Acoustic Battleship

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Abstract— **As digital distribution platforms have risen in popularity, board game classics are surprisingly still relevant in today's society, but they have failed to adapt to the technological advances of today's market. This points to an opportunity to adapt the classics that have stood the test of time with some innovative electronic-based interfaces. We would like to implement an electronic medium to the classic game of Battleship. Acoustic Battleship innovates on the traditional Battleship game with acoustic localization technology, making accuracy part of the fun of the game.**

I. Introduction

THE traditional boardgame has fallen out of favor in the gaming market. We want to put a technological spin on the game of Battleship.

A. Significance

In the current era of electronic video gaming, one may ask, "where have the classic board games gone?" One may say that the classic board games such as Monopoly, Risk, Clue, and even Battleship have become outdated. Within the past decade, there has been an increasing selling rate of tabletop games being sold each year, especially around the holiday season [4]. What we are trying to do is add an electronic medium to the classic game of Battleship to enhance the entertainment amongst players. Although the classic game is actively being played today, we are trying to introduce a technologically modified version of it that will be more intriguing towards the audience of this generation.

B. Context and Existing Products

This is not the first time someone thought of bringing electronics and classic board games together. Throughout the years, we have seen applications through our smart mobile devices such as Scrabble, Monopoly, and even Battleship. One of the critical viewpoints on these electronic board games is that it doesn't bring people and families together at the same place as would a classical board game.[1]

There are electronically developed board games such as "Electronic Battleship: Advanced Mission" which has special sound effect features that respond to the player's imputed coordinates [2]. Another product that has been electronically implemented is Monopoly, where you are now able to use a bank card to make transactions rather than using Monopoly dollars [6]. In 2017, A senior design project at the University of Massachusetts Amherst called "Castle Quest" consisted of modifying the classic board game of Dark Tower by implementing electronics and software to provide technological entertainment that is group-centric [5]. Acoustic Battleship will also implement these technological characteristics in turning the classic board game into an electronically assembled accuracy-based game that will be interactive and entertaining. We hope that this technology will be adaptive in terms of being implemented in other classic games such as darts, ping-pong, etc.

C. Societal Impacts

We hope that Acoustic Battleship will make a social impact terms of bringing a more interactive community together to enjoy a new interface of the classic board games that we love. We hope to see this project be used in public settings such as arcades and game rooms, hopefully to one day be portable enough to be brought and played anywhere.

D. Requirements Analysis and Specifications

We want our design to meet the specifications shown in Table 1. Accuracy will play a key role in trying to fairly calculate where the projectile hit on the playing surface. We also want our project to be quickly responsive towards outputting coordinates to specify a specific LED that will determine whether the projectile hit or missed a battleship.

Requirement	Specifications	Goals
Accuracy	Algorithm Accuracy	95 %
	Time Differences Captured	Times captured in microcontroller match the times monitored by Logic Analyzer
	Distance Error	$\leq 5\ cm$
Responsiveness	Response Time	$\leq 500\ ms$

Table 1: Requirements and Specifications

II. Design

A. Overview

Our approach to this problem is to develop and deploy a robust sensor network on a playing surface much larger in area than the traditional Battleship game. The sensor network will consist of 4 omni-directional microphones, a microcontroller, addressable LEDs, and a power supply. We considered the implementation of a sensor network consisting of infrared LEDs, though we felt that management of this system would be through brute force, and would be an unimpressive, highly wasteful, iteration of localization.

While the game rules will remain the same, i.e., to win, you must eliminate your opponent's battleships, the accuracy mechanism is now a projectile you will throw toward an intended coordinate on your opponent's side of the playing surface. We have chosen to implement three blocks: Sensors, Microprocessor, and our User Interface (UI). This solution transforms the lackluster pace of a traditional marketplace into a more technologically mature space. By placing the accuracy of the game into the hand of the end user, we anticipate a greater interest in the final product than the Battleship of old.

Our microphone sensors will receive sound produced by a projectile striking the surface of our apparatus. One of the tradeoffs that we dealt with was trying to capture signals only at frequencies of the projectile hitting the playing surface. Frequencies of around 7kHz to 10kHz is what we desired, but surrounding noise such as clapping, or yelling can vary amongst those ranges as well.

