Acoustic Navigation For Mobile Robots
Senior Design Project

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Abstract

The goal of this project is to develop a microphone array module that will allow a mobile robot to detect acoustic beacons in its surroundings. The array will consist of miniature microphones in a ring configuration to provide 360° sound localization. This will allow the robot to display a number of phonotaxis behaviors, e.g. homing in or fleeing from acoustic sources.

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1 Objectives

The requirement of this project is to design an acoustic navigation module that will detect sound in a 360° planar environment using a microphone array that will allow a mobile robot to perform movement based on sound location. This project will involve all aspects of engineering design, from planning to implementation.

Our objectives are the following:

- Develop a printed circuit board interface for the microphone array.
- Design acoustic fixtures to increase directionality of microphones.
- Develop algorithms to determine the angle and position of the transmitted sound.

2 Initial Design

The proposed design of this project, shown in Figure 1, has evolved over the course of the semester. There are several aspects of the design that remained the same. Many of the concepts introduced in the proposal made their way into the final design, but with many improvements. The first change was to allow the μController to chose which microphone to listen to, as well as which frequency range to listen for. This was different from the proposal, in that the proposal called for an onboard clock to cycle through each of the microphones and each of the filters. This would have required the μController to wait for the interface board to cycle, until it reached the combination of microphone and filter that it wanted. The next big change was the addition of a switched-capacitor filter to the design. This was different from the two RLC filters that our team originally proposed. The addition of this active filter added the ability to band filter the signal across many different frequency ranges. This also increased the functionality from one low pass and one high pass filter to essentially eight different band-pass filters. A switched-capacitor filter requires an external clock signal to determine the center freqency of the band-pass. The final design incorporates a 1 MHz crystal being clock divided by two cascaded 4-bit counters. Each of these halving frequencies is fed through a multiplexer, where the desired clock frequency is chosen to be fed into the filter chip. The signal rectification of our design has also changed several times during the semester. The design of our rectification has moved from simple full-wave and half-wave rectification circuits, to super-diode circuits, to finally an IC that performs a true RMS-to-DC conversion. The analog to digital conversion only changed slightly during these many weeks. This change was from a 4-bit A/D converter to an 8-bit A/D converter. These changes enhanced the functionality of our design, and also add to the elegance of our design solution.

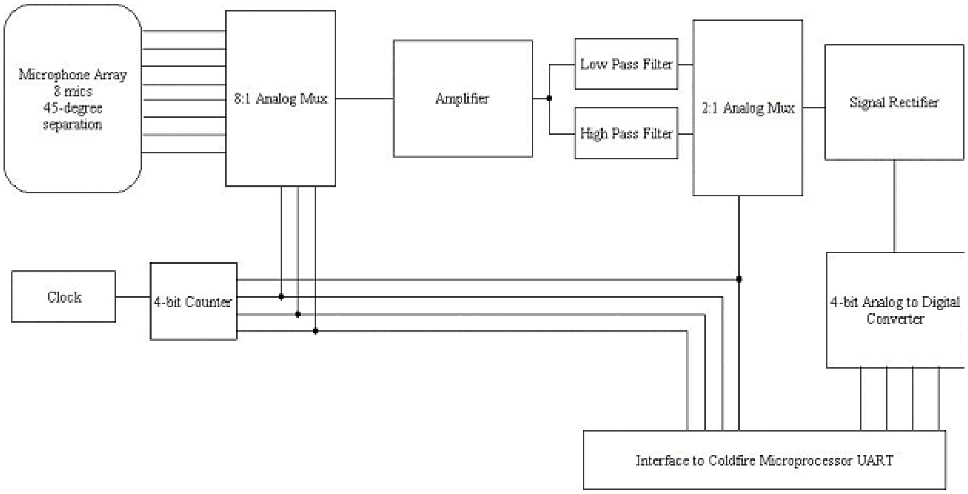

Figure 1: Proposal Block Diagram Design

3 Microphones

Our team selected the Panasonic WM-65A103 electret microphone for use with our project design goals. These microphones are cheap, small, and are suitable for this application. This microphone uses a load resistor to develop power, and although the signal is relatively small (30 milliVolts), pre-amplification is not required and therefore reduces the complexity of the design. The datasheet claimed these microphones are unidirectional; however, they are not as directional as hoped. Therefore, additional sound dampening was required to increase directionality.

The schematic for this microphone calls for the use of a 2.2 kΩ resistor for developing the output. After many hours of testing, our team determined that a 10 kΩ resistor produces the best output. The exact waveform produced by these microphones was in great question before the microphones actually arrived. Once they arrived, it was determined that they produced an AC signal, with a DC offset. The AC component of the output signal is quite small, ranging from 5 to 200 mV.

