Application of COMSOL to Acoustic Imaging

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Abstract: Acoustic Imaging of hand movement is being studied with COMSOL and Matlab. COMSOL v3.5a is used to repeatedly calculate the diffraction pattern from a small scattering center, approximately 1.0cm in diameter. In conjunction with a hardware setup, COMSOL was instrumental in the design phase of the project, helping to establish running parameters such as wavelength, timing resolution as well as detector placement. The goal of the project is to collect wavefront arrival times which is then correlated to positions of the scattering centers. A neural network is employed to map the arrival time vector to the collection of scattering center positions. A human hand can be approximated as roughly 30, 1cm marble sized balls. The final position of the scattering centers enables software to reconstruct the hand position, making the device effectively an acoustic imager of hand movement, to be used for control systems. No moving parts!

Keywords: acoustic, scattering, imaging, neural networks

1. Introduction

Acoustic imaging has a long and rich history, particularly in the ultrasonic regime, where medical tomography is possible. Similarly, inverse problems also have a long history covering a range of applications using diffraction phenomena from acoustic, electromagnetic and fluid based media[1,2,3]. Real-time control systems benefit from assorted human-based recognition systems, particularly haptic controls, where the users hands play a central role.

COMSOL has been used towards the development of an acoustic scattering experiment, designed to image hand positions in real-time. Applications range from robotic controls to video game inputs, competitive with the current round of devices, Nintendo's Wii and the Sony Play hand device. For lack of a better name for the controller, the "Mii" will be used throughout the article, for simplicity.

1.1 Description

The Mii is a hardware-software combination system, using a NI-PXI crate, running a 2-GHz embedded windows system. The data collection is achieved through two NI-PXI-7813R digital input/output FPGA boards. Driving the data acquisition (DAQ) system is LabView 7.5. This particular hardware choice was driven by design considerations discussed in the following sections. LabView was chosen due to its flexibility and extensive library of routines and large user base. The collected output from the DAQ will be written to disk and analyzed in real-time using the Neural Network toolbox for MatLab.

A 16x16 array of ultrasonic transducers will be employed to create a plane wave used to analyze the targets in questions (hand positions). A similar array of 16x16 ultrasonic receivers will be used to measure the arrival times of the acoustic wavefront coming from the transducers. Figure 1 illustrates the hardware configuration currently being pursued.

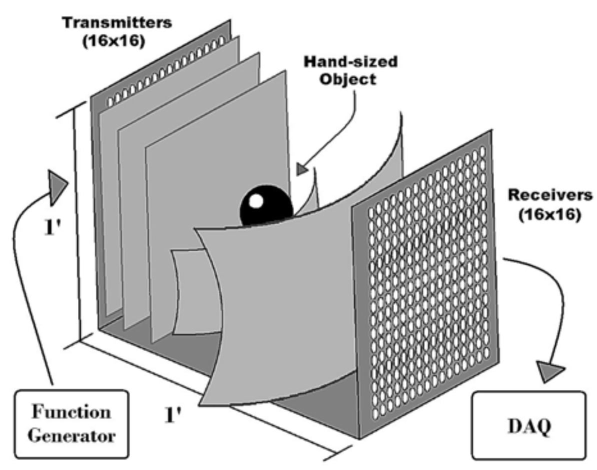

Figure 1. Schematic of the "Mii" scattering experiment. Transmitters are on the left, receivers on the right. As plane waves cross the apparatus, they diffract into spherical harmonics.

The size of the device is planned to house the 16x16 grid array on a 12"x12" aluminum sheet for both the transmitters as well as receivers. the plates will be separated by 12", giving the overall shape to be three sides of a 12" cube. The user will place their hand inside the cube and gesture.

2. Design Considerations

In order for a significant amount of diffraction to occur, the acoustic wave formed should have a wavelength of a comparable size to the object causing the diffraction pattern. For point scatterers, too large of a wavelength leads to a first diffraction minimum occurring beyond 90 degrees, in other words, no diffraction noticable. Too small of a wavelength for point scatters leads to too many diffraction peaks, which aggregate into one large pattern, undiscernable.

The average human hand has fingers approximately 1.0cm across, suggesting a wavelength of 1.0cm. For acoustic scattering in air under STP, the speed of sound is 343 m/s, suggesting a frequency of 34.3kHz. Cheap ultrasonic transducers are available at 25kHz and 40kHz, equivalent to wavelengths of 1.37cm and 0.86cm respectively. At present, 40kHz transducers are being used in a 3x3 array. The final design might consist of a mixed array interlaced with both 25kHz and 40kHz transmitters.

