey, he enjoys the outdoors, video games, and watching football. After college he plans on moving to Colorado and working in the aerospace industry before returning to school to get a Master’s degree.

Myles Siglin: Myles was born in Anaheim, CA but considers Flushing, MI to be his home. He is a senior in UM’s Mechanical Engineering program and will graduate in April of 2021. He is a lover of trivia, making numerous state and national appearances in Quiz Bowl and bar trivia tournaments. His hobbies include tinkering and cooking. Upon graduation, Myles plans on joining Southeast Michigan’s auto industry as an automotive engineer.

Joshua Clark: Joshua grew up in South Lyon, MI, 30 minutes away from Ann Arbor. He is a senior in Mechanical Engineering at the University of Michigan and will graduate in April of 2021. At Michigan, he spent 3 years on the Human Powered Submarine student project team, taking on the role of manufacturing lead his second year on the team. He is also an avid runner and enjoys video games and attending Michigan basketball games. He hopes to pursue a Master's degree after spending some time working in industry post graduation.

Carl Johnson: Carl is a senior student at the University of Michigan graduating this fall from a dual degree program in mechanical engineering and applied physics. At Michigan he has spent 2 and half years working in an acoustics lab on non reciprocal wave propagation, conducting experiments and various analysis for the research. He enjoys spending time with friends, going out and has hopes of pursuing a career in design in the Silicon Valley.

Justin Campau: Justin is a senior Mechanical Engineering student at the University of Michigan. Outside of work and school, he spends his time on DIY projects, games with family and friends, and crafting his own fantasy world. After graduation, he hopes to get a job within the nuclear energy industry or automotive industry.

Acknowledgements

Thank you to Professor Bogdan Popa for allowing us to work on his project and for his knowledge and advice regarding this project. Thank you to Professor Kira Barton for providing support, knowledge, and encouragement throughout the duration of this project.

References

1. Kurtz, David W. *"Developments in a free-swimming acoustic leak detection system for water transmission pipelines.*" Proceedings of the 2006 Pipeline Division Specialty Conference - Pipelines 2006: Service to the Owner, v 211 40854, p 25, 2006

2. Guedes, P. et al. "*Low Cost Underwater Acoustic Positioning System with a Simplified DoA Algorithm."* OCEANS 2019 MTS/IEEE SEATTLE, 8 pp., 2019; ISBN-13: 978-0-578-57618-3;

3. Zhai, Yuxin, et al. *"Active Willis Metamaterials for Ultracompact Nonreciprocal Linear Acoustic Devices."* Physical Review B, vol. 99, no. 22, June 2019, p. 220301. APS, doi:10.1103/PhysRevB.99.220301.

4. Dr. Bogdan Popa, Personal Communication, September 2020.

5. Van Dyke, Michael et al. *"Spatial variability caused by acoustic wave interference in single-drive direct field acoustic testing."* Journal of the IEST, v 54, n 2, p 54-74, October 1, 2011; ISSN: 10984321; DOI: 10.17764

6. Lin, Wang-Sheng et al. *“Characteristics of mapping domain of the acoustic field interference structures radiated by a moving target”* Acta Physica Sinica, v 63, n 3, 034306 (12 pp.), Feb. 2014; Language: Chinese; ISSN: 1000-3290; DOI: 10.7498/aps.63.034306; Publisher: Chinese Physical Society & Institute of Physics, China

7. Ginzburg, B.M et al “On the transition from intensive to moderate wear in the friction of solid objects” Technical Physics Letters, v 21, n 1, 18-19, Jan. 1995; ISSN: 1063-7850; Country of publication: USA

8. Mingye Zheng, Yi Chen, Xiaoning Liu, and Gengkai Hu. *"Two-dimensional water acoustic waveguide based on pressure compensation method."* Review of Scientific Instruments 89, 024902 (2018); https://doi-org.proxy.lib.umich.edu/10.1063/1.5008823

9. G. Lindner, H. Faustmann, S. Krempel, M. Munch, S. Rothballer and F. Singer, *"Wave propagation in an acoustic waveguide sensor for liquids driven by pulsed excitation of surface acoustic waves,"* 2008 IEEE International Frequency Control Symposium, Honolulu, HI, 2008, pp. 39-43, doi: 10.1109/FREQ.2008.4622952.