For future use of this design, our team suggests more research into a more directional microphone. Although our team feels that the sound dampening fixture should be used regardless, increased directionality would ensure better accuracy. It is also suggested that another type of microphone be used. Electret microphones have been found to be very sensitive to heat. Since these microphones do not come with leads, leads must be soldered on, artifically creating a heat issue. There are other similar microphones that are not as susceptible to heat damage. During the soldering of these microphones, preflux was used. It is also possible that excessive flux leaked into the microphone, causing damage. Also, these microhpones have been quite fickle in their ability to produce a reasonable and reliable signal. During the beginning of the semester, peak-to-peak voltages produced by these microphones ranged from 30 mV to over 2 V. The current microphones used in our final demo are currently producing signals on the order of a single milliVolt. Our team suggests that a great deal of research go into microphone choices in tne future. The necessity of soldering leads onto these particular microphones has caused a great deal of trouble. Choosing microphones that already have leads attached would be immensely suggested. Also, future work should contact the manufacturer to find out the exact specifications of expected output of the microphones and any caveats that should be looked for and avoided.

4 Microphone Array Board

The microphone PCB board consists of an 8-microphone array, load resistors, and the sound dampening fixture. The microphones are evenly spaced on the board, giving each microphone 45° of coverage. The boards signals are sent to the controller board for processing via a 10-pin ribbon cable.

Originally, the controller board housed the microphones. However, our team quickly realized that this increased difficulty of placement and maintenance. Additionally, increasing sound localization with the use of other materials on this PCB would have been much more difficult, as each microphone's directionality would be dealt with separately. This would have created nonuniformity in that each microphone would have different levels of directionality and sound localization capability. Because of this, or team decided to use a separate PCB to hold the microphones. This allowed the above mentioned fixture to be placed on the PCB without interfering with any other components. Components would have been an impediment, had the fixture been attached to the controller board. Further, using a separate PCB made the design more modular, which aided in construction, testing, and maintenance, as it allows for the removal of the microphone array PCB from the rest of the design, and eased troubleshooting and maintenance, independently of the other components of the design.

Section 5 states that, if microphones that provided acceptable directionality on their own could be found or bought within the allowed budget, or if a complex algorithm was used such as beamforming, placing the microphones on the controller board would be more feasible. This would decrease the project's cost and complexity, from a standpoint of physical size and required construction.