Using a wave-shaping network to convert our analog sound signals to 5V digital pulse signals, we can input these signals as triggers to our microcontroller in the Processing Unit. These digital inputs are representative of our Time Difference of Arrivals (TDOAs). By implementing polling in our microcontroller programming in the Processing Unit, we can accurately measure our TDOAs. These signals are then computed in our multilateration algorithm to produce the coordinate of the sound source. We then will light up the coordinate that is computed with byte addressable LEDs (i.e. WS2801 4-wire controlled by SPI) in the User Interface. The color of the LED will be dependent on if that coordinate currently contained the position of a battleship (we anticipate using contrasting colors such as red and green to mark a "hit" or a "miss"). To position the battleship targets, we would like to implement a controller for each player, and an additional, smaller coordinate system that indicates the positions of a participants own battleships.

See the block diagram in Figure 1. It demonstrates the processes of the system and the interfaces. The sound signals as input enter the system through microphone sensors. First, they go through signal processing which includes filtering, amplification and wave-shaping. The processed signals then enter the microcontroller, which receives and stores the times of arrivals of signals into registers. The times then are used to calculate the target position through some algorithms. The results are finally output and displayed on the LEDs on boards.

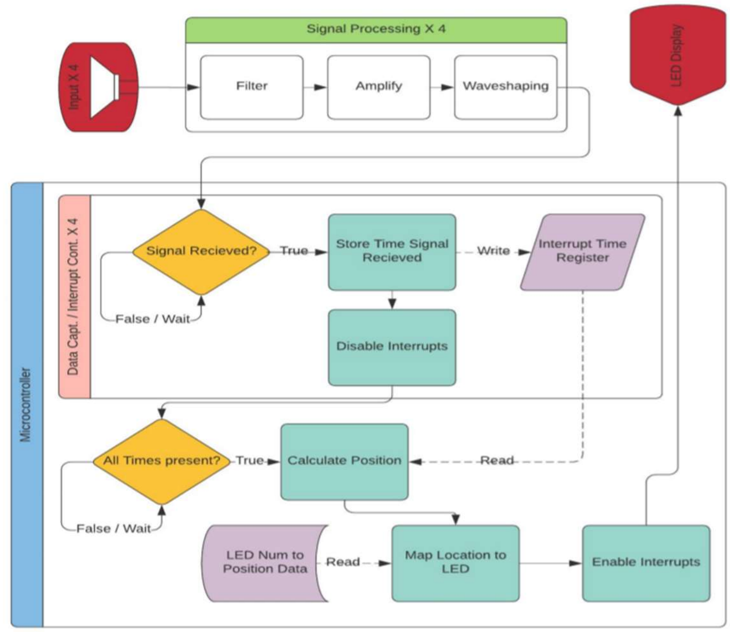


Figure 1. Block Diagram

B. Sensors

Our design implements 4 omni-directional condenser microphones that are capturing the sounds produced on the playing surface between the frequencies of 5kHz and 10kHz. In Figure 1 you will see a block diagram that represents the design of the microphone sensor network which includes that of frequency filtering, amplification, and wave-shaping phases (schematic in Appendix B).

The filtering stage consists of a 4-pole bandpass RC filter with frequency cutoffs at 7.23 kHz and 10kHz. The value of the cutoff frequencies is due to the robust testing (See Appendix B) that resulted in capturing the frequency of a ping-pong hitting a 1m x 2m Lexan surface. Our goal was to filter out human conversation along with any sound that may interfere with the microphone sensor network which can result in false data being processed in the MCU.

The amplification stage has been placed to follow right after the filtering stage because of the amount of loss in gain due to the 4-pole bandpass filter [7]. The non-inverting amplifier has been designed to have a gain of 40dB which will help amplify the analog signal coming in at around 20mV.

We now have a signal that has been filtered and amplified, which leads to our next stage of converting the analog signal into a rising edge digital pulse. This was done by implementing a combination of an inverting comparator and a 555-timer. The purpose of the inverting comparator was to provide a trigger from high (5V) to low (0V) which will initiate the monostable 555-timer. After being triggered, the 555-timer will output a rising edge pulse (0V to 5V) with a period of 200ms which will then be inputted into the MCU. Each microphone (4 in total) will have these 3 stages integrated in their personal PCB and will all have the same output of a 200ms pulse. Through our testing results, we all agree that the microphone sensor design provided our system with consistent and reliable data attributing to the time of arrivals in each microphone.