10. Liu, G., Zhou, Y., Liu, M. et al. *“Acoustic waveguide with virtual soft boundary based on metamaterials.”* Sci Rep 10, 981 (2020). https://doi.org/10.1038/s41598-020-57986-9

11. Vatul’yan, A.O., Morgunova, A.V. *“Study of the dispersion properties of cylindrical waveguides with variable properties.”* Acoust. Phys. 61, 265–271 (2015). https://doi-org.proxy.lib.umich.edu/10.1134/S1063771015020141

12. Lee, D.-S. and Gilbert, R.P. (2006), *“Identification of objects in an acoustic wave guide inversion II: Robin–Dirichlet conditions.”* Math. Meth. Appl. Sci., 29: 401-414. doi:10.1002/mma.687

13. Stan Gibilisco. Alternative Energy DeMYSTiFieD, Second Edition. Advanced Propulsion Methods, Chapter (Publisher: McGraw-Hill Education: New York, Chicago, San Francisco, Athens, London, Madrid, Mexico City, Milan, New Delhi, Singapore, Sydney, Toronto, 2013). https://www-accessengineeringlibrary-com.proxy.lib.umich.edu/content/book/9780071794336/chapter/chapter9

14. Christian, J.L, S.R. Daly, S. Yilmaz, C. Seifert, and R. Gonzalez. (2012). Design heuristic support two modes of idea generation: Initiating ideas and transitioning among concepts. *American Society for Engineering Education*. 101(4): 601-629.

15. Serrat, O. (2009). The SCAMPER Technique. *Knowledge Solutions,* 31-33. Retrieved October, 2020, from https://www.adb.org/sites/default/files/publication/27643/scamper-technique.pdf

16. Jipeng Li et al “Motion stability of the magnetic levitation and suspension with YBa2Cu3O7-x high-Tc superconducting bulks and NdFeB magnets” Journal of Applied Physics, v 122, n 15, 153902 (8 pp.), 21 Oct. 2017; ISSN: 0021-8979; DOI: 10.1063/1.4994903; Publisher: AIP - American Institute of Physics, USA

17. Stan Gibilisco. Alternative Energy DeMYSTiFieD, Second Edition. Advanced Propulsion Methods, Chapter (Publisher: McGraw-Hill Education: New York, Chicago, San Francisco, Athens, London, Madrid, Mexico City, Milan, New Delhi, Singapore, Sydney, Toronto, 2013). https://www-accessengineeringlibrary-com.proxy.lib.umich.edu/content/book/9780071794336/chapter/chapter9

18. Xing Pan et al “Research on Human Error in Operation Task Under the Coupling of Time of Day and Stress” Advances in Human Error, Reliability, Resilience, and Performance. Proceedings of the AHFE 2019 International Conference on Human Error, Reliability, Resilience, and Performance. Advances in Intelligent Systems and Computing (956), 65-74, 2020; ISBN-13: 978-3-030-20036-7; DOI: 10.1007/978-3-030-20037-4_6; Conference: AHFE 2019 International Conference on Human Error, Reliability, Resilience, and Performance, 24-28 July 2019, Washington, DC, USA; Publisher: Springer International Publishing, Cham, Switzerland

19. V. C. Venkatesh; Sudin Izman. Precision Engineering. ROLLING ELEMENT, HYDRODYNAMIC AND HYDROSTATIC BEARINGS, Chapter (Tata McGraw-Hill Publishing Company Limited, 2007). https://www-accessengineeringlibrary-com.proxy.lib.umich.edu/content/book/9780070620902/chapter/chapter6

20. Lehner, Günther. Electromagnetic Field Theory for Engineers and Physicists. Springer Berlin Heidelberg, 2008. DOI.org (Crossref), doi:10.1007/978-3-540-76306-2.