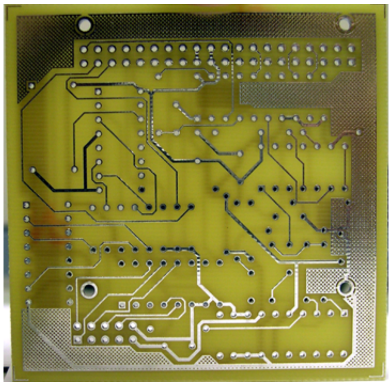

Figure 2: Empty Microphone Array Board

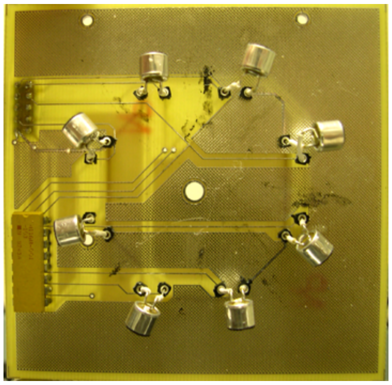

Figure 3: Completed Microphone Array Board

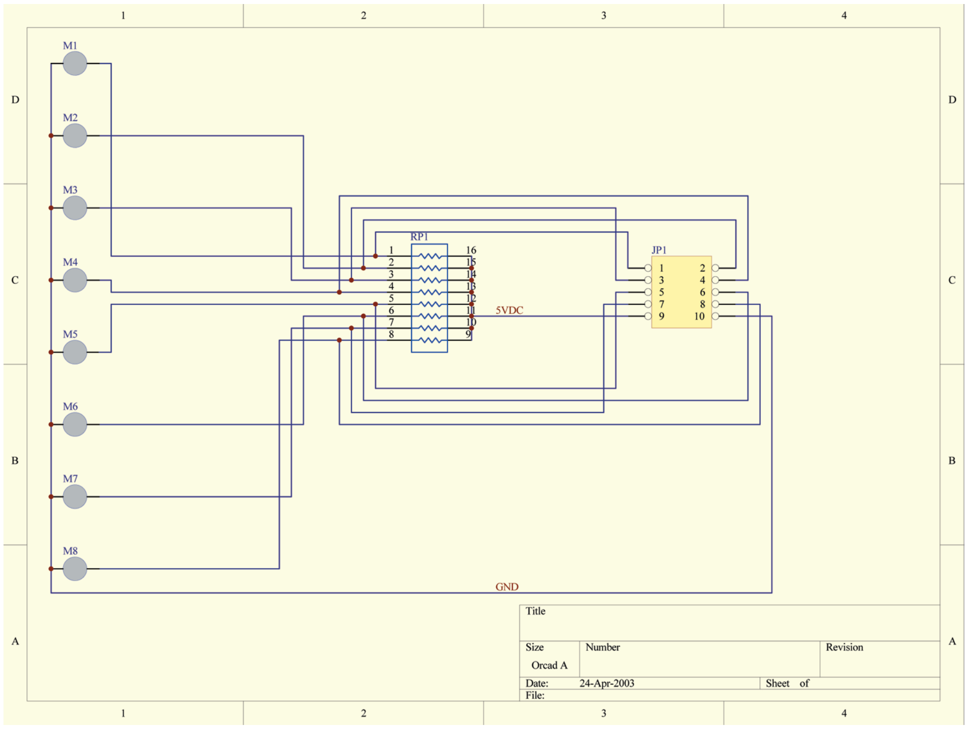

Figure 4: Microphone Array Schematic

5 Acoustic Fixture

The sound dampening fixture was designed to increase the level of directionality of our microphones. This fixture was very inexpensive to make and satisfies our design requirements. Plexi-glass and super glue was used to construct the fixture, and flexible rubber tubing and a hollow aluminum insert was used as the center piece to glue all the fixture walls in place as well as provide a point in which to attach it to the PCB. A small bolt and nut was used to secure it.

Our original ideas called for the use of either cardboard rolls (similar to empty toilet paper rolls) or the use of straws. However, our team wished to create a single fixture that would increase directionality of all microphones uniformly, but allow us to remove it easily and quickly for maintenance and modularity. Our final result accomplished these requirements as well as being inexpensive to fabricate.

Ultimately, having directional microphones that would provide accuracy without the use of this fixture would be optimal. However, microphones with this capability do not exist on a level equal to that of this project's budget. A future recommendation for continued use of this design would be to use software to help localize the sound. Research during the proposal revealed a practice called beamforming, which uses complicated algorithms to pinpoint the sound location in a microphone array. However, considering the time restraints and current complexity of this project, our team implemented this simpler method of an acoustic fixture. Figures 5 and 6 show the final product.

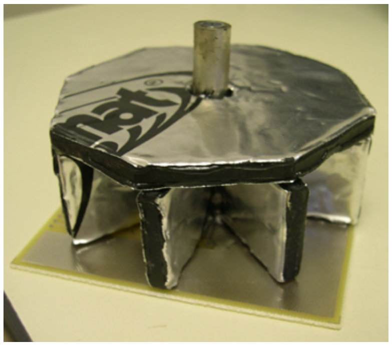

Figure 5: Top view of Acoustic Fixture

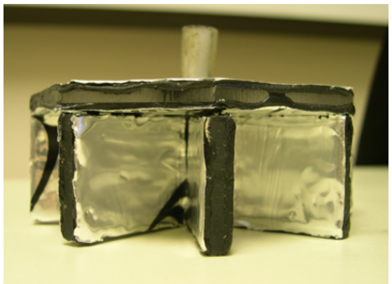

Figure 6: Side view of Acoustic Fixture

The top plate of the fixture is an octogon, with side lengths of 1.25”. The total width of the octogon is approximately 3.25”. Each of the blades are 1” tall and 1.5” long. They are evenly spaced, having approximately 45° between each.

6 Controller Board

The controller board essentially consists of a switched-capacitor band-pass filter, RMS-to-DC converter, and an analog to digital converter. The signal passes through each of these in turn, producing a digital value, proportional to the amplitude of the sinusoidal signal, in a certain frequency range, determined by the characteristics of the band-pass filter.

6.1 Band Pass Filter

The original and proposed design for filtering the signal from the microphones was to simply use one high-pass and one low-pass filter. These filters would simultaneously filter the signal, with a multiplexer choosing which filter would be analyzed by the rectification and analog to digital portions of the circuit. During a design meeting, our advisor suggested that our team research active band-pass filters as a possible solution. While doing research on this topic, several possibilities emerged. Avens Signal Corp. [1] produces several digitally programmable filters, but at a premium price. While speaking with one of their engineers, switched-capacitor filters were brought up as a cheap alternative. These switched-capacitor filters allow low-pass, high-pass, band-pass, notch-pass, and all-pass filtering capabilities. This type of filter also allows for the characteristics of the filter to be changed using simple external discrete components and the use of an external clock. The addition of this integrated circuit allowed our project to now have eight band-pass regions, selectable by the μController. This was possible through the use of a crystal operating at 1 MHz, coupled with two 4-bit counters that provided clock division. The resultant clock pulses were then mulitplexed and fed to the clock input of the switched-capacitor filter.