Although the fingers of the hand exhibit the most dexterity, the palm of the hand must also be considered, suggesting a dual wavelength scheme might be desirable. Figure 2 illustrates the modeling of a human hand as if it were comprised of approximately 30x1cm ball scatterers. The initial studies done reconstruct the positions of individual 1cm scatterers.

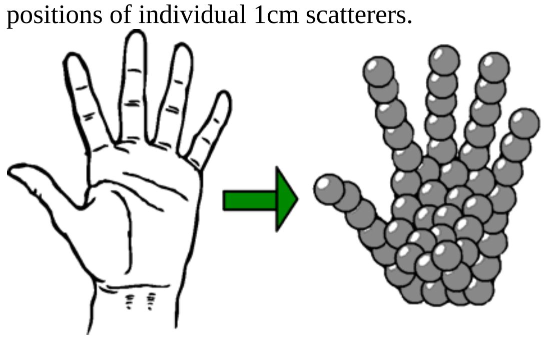

Figure 2. The human hand, as modeled by ~30x1cm hard scatterers.

3. Inverse Problem

The stated goal of this project is a classic "inverse problem", using measured data from an acoustic diffraction pattern in order to ascertain the positions of scatterers, targets in the field of view of the incoming wave. The general inverse problem studied here is how to extract position information for multiple scattering centers based on the arrival times collected from the acoustic wavefront.

The DAQ maintains a clock, which measures the arrival times of the acoustic wave at the position of each receiver, once the amplitude has crossed a threshold value. The collection of arrivals time is measured relative to the beginning of the wave initiated by the transmitters. These values are placed in a vector of Δt's, later to be used as the input vector to the neural network.

Once a receiver has crossed the threshold amplitude, the DAQ latches that channel so that it cannot re-fire. The timing structure for the acoustic wave formed, must start, oscillate at 40kHz, then stop such that the wave propagates across the 12" scattering zone, followed by silence, allowing the DAQ to collect the wavefront only and no reflections off of the apparatus. Figure 3 illustrates the timing structure for a single transmitter channel.

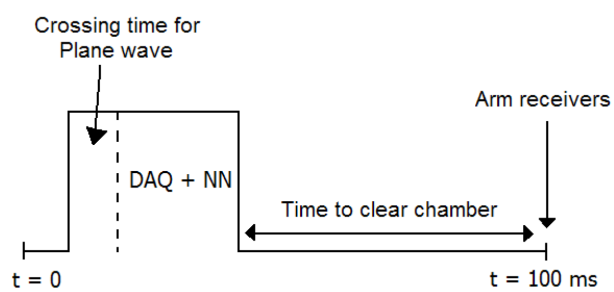

Figure 3. The timing structure for the transducers and receivers.

Once the DAQ has collected all receiver channels, a "clear" signal re-arms the DAQ so that it may be repeated as quickly and often as possible. Typical fast human response times are between 10-30Hz, suggesting a 100ms overall timing structure, which should give the DAQ time to recover.

4. Initial Study

An initial study was done using COMSOLv3.5a to simulate the acoustic wave and its diffraction pattern from a 1cm scatterer. Various designs were pursued, attempting to capture the full structure of the apparatus. Ultimately, this approach yielded to a simpler model, which only modeled the placement of the transmitters and the floor of the detector. By choosing timing such that no reflections can possibly reach the receivers in the time allotted, the simulation can focus on modeling only the essential elements of the apparatus and ignore the complicated geometries of the aluminum plates, the wiring, the interior of the transducers, etc... Further simplification was achieved by realizing that once a receiver has acquired a signal, any further physical interactions with the detector are irrelevant. This allowed the design to be limited to the transmitters only. Figure 4 is a sample mesh used for a scattering center near the upper left-hand corner of the active region of the detector. The dark line of 16x1cm line-segments represent the 16 transmitters in this 2D simulation. The floor is placed approximately where the base of the detector would stand. The upper 1/3 of the spatial domain is open far enough that no reflections reach the receiver plane in the time allotted. The mesh is refined in the active region, however, the region behind the transmitters are left "open" so that no reflections arrive from the transmitter plate.

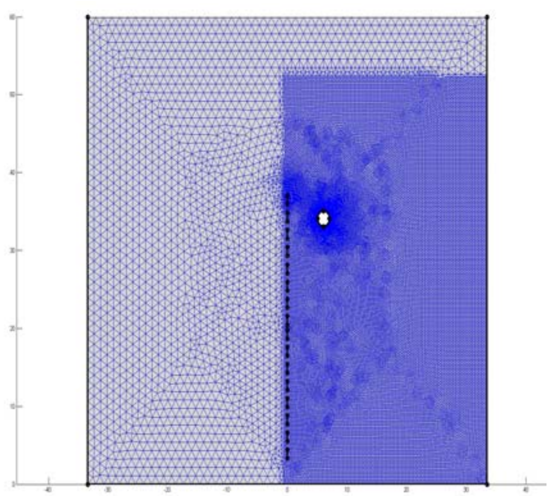

Figure 4. The mesh produced in COMSOL approximating the apparatus.