21. W. Palm, System Dynamics, Third edition, McGraw-Hill Education; (March 19, 2013)

22. https://omnexus.specialchem.com/polymer-properties

23. D. Kazmer, in: M. Kutz (Ed.), Three-Dimensional Printing of Plastics, AppliedPlastics Engineering Handbook – Processing, Materials, and Applications, A Volume in Plastics Design Library, 2nd ed., 2017.

24. I-T Maries, C Vilau, M S Pustan, C Dudescu and H G Crisan, “Determining the tribological properties of different 3D printing filaments.” Published under licence by IOP Publishing Ltd IOP Conference Series: Materials Science and Engineering, Volume 724, International Conference on Tribology (ROTRIB'19) 19–21 September 2019, Cluj-Napoca, Romania

25. https://3dinsider.com/3d-printing-filament-cost/#:~:text=Regular%20PLA%20and%20ABS%20filament,Not%20even%20close

Appendices

Appendix A: Engineering Drawings

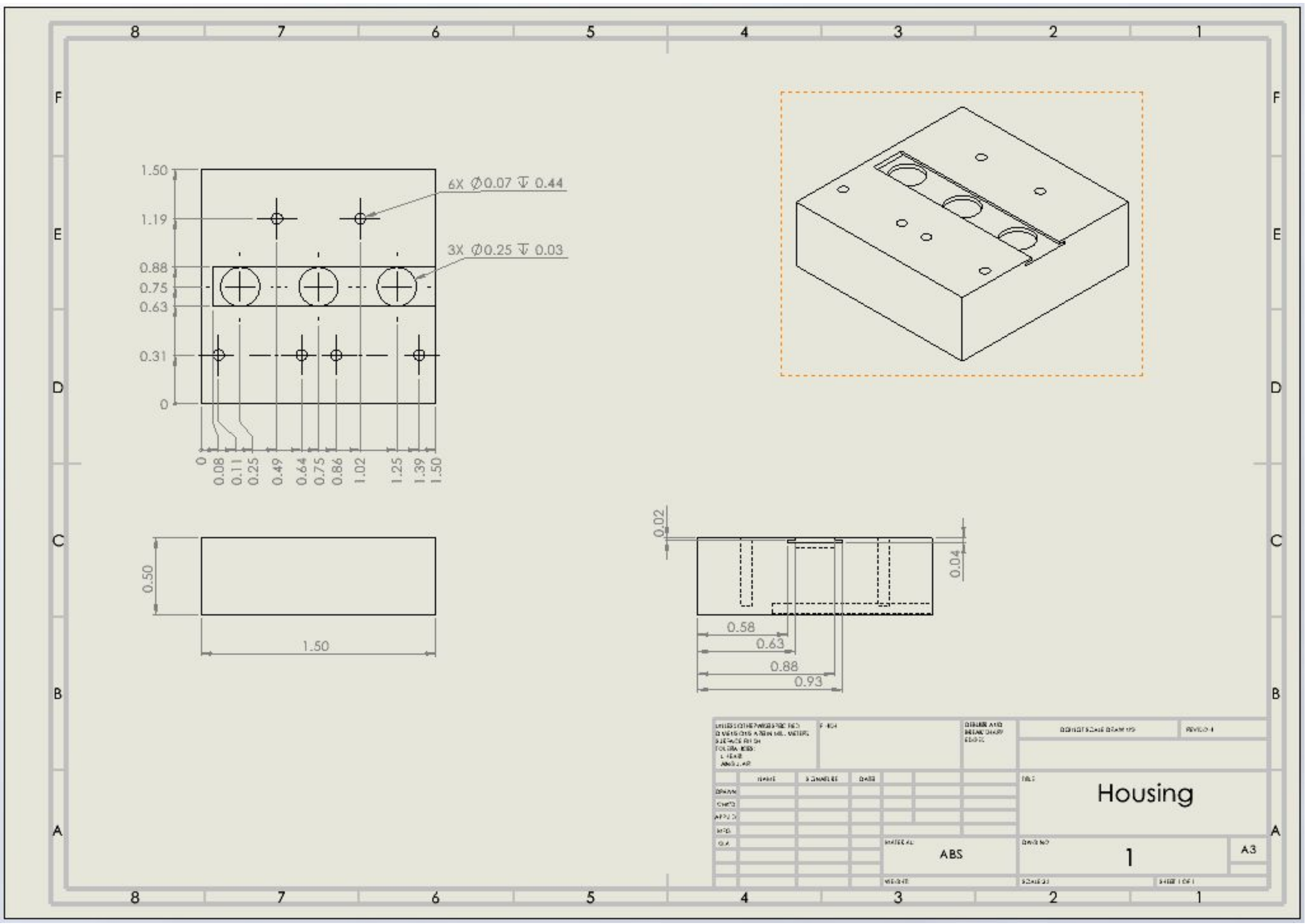

Figure A.1: Engineering drawing of the 3D printed housing.