The chosen switched-capacitor filter for our design is the LMF100 [5], from National Instruments. Like the requirements for every chip in our design, this integrated circuit operates on a single five Volt power supply. The LMF100 operates in several different modes that provide different filter configurations. The chosen mode offers a band-pass filter that requires a minimum of external resistors and allows for the four needed resistors to modify the center frequency of the band-pass, the center frequency gain of the band-pass, and the "Q," or exact waveform of the band-pass. Our team chose Mode 3 of the LMF100, of which several equations are given for these qualities:

$$f_0 = \sqrt{\frac{R_2}{R_4}}$$

$$H_{OBP} = -\frac{R_3}{R_1}$$

$$Q = \sqrt{\frac{R_2}{R_4}} * \frac{R_3}{R_2}$$

The chosen values for R_1, R_2, R_3, and R_4 are, respectively, 2.2 kΩ, 100 kΩ, 300 kΩ, and 100 kΩ. These values produce a "Q" equal to 3, the gain equal to approximately 136, and define the center frequency to be a multiple of either 50 or 100, depending on the value set to the 50/100 pin of the LMF100. Our design uses the 100 multiple, making the center frequency equal to the frequency at the CLK_A pin, divided by 100. The final design only requires one side of the dual switched capacitor. The single supply nature of the circuit requires that great attention be paid to the datasheet. There seem to be several contradictory statements in the datasheet. Pins

$AGND$ and SI_A are required to be set to $V_{CC}/2$. This is accomplished by using a simple Voltage divider circuit and a levelling capacitor. This exact design was taken as suggested by the filter datasheet, using 100 kΩ resistors and one 1μF capacitor. Figure 7 illustrates this design.

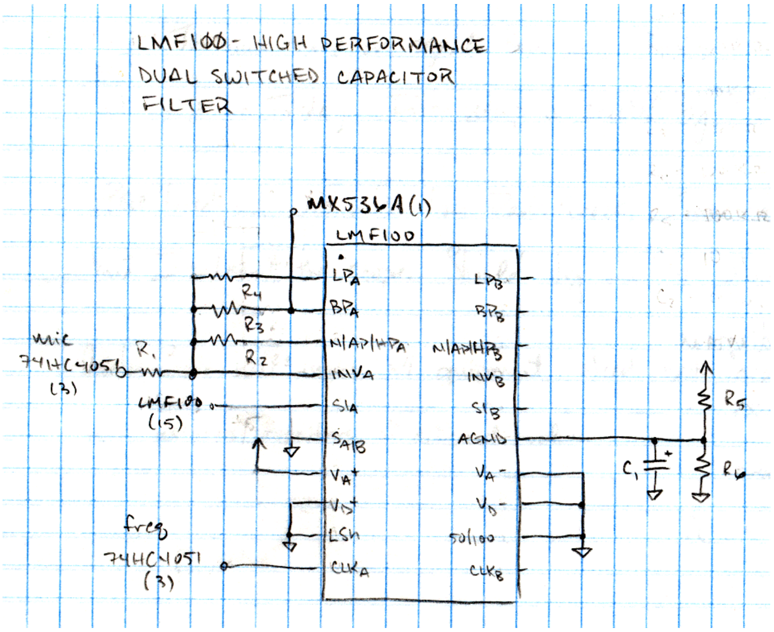

Figure 7: LMF100 Schematic

6.2 Clock Division

The switched capacitor filter requires an external clock signal. This external clock signal will then be proportional to the center frequencies of the different filters of the LMF100. This signal is produced by a 1 MHz crystal oscillator, MX045, which in turn controls two cascaded 4-bit counters. The chosen 4-bit counter for this project is the 74LS191 [8], from Fairchild Semiconductor. These counters operate on the required five Volt power supply and are standard parts, readily available in the Computer Science department. These particular counters are cascadable, using RCO output pin of the first counter, which is then the signal to the clock input of the second counter. Each output of each of the counters is then fed into an analog multiplexer, 74HC4051 [7], from ON Semiconductor. The μController then is able to control this multiplexer to choose the desired range of the band-pass filter. Figure 8 illustrates this design.