COMSOL was used to simulate a simple wave equation for the domain, with the line segments acting as acoustic sources, by setting the Dirichlet boundary conditions to be sinusoidal at 40kHz.

Figure 5 shows the results for one particular scattering center. Note the wave pattern on the far right of the domain. The arrival times of the wavefront are recorded based on the amplitude of COMSOL's simulated wave at the locations of the receivers.

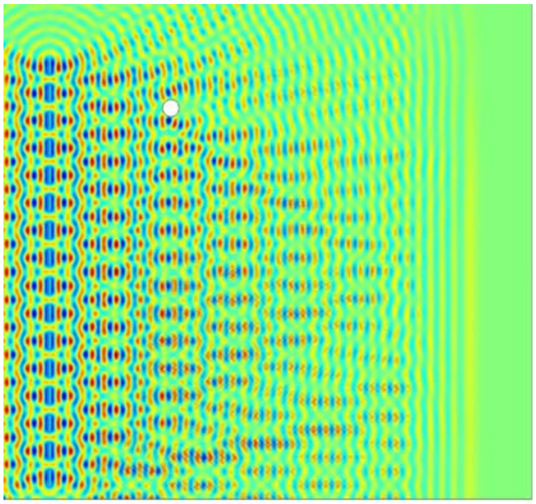

Figure 5. A sample wave diffraction pattern using 940,000 elements. A 1cm scatterer is located in the upper left-hand corner, near the plane of 16 transducers. Note the wavefront pattern on the far right, near the plane of receivers.

5. Refinement

MatLab was used to automatically create a COMSOL simulation, recover the result, the "fem" structure, and then extract the wave amplitudes at the locations of the receivers. Several questions arise from this process of extracting the necessary information used by the neural network to achieve the projects goal.

- What timing resolution must be maintained to guarantee position resolution in the result? In other words, how close in time can the wavefront arrive at the detectors?
- How refined does the spatial mesh need to be?
- How close to the correct positions does the spatial grid need to be aligned to the receiver plane?

The answer to the first question is the hardest. For a plane wave, the wavefront arrives synchronously at the detectors. This suggests that the minimum Δt could be as low a 0.00s. In truth, this lower bound is set by the timing resolution of the DAQ, which can operate at 25MHz, leading to a minimal time resolution of 40ns. So, the question more properly becomes, is 40ns timing resolution necessary for a spatial resolution of 1cm scatterers? Given that the size of the human hand is typically of the order of 1cm, a spatial resolution of 1mm should be more than adequate to resolve hand motions. Also, the wavelength dictates that features below 0.8cm will be un-focused with respect to the diffraction pattern, obviating the need for any further timing discussions. Still, the simulation requires a time scale to be determined. For these simulations, a timestep of 10μsec was used. Once imported into MatLab, the time steps were further interpolated down to 1μsec.

The spatial mesh needs to be small enough to adequately simulate the waves propagated through the air. For 0.8cm wavelength waves, a spatial resolution of 0.08cm should be appropriate. Careful manipulation of the mesh generators is done to ensure the proper mesh is used.

Once the "fem" structure is transferred over to MatLab, a grid is formed so that the mesh from COMSOL can be interpolated onto it, allowing the solution to be calculated at any location the user desires, in this case, the positions of the receivers. MatLab's "griddata" command was used to accomplish this. Future MatLab releases suggest using the new "TriScatteredInterp" object within MatLab.

6. Neural Networks

Solving the inverse problem analytically for a single point scatterer is mildly difficult. Solving the inverse problem for a collection of 30 point scatterers can only be done numerically with any confidence. In order to map the arrival times to their respective positions from the scatterers, a neural network is employed.

At the present stage in the project, only 2D simulations have been performed using single 1cm scatterers. The receiver plane has assumed 16 locations are active, meaning that the input vector to the neural net are 16 arrival times, $\mathbf{\Delta t}$.

The training pair to the input vector, typically referred to as the "target" vector, are the position vectors of the scattering centers, in this case, only one scatter's position, $\mathbf{r}$.