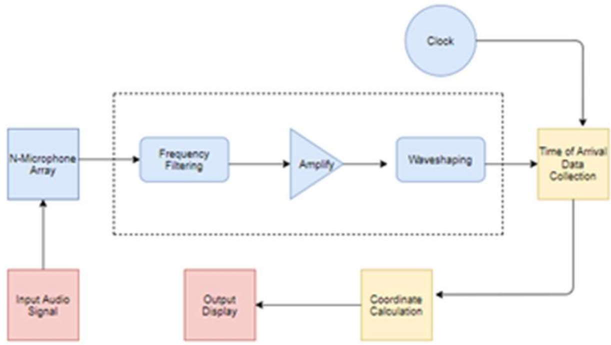


Figure 2*. diagram of the microphone sensor network*

C. Microprocessor

To begin the data collection, we prescaled our system clock to 250kHz. In theory, this clock frequency will allow for roughly 2mm accuracy (much greater than we initially anticipated). We reached this figure by calculating each clock tick to be 4 microseconds, which in turn, equates to a maximum distance error of 1.372 millimeters. We anticipate this resolution to increase our accuracy of localization greatly when compared to our initial specification. To produce a calculation for our TDOAs that will produce an accurate coordinate, we derived a two-dimensional multilateration algorithm.

Our derivation of a two-dimensional planar algorithm for multilateration uses TDOAs and energy waves of a known propagation speed (the speed of sound in dry air at 20°C, 343 $^{m}/_{sec}$). To comprehend the algorithm we will be implementing, it is useful to refer to. As can be seen, our initial time of travel *a* (the red circle) to our first microphone is an unknown. This is evident, as we do not know when the projectile will strike the surface of our playing surface, we only can mark the arrival of the energy wave in time. We do know the *time difference of arrival* of that same energy wave to our second and third microphones, located at either end of the hypotenuse of our triangle in Figure 2.

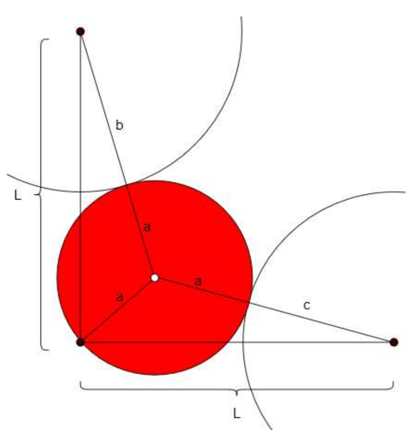


Figure 3*. A visual representation of the initial sound source being received at 3 microphones arranged in an isosceles triangle*

These known values are represented by *b* and *c* in Figure 2. It is then helpful to imagine TDOAs *b* and *c* as the radii of circles generated by the formula: $d_{b,c}$ (distance) = rate (the speed of sound in dry air at 20°C, 343 $^{m}/_{sec}$) x time ($TDOA_{b,c}$).

These calculations produce two known radii (though without a known angle of arrival), we can produce the initial location of sound using multilateration. For a comprehensive visual of our process, please refer to Figure 3. Through analytical geometry, we can determine the precise point of a sound source. If we allow the unknown distance of *a* to go to zero, we are left with two known distance *b* and *c*, which are the radii of two circles whose origin is at a given microphone, and whose perimeter coordinates are stored in an array, we can form a new circle, with radius *d*, around the microphone that first receives the sound signal. As we increase *d*, we increase both *b*,and *c*, by *d*. As *d* increases, we will eventually find a common intersection of the three circles. This intersection is the source of the sound.

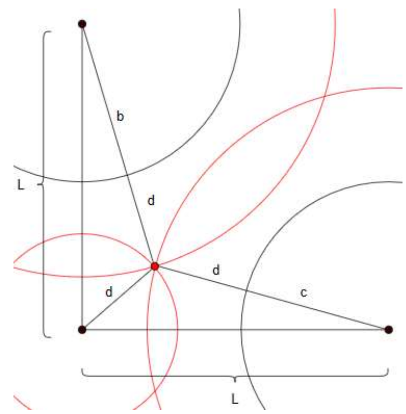


Figure 4. *Iterating through different values of d produces the unique intersection.*

We have produced a C++ function and in Appendix B have a further explanation for the experiments we performed to ensure our calculations are accurate.