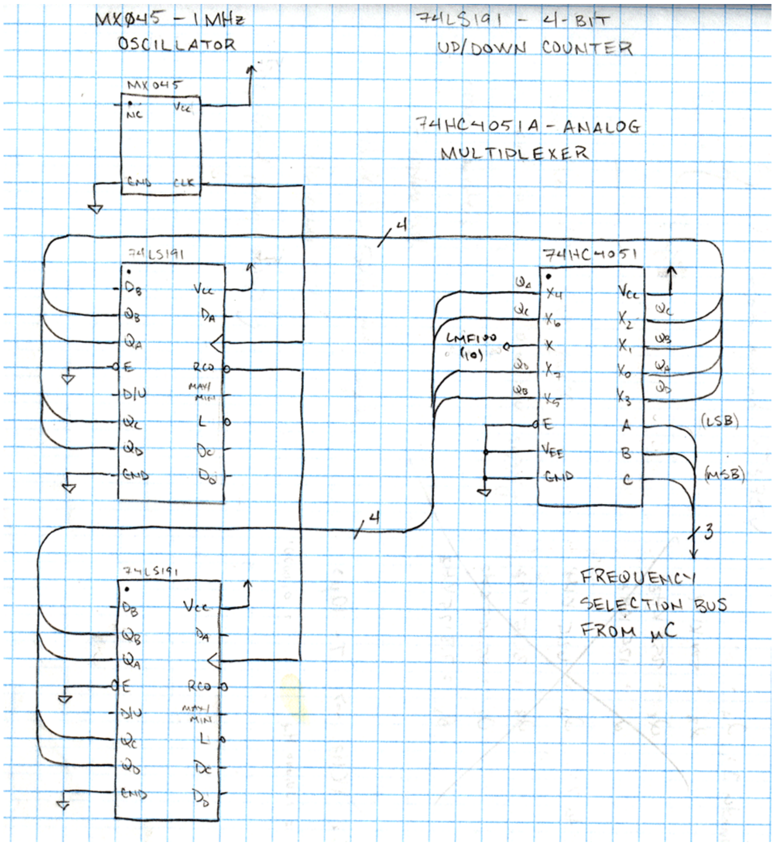

Figure 8: Clock Division Schematic

6.3 Rectification

The objective of this project is to determine the loudest signal from an array of microphones. The signal derived from the microphones is discussed in Section 3. The amplitude of the AC signal is proportional to the loudness of the sound being registered by the microphone. The proposal did not explicitly describe how to accomplish this. The problem was compounded by the fact that the AC signal has a corresponding DC offset. Using PSpice, a circuit was modeled to accomplish this task. Using a diode, a 100 μF capacitor, and a discrete low-pass filter, a DC Voltage was produced, proportional to the RMS value of the sinusoid. When the circuit was actually built, the output did not perform as planned. The large capacitor took a very long time to remove the offset, and the offset was not completely removed. During this preliminary phase of planning, our team decided to use the second side of the LMF100 as the low-pass filter, instead of designing a low-pass filter from discrete components. This also posed a problem, since the available transfer functions of the low-pass filter of the LMF100 were not as ideal as were expected.

An electronics book from ELEN325 contained a design for a so-called superdiode. This superdiode created an almost perfect diode transfer function, using a network of two op-amps, two diodes, and several resistors. This design overcame the nonideal operating characteristics of a diode. Normally a diode will not operate unless the Voltage across the diode is more than 0.7 Volts. Since the amplitude of the signal from the microphone will be much less than that, in the range of 30–200 mV, this nonideal characteristic makes using a regular diode impossible. The output of this design produced a DC value proportional to the RMS value.

But, our team finally came across a monolithic RMS-to-DC converter. As a general rule, these types of IC's produce a DC Voltage equal to that of the true RMS value of the AC signal. These also produce a value whether or not a DC offset is present. This IC solved virtually all of our team's problems dealing with the rectification. Our team also was able to talk to an applications engineer at Analog Devices to choose several of the values of resistors and capacitors for our needed application.

The first IC chosen for our project was from Analog Devices, the AD737 [10]. This chip was difficult to obtain, requiring almost a month's wait, and was also prohibitively expensive. An alternate chip, the MX536A [9], was located at Maxim-IC. This chip performed very similarly to the AD737 and was readily available. The main choices in the application description from the MX536A datasheet were the choice of resistor R_7 and the capacitor C_3, specified in the schematic shown in Figure 9. These were chosen to be 1 kΩ and 3.3 μF, respectively. The values of the other discrete components were given in Figure 5 of the MX536A datasheet [9].