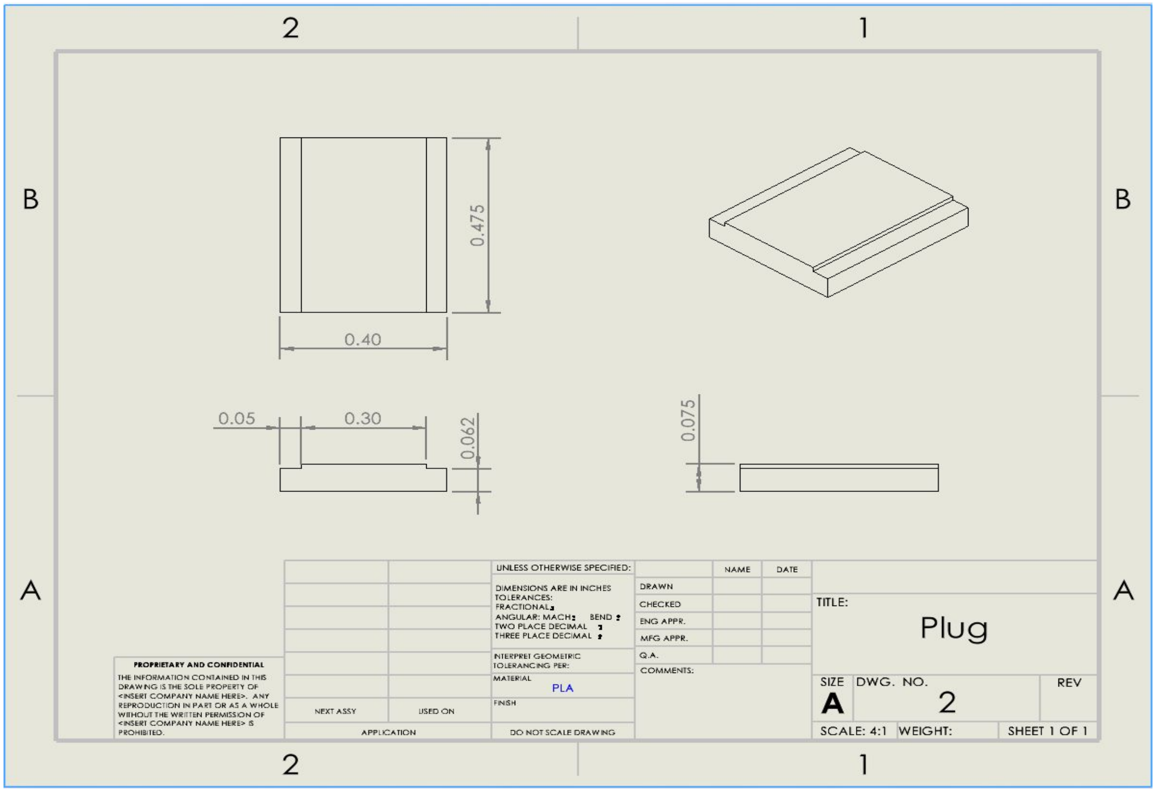

Figure A.2: The dimensioned engineering drawing of the bottom slot plug

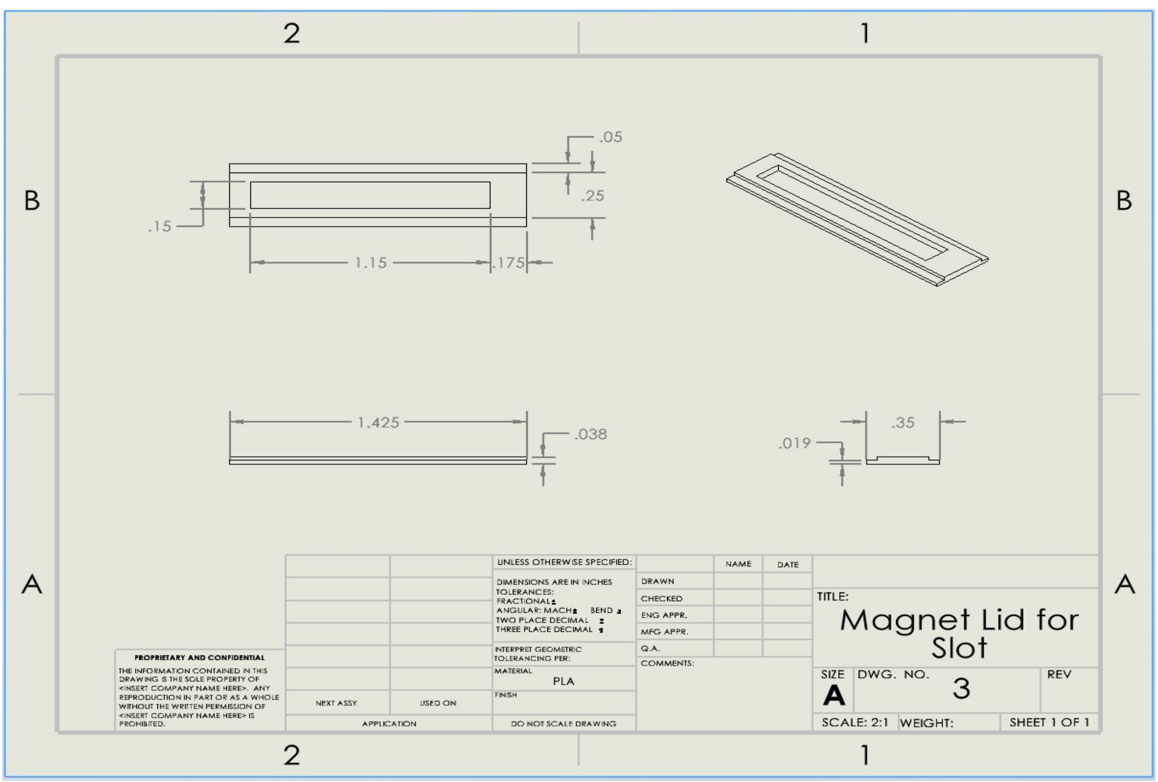

Figure A.3: The dimensioned engineering drawing of the magnet lid for the top slot

Appendix B: Bill of Materials

Table B.1: Bill of Materials for our final design solution.

Item	Description	Quantity	Cost (each)	Total (Shipping and Tax)	Vendor	URL
Plexiglass Sheet	Clear Scratch-and UV-Resistant Cast Acrylic Sheet,12" x 12" x 1/4"	1	$17.34	$26.42	McMaster-Carr	https://www.mcmaster.com/plexiglas/
Microphone	SparkFun MEMS Microphone Breakout - INMP401 (ADMP041)	1	$10.95	$26.27	SparkFun	https://www.sparkfun.com/products/9868
Ball Casters	Pololu Ball Caster with 3/8" Plastic Ball	4	$1.99	$13.15	Pololu	https://www.pololu.com/product/950
Magnets	Neodymium Disc Magnets 1/4 in x 1/32 in N42	10	$0.07	$20.73	Applied Magnets	https://appliedmagnets.com/

Appendix C: Assembly Instructions/Recommendations

1.) Insert Magnets into designated holes on the housing.
  a.) For a more permanent configuration, alter design of housing by eliminating the slot for the magnet lid, making magnet holes slightly deeper, and epoxying magnets into holes.
  b.) Can easily alter holes to fit other size/shaped magnets.
2.) Slide the lid for the slot into place over the magnets.
3.) Position ball casters over designated holes and screw in to secure.
  a.) Can use provided screws, or any self tapping screw.
4.) Slide microphone into slot on bottom of housing, followed by the plug for the slot to keep it in place.
  a.) Can redesign/position slot anywhere else on housing based on need.