In order for neural networks to be effective, a large statistical sample of various scatterer positions need to be generated. MatLab was used to automate the creation, placement and collection of $(\mathbf{\Delta t}, \mathbf{r})_i$ vectors. Over the course of one weekend, MatLab drove COMSOL to simulate 2859 positions and diffraction patterns. The simulation was 2D and had only one 1cm scaterrer; however, based on the results from these simulations, a neural network was able to reconstruct positions to within a 2% relative error for the mean-squared-error across the data set.

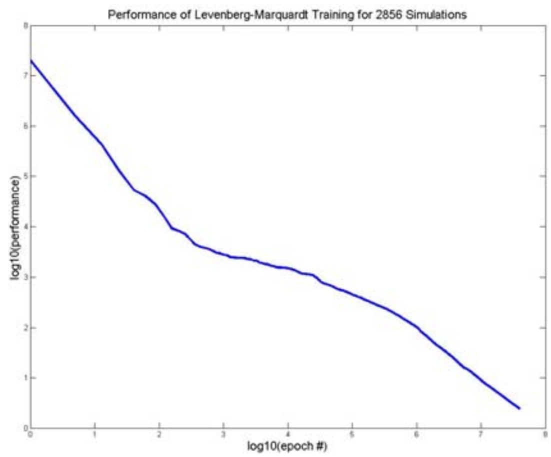

Figure 6. Performance of the neural network training with the Levenberg-Marquardt technique for the full set of 2859 simulations.

Figure 6 shows the performance curve for the 2800 pairs used with a Levenberg-Marquardt optimization technique employed. In order to avoid over-training, a suite of optimization techniques was used instead, training a set of 1000 pairs, out of 2800, then comparing the trained results against the remaining 1800 untrained pairs as a control. After each iteration, a different technique was employed, followed by a different set of 1000 training pairs. In this manner, the neural network achieves true "robustness", by never over-training any one set within the larger pool of vectors considered. Figure 7 shows the performance curve for the suite of techniques employed, using Levenberg-

Marquardt (LM) (2 epochs), followed by Broyden, Fletcher, Goldfarb, and Shannon (BFGS) (2 epochs) followed by scaled conjugate gradient (SCG)(100 epochs) followed by the one step secant (OSS) (5 epochs), at which point the whole sequence is repeated.

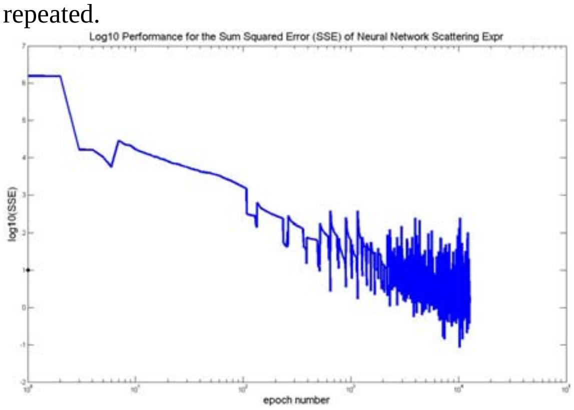

Figure 7. Performance of the neural network training with the suite of techniques discussed for random sets of 1000 training pairs out of a possible 2859 pairs.

7. Future Work

This project and goals require the use of COMSOL to repetitively simulate an acoustic wave diffraction pattern, which is analyzed by MatLab. Although not cutting edge science, the application and the suite of tools required to accomplish this task took the better part of one year working with a senior under-graduate, MIDN 1/C Jean-Carlos Hernandez. Part of the difficultly in this project involves "looking under the hood" of both COMSOL and MatLab in order to get the required results, namely, extracting the result in MatLab with sufficient resolution to be useful as a training set for the neural network. Further insight was gained by realizing that not everything needed to be modeled as the neural network can be trained on a data set under pristine conditions, yet still produce a result with a certain amount of noise present in the signal (Δt's).

This year, a new student will be committed to extending the model to include more scattering centers, and eventually re-design the experiment for a full 3D environment, utilizing 256 transducers and 256 receivers. As the dimension size increases, the training set will be increased up to 50,000 pairs, requiring substantial computational resources.

The silver lining to this approach is that once a good training set is formed, it can be trained at length until it has reached the appropriate resolutions required for the task. At that point, the neural network, as a matrix, will be loaded into the NI-PXI computer and simply "run" as an analyzer to the incoming data from the DAQ.

8. Conclusions

This project will span several years. Already, three midshipmen have committed one year of their time to its design and implementation. Further hardware refinement will be ongoing as the feedback loop between neural network and DAQ is closed. Ultimately, the goal would be to provide a human hand wireless interface, which does not require a glove to use as part of a control system.

9. References

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