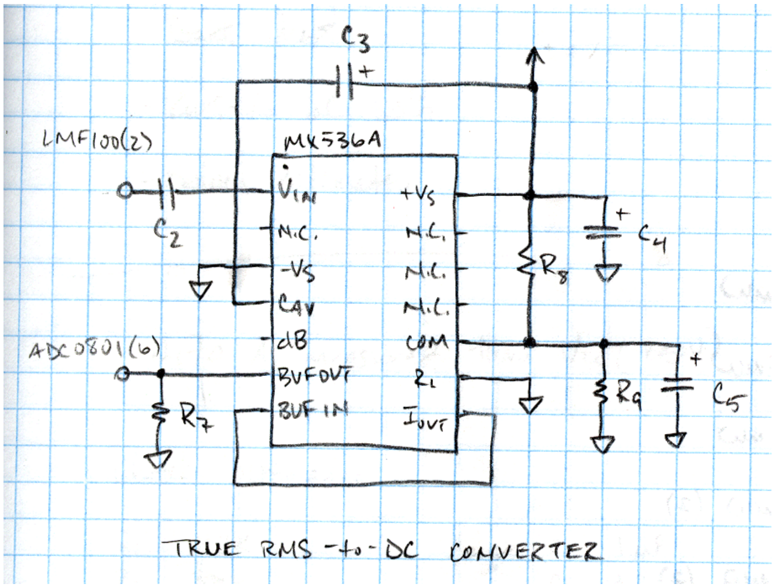

Figure 9: MX536A Schematic

6.4 Analog to Digital Conversion

The analog to digital conversion in our design has changed little over the course of the semester. The only real change was an increase in the resolution from a 4-bit to an 8-bit A/D converter. This change was prompted due to the fact that there are extremely few 4-bit converters being produced, while 8-bit converters are readily available. The design of this subsystem was taken from the datasheet of the ADC0801 [6], from National Semiconductor. Our design calls for a free running, self clocking mode, coupled with an ability to directly convert a low-level signal. Both of these criteria were satisfied using designs from the Typical Applications part of the A/D datasheet. The free running mode specified most of the pin voltages, as well as specifying the values of R_{10} and C_6 of the schematic in Figure 10. The datasheet also explains that pins WR and $INTR$ be temporarily grounded, and then be allowed to float, to guarantee operation. The final design decision of this subsystem was that of the $V_{REF}/2$ pin. This pin determines the range of the resolution of the A/D. Since any circuit is not ideal, the choice of a simple voltage divider in our circuit to determine this voltage was somewhat error prone. Since the impedance of the other elements of the circuit must be accounted for, the ideal output voltage of our voltage divider was not achieved. Instead, estimation was used to determine the proper value of the resistors to achieve the proper voltage of $V_{REF}/2$. Figure 10 shows the A/D subsystem schematic. Using 270 kΩ for R_{11}, 270 Ω for R_{12}, and 1 μF for C_7, a small voltage was achieved, on the order of 100 mV. This very small voltage provides a range of 200 mV for the A/D. This small range was chosen because of the extremely small Voltages being produced by the microphones, a well as the low volume of sounds that are expected to be picked up by the microphones in future robot applications.

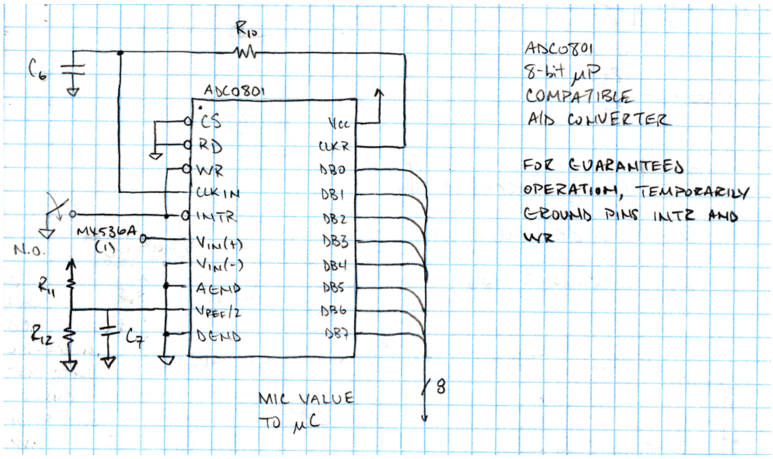

Figure 10: ADC0801 Schematic

7 Printed Circuit Board Design

Our team chose to use Protel Design Explorer 99 SE as our software design tool for developing our PCB's due to its wide acceptance and powerful functionality. Originally our team used the free Eagle software for the PCB design, but found it difficult and combersome to use. Protel links schematic diagrams with PCB designs by means of footprints — physical device specifications associated with a schematic part. For each IC, counter, header, resistor, and capacitor used in our design, a footprint and pin out were specified. Once every route was fully connected, the dimensions of our PCBs were specified, as well as the keep out areas and drills. Protel then placed each part in the PCB editing window for placement. Each component was then placed on the PCB in such a way that optimized route lengths and space consumption, which was aided by Protel with a color indicator that shows optimal placements for components by analyzing its connections. Once every component was placed as desired, the design rules were specified, specifically the widths of the power traces and signal traces. We used the Protel autorouter to create our initial routes, and then added additional ground planes in the remaining exterior areas on both sides of the boards to shield noise. The Protel CAM manager was then used to produce our output gerber files and drill files required by our manufacturer, AP Circuits [2].

The decision of the actual manufacturer of our PCB came with much deliberation. There are many companies around the world that will produce PCBs for a relatively small amount, in a short amount of time. The Electrical Engineering Deptartment of Texas A&M also produces PCBs. The choice of Protel was also influenced by this, as they only use Protel for their design applications. But, they do not perform the drill-thru technique that would require the use of vias. This would make our assembly much more time consuming and subject to failure. Several other companies, Omilex [3] and Custom PCB [4] were also considered. These were ruled out due to the fact that both of these companies are overseas, which would require larger shipping costs, and, more importantly, the quality of their work is unknown. Poor quality PCBs would have made our success extremely difficult.