D. User Interface

Our User Interface will be responsible for providing feedback for the end user, as well as allowing the end user to view the positions for their Upon striking the surface of the board, our user interface would display the LED response necessary to indicate if the coordinate contained a target or if the coordinate was empty. To achieve this, we anticipate using byte addressable LED strips that allow us to choose the color and location. At the current time, we anticipate randomly generating the positions of each battleship. As our ambitions for this project have grown, we need to first implement the core of the project before reaching our stretch goals.

III. The Product

A. Product Overview

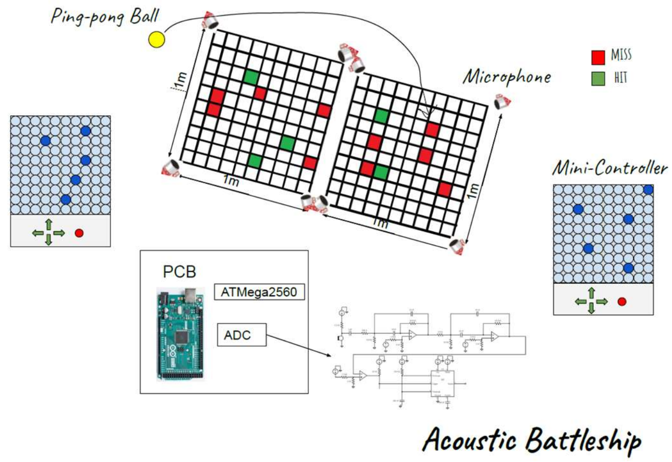
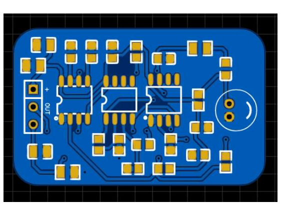


***Figure 5**. Product Sketch*

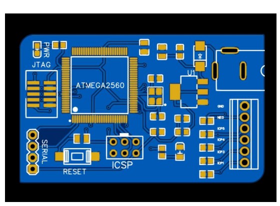
The product contains a rectangular board consisting of two LED-gridded "battlefields", one for each player. Microphone sensors surround the board, receiving the sound of the ball hitting the board. Each player has one mini-controller to register their own target locations in the beginning of the game. At each play, a player throws the ball at their opponent's board; the sound signals created will be input to the system through the microphone sensors; then after signal processing, the microcontroller computes the target based on the input; in the end, the results are displayed on LEDs on the corresponding board.

B. Electronic Hardware Component

Our hardware consisted of two PCB designs. One design used for each microphone and the main control board. The microphone board design consisted of our amplifying and signal processing circuits. Our mainboard was based around the Atmega 2560 and broke out the Interrupt Control Pins along with other pins important for testing our design. The mainboard also includes a clock circuit to be used by the Atmega and a power supply circuit partially borrowed from Arduino's open-source designs.



Micophone PCB



Main Control Board PCB

Both boards were designed using the EasyEDA design software which gave us the footprints for many components from LCSC Electronics' catalog. This allowed us to use to easily source our parts and take advantage of JLCPCB's SMT Assembly. That meant we were able to construct our PCBs out of fully SMT parts, excluding the microphones, and have them fully assembled at the factory. All that was required to accomplish this was to give JLCPCB our part numbers for each component and have the correct footprints in our designs.

C. Product Functionality

At the onset of the Cumulative Design Review our team was able to produce a scaled test bench of our MDR prototype. From Figure 1, our microphone sensing network was adjusted and produced accurate date to be processed in our main computation for localization. This portion of the project was tedious, as we were required to determine which pull-up resistor in a comparator circuit responsible for setting a threshold voltage that would trigger the next stage in the circuit. Effectively, correctly selecting the value of this resistor would allow us to detect a projectile striking the playing surface at all four microphones at all locations on the playing surface.