Supplemental Appendix

Engineering Standards

While engineering standards are important to follow and implement in design solutions, our specific project did not require any standards to be incorporated. Our project was very specific to one experiment in one research laboratory. This means that our project won't be used in industry, won't be sold/redistributed, and won't be incorporated into any other research labs or projects. Due to this, it was not necessary to reference any engineering standards into our design solution. Additionally, our solution is fairly simple, consisting of a small 3D printed housing, a few magnets, and some plastic ball casters. None of these components required us to incorporate any engineering standards when designing, manufacturing, or testing our solution.

Engineering Inclusivity

Another important aspect in any design process is practicing proper engineering inclusivity. Our team did practice proper engineering inclusivity, but we believe we could have done so a little better. While the stakeholder meetings we did have were very informative and helpful, our team possibly could have had better communication with our stakeholder. Additionally, inclusion of our stakeholders GSI's that worked on this particular experiment could have added another perspective and helped us practice more inclusive engineering practices.

Environmental Context Assessment

Our design makes significant contributions to solving Professor Popa's problem, while avoiding environmental and social consequences that outweigh the benefits. Our solution allows Professor Popa to remove the drive belt spanning the length of the chamber to improve the quality of results. Our solution also limits any environmental consequences that could arise. The solution requires little use of energy, as all that is needed is the energy to print the housing and whatever is put into making and delivering the components (which we believe to be small). Additionally, the housing is made of a strong material and experiences very small loads, so it won't break and require it to be remanufactured several times. Even if the housing does need to be remade, it only consists of about 1.7 in^3 of material, which is very minimal. ABS can also be recycled if disposed of properly, avoiding any environmental consequences coming from its disposal.

Social Context Assessment

Since we are working on an experimental setup for Professor Popa, the social context for our project is limited. We identified Professor Popa as the resource provider as he funded our project. Because of this, we made sure to run any important decisions by him such as possible budget adjustments . We also identified him and his graduate students as the beneficiaries of our project so we were consciously considered how the professor and his team would make use of the product. This assessment helped us develop the requirement that components are easily removed and replaced. We recognized that as the magnets lose their strength or the microphone wears out, Professor Popa would want that capability.

The other consideration is the impact of Professor Popa's research. His research into Willis structures and other metamaterials can lead into various devices that would be beneficial. The ability to suppress unwanted sounds and noise has a wide range of applications in many industries. Indirectly, by helping Professor Popa improve his experimental setup, we are contributing to the possibilities that metamaterial research can achieve.

Ethical Decision Making

The scope of our project is very narrow, however it is still very important to make ethical decisions. Throughout the design process, we made decisions that not only considered inclusivity and environmental context, but ethics as well. The team was very considerate of each member, making sure that we would not neglect each other's input and encouraging thoughtful collaborative teamwork where we could all learn and use our skills to use effectively. During the ideation process we did not shun each other's ideas and enjoyed developing concepts that were outlandish but also intriguing. Our project was unique in that it already had a solution however we adhered to ethics by strictly following the design process as prepared for this course and evaluating possible solutions without bias.

We made sure to conform to proper engineering analysis so that our design would work as intended with minimal reason for failure. Our inability to prototype and test the design greatly inhibited our ability to check and ensure we were delivering a product that works effectively. We also kept accurate and professional records of the engineering work we conducted.

The team also worked hard to ensure that we would conform to all social distancing measures for the safety of the team. Decision making during the course of the project also prioritised the welfare of the team members. The semester was very rough, with a few members having to deal with family emergencies. The team was very considerate and ensured the respective members would take the time they needed to focus on family.