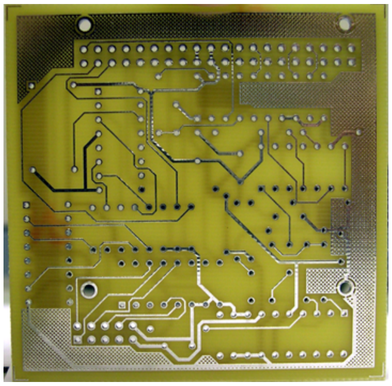

Figure 11: Empty Controller Board

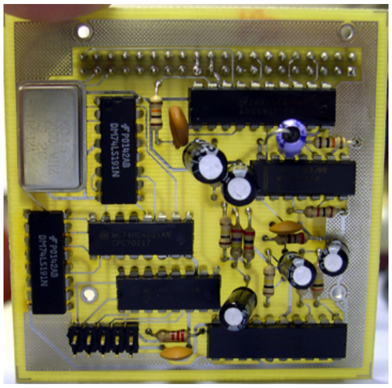

Figure 12: Completed Controller Board

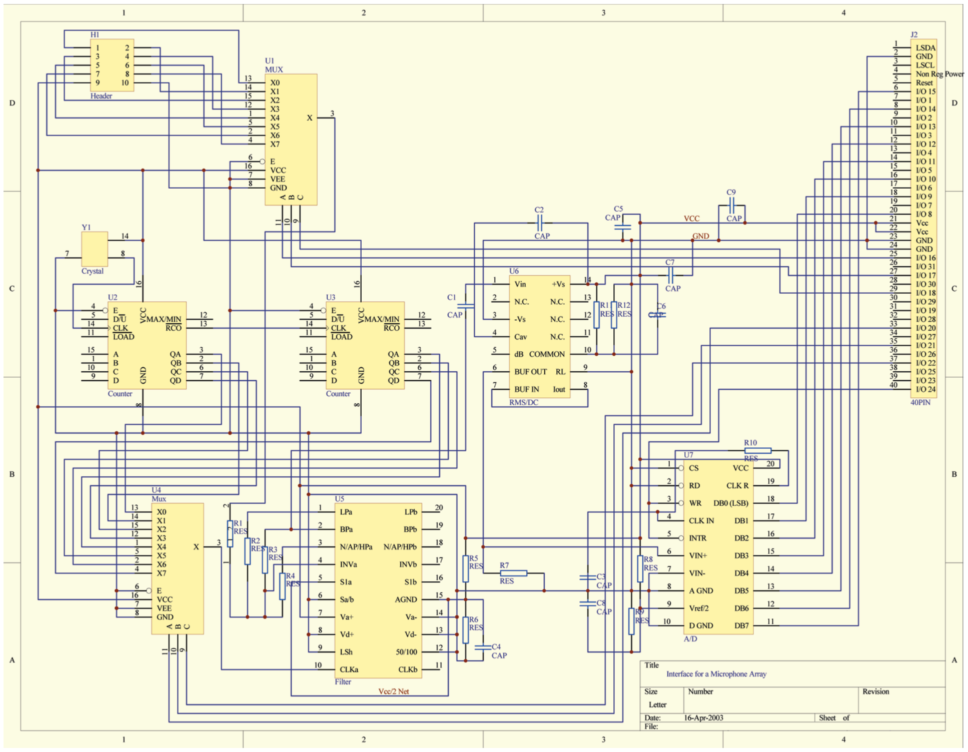

Figure 13: Controller Board Schematic

8 Robot

The robot our group has chosen for this project is the Mark III. Our professor and teaching assistants suggested this robot to us. It is inexpensive, small, mobile, and is expandable. The Mark III also has many other features that made it suitable for our project.

The Mark III consists of a PIC16F877 20MHz Microprocessor. It also has a 40-pin OOPic-compatible header that will be used to add our own microprocessor and microphone array. One feature that made the Mark III different other robots is that it has both analog and digital inputs. The Mark III has some sensors that already come with it like the Fairchild photoreflector for line following and the Sharp infrared ranging sensor used for ranging. A key feature of the Mark II is that it is programmable via a serial cable. It is can be programmed with Java, C, Basic, and OOPic.

Unlike other robots, the Mark III did not come assembled and which required our team to assemble and solder it. This was not much of a problem for us and it did not take too long to assemble. After the assembly was completed, the robot was tested to ensure proper operation. A test program was loaded that calibrated the servos to test the robot's connection and functionality. The test was a success and the robot was ready to go.

While learning to program the robot, a line following program was used to illustrate the use of I/O lines for the robot and control of the servos. The robot stayed stationary until a black line was shown in front of the sensors. It then followed the black line until the line disappeared. The black line, in this case, can represent our sound source, and how the robot will follow the sound source until the sound stops.