When the input to our microprocessor, an ATMega 2560, was correct and computable data (i.e. non-ideal TDOA that are within a percent error), we found our microprocessor was unable to produce correct or computable data with any consistency. We feel that because we were using an Arduino with the ATMega 2560 surface mount soldered, that there may have been certain background protocols we may not have been aware of this. We cleared the bootloader of the Arduino and used a bootloader compatible with our microprocessor to upload our software, we found that this improved the fidelity of our results negligibly.

We were able to confirm the robustness of our searching algorithm by implementing a binary search through precomputed values in an array. We tested this array by inputting real values, ideal values, and false values. Our test cases were successful, rendering the incorrect results only in instances of anomaly.

At the conclusion of laboratory testing, the final piece of our final product was ensuring that the LEDs were correctly configured. This portion of the project was quite time consuming. We determined that we would pre-solder strings of LEDs, connect the strings data pins serially, and power in parallel. After running tests, we found that our LEDs were correctly implemented.

D. Product Performance

Although the functioning product was still in progress, the desired specifications were met through the robust testing methods and results that were attained in our MDR prototype. By CDR, our microphone sensor network was properly capturing signals and demonstrating accurate time difference of arrivals (through Logic Analyzer) on a 1m x 2m playing surface and our MCU was outputting coordinates. Due to the COVID – 19 pandemic, we were unable to integrate our PCBs and analyze the performance of what would have been our functioning product.

IV. Conclusion

In a way, our group has a unique insight to the anticlimactic ending to SDP20. At the beginning of ECE 416, one of our group members was unable to physically return to campus due to Covid 19. The remaining group members worked on maintaining communication with our remote group member, and proceeded with plans to complete the project, in spite of the loss. We feel we had gained momentum heading into FDR and were in position to have a fully functioning Acoustic Battleship game. Unfortunately, the semester was cut short and we were unable to see our vision for this game come to fruition.

References

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[6] Smith, Chris. "Monopoly Ultimate Banking Goes Cashless to Oust the Family Cheat." Trusted Reviews, 15 Feb. 2016, www.trustedreviews.com/news/monopoly-ultimate-banking-goes-cashless-to-oust-the-family-cheat-2946006.

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Appendix

A. *Design Alternatives*

For algorithms, we struggled at first to find an analytical solution for solving the coordinate of the sound source so we made a solution with lookup table. In simulation, the lookup table solution performed poorly for positions that are not in the lookup table. We then found an analytical solution whose accuracy is perfect and stable with various simulated inputs.

B. *Technical Standards*

LEDs:
One standardized piece of hardware that was implemented in our system was that of LEDs. According to IEEE standard 1789-2015, we had to ensure that any flickering that may occur during gameplay would not pose possible health risk to the users.

C. *Testing Methods*

Experiment 1 – Time reality check to test the quality of the digital input for microcontroller.

We monitored the input signal with logic analyzer, obtained the time difference of the edges of arrival at different sensors, calculated the difference of distances time travels and compared it to the actual difference of distances from the sound source to each sensor. We found that the results calculated are very close to the actual values when sound source happens at a reasonable distance (not too close or too far) from the sensor. For this experiment, we are essentially testing the quality of our wave-shaping network (figure 4). It was proved that the input to the microcontroller was of good quality. The restriction of the distance from sound source to microphone might be caused by the location of the sensor network on the board. Further testing is required to find out what distance range will give the most accurate results and make our play area mostly fall in that range.

We produced the rising edge pulse output to ensure we are receiving digital signals at the input of our microcontroller.

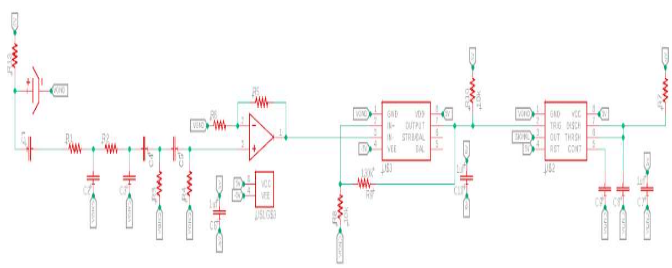

Figure 6. *Schematic of wave-shaping network*

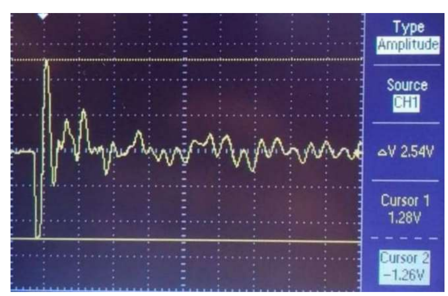

Figure 7*. the expected voltage signal from the projectile striking the playing surface*

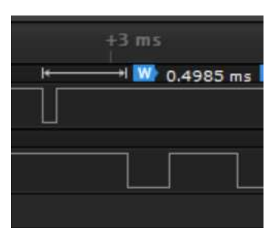

Figure 8*. An example of the TDOA measurement when implementing a wave-shaping sensor network.*

Our eventual output on the logic analyzer produced satisfying results that would allow us to readily capture time differences between sound sources striking the playing surface

The purpose of this experiment was to ensure we will be able to receive consistent signals to all microphones with a measurable TDOA. This is an imperative portion of our testing, as without the ability to measure the TDOA with good accuracy, we will not be able to produce accurate coordinates.

Experiment 2 – Algorithm simulation

To test the validity of our analytical algorithm, we implemented the algorithm in MATLAB first and then translated into C++ which is needed for Arduino. We simulated some sets of ideal time of arrival inputs and used those as the input to our algorithm. The output of our algorithm matched with the original data we used to the simulated time inputs, which proved that our algorithm is able to calculate accurate coordinates of the sound source given accurate inputs of time of arrivals. No further testing is needed until we got our microcontroller to capture the correct time of arrivals. For this experiment, we were testing on the algorithm running on the microcontroller.

D. Team Organization

We consistently communicate on a regular basis on what is currently being worked on. Discussions are held through group messenger, and we collaborate in graphical web-based interfaces which currently include Github and Slack. We also meet once a week with our advisor to discuss our updated progress and our plans moving forward. Communication is prioritized within our group in order to maintain structure and organization, as well as provide help and feedback when one comes across a problem. Some issues have come up along the way as far as completing tasks according to our group's desirable deadlines. We strongly plan moving forward to time manage more efficiently in order to provide positive feedback and complete the project by CDR.

E. Beyond the Classroom

Adrian Sanmiguel - What I have learned on this project is a technical understanding in frequency filtering, voltage amplification, and wave-shaping applications towards the analog behaviors being outputted using electret condenser microphone devices. Some of the engineering traits that were attained in this project include time management, robust testing techniques, and experience in the design, build, test, and production stages of our year-long project, which will carry with me moving forward in my engineering career.

Liam Weston - I have utilized analytical geometry in my first semester of SDP. I have applied plane wave theory and used my understanding of electronics 1 to produce tangible results that will be beneficial to our group going forward. I hope my experience as group manager continues to grow myself as a person and a professional (as well as developing the managerial skill as a whole). Capstone was certainly a learning experience. It likely shaped my academic experience for the better, though the wound of SDP ending early is still open. I feel our group was able to pull together through adversity to deliver when we had to. I think it would be interesting to see our evaluators' reflections of their interactions with the teams, same for the advisor to each team. I found the structure of SDP to be well suited for someone like myself. It allows the individual to determine the best possible route for a project to take, but the relationship with advisor and faculty can positively or negatively affect that. I will take the lessons I learned from my Peers, Professors, and Dean with me for the remainder of my professional career. I am not sure where I am headed, but I know where I have been.

Xinyu Cao - I learned about how interrupts work in Arduino Mega2560 and setting modes for the microcontroller through bit manipulation according to the datasheet. I also learned how to break an engineering problem into theoretical math models and applied the math model back to solving the problem; this gave me good experience in applying what I learned to a real-world problem, which was very important in helping me grow as an engineer. Internet has always been a great source to learn from, so are my professors and my fellow engineers.

Justin Forgue - As far as skills I had to learn, C++ and microcontroller programming were the top two. I certainly also had to learn how to read datasheets and when to ask for help! I was also reminded of how important testing is, never assume something works. Our advisor has been a great resource to me and really helped steer me in the right direction. Without him I would have bought a better, more expensive microprocessor and still have the same problem.

The project has been very realistic for me as working with ASICs and other embedded systems is what I want to do. Working on similar problems here has really helped me understand the embedded systems world. Beyond that this project has really taught me how to efficiently work in a team.