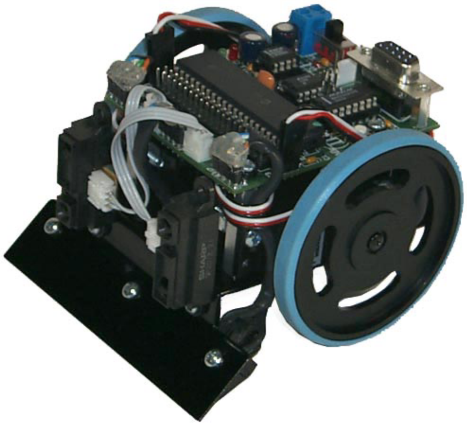

Figure 14: Mark III Robot

9 Recommendations for Future Work

Throughout the semester our team encountered many problems with our design for this project. We have made several recommendations for future implementations of our project.

One thing to be aware of are the I/O lines and the pins they are assigned to, especially those that are assigned to the servos. Our team initially used these I/O lines for our own use, but re-routed the servo lines to lines not being used by our project. So, make sure to use those I/O lines that are not in use.

When designing the control board and microphone array board notice the way headers are oriented so that the 40-pin ribbon cable can connect in an easy and efficient manner. Also, our team recommends making the drill holes for the standoffs larger to accommodate for nuts and bolts.

One of our biggest problems with our design was that our program accidentally made the robot continually write to the serial I/O causing us to resort to programming with the parallel port. A programming cable for the parallel port then had to be purchased.

It is also recommended that socket connectors be on the board for the IC's and the microphones. These can come in real handy for the mics, since they seem they can break very easily. Pots can also be added to regulate the gain.

10 Management

Table 1 illustrates the division of labor of our team. Many of the tasks were worked on as a group, and most roles contained overlap among the team members.

Member	**Role**
Josh Earley	Development of array, acoustic directionality, board design
Trent Foley	Development of rectification system, schematic design, and PCB design
Thomas Garner	Development of board design
Chris Gonzales	Development of software design

Table 1: Management Structure

11 Schedule

Figure 15 shows our team's progress in many areas and aspects of the design process.

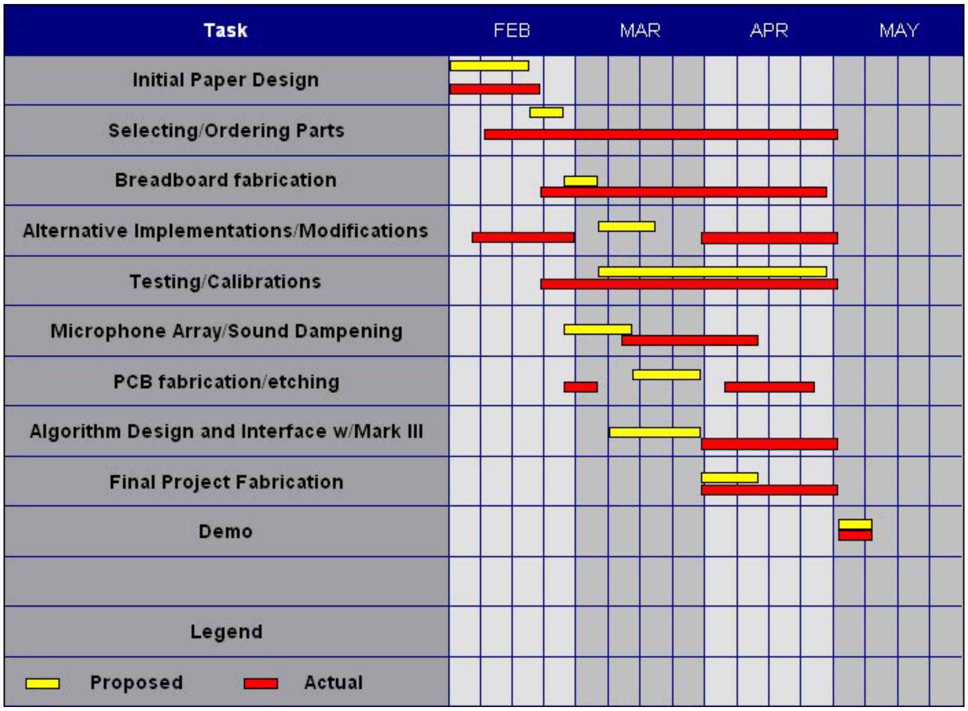

Figure 15: Gantt Chart

12 Budget Analysis

The following table is an analysis of the expenditures of our team during the design process. The final cost of this project was approximately $496.24, within rougly 3% of the proposed budget of $481.

Part	**Qty.**	**Price**	**Total**
1 MHz Oscillator	2	$-	$-
4-bit Counter	4	$-	$-
8:1 Analog Multiplexer	4	$-	$-
RMS-to-DC Converter	2	$-	$-
Switched Capacitor Filter	2	$-	$-
4.7 kΩ Resistor Pack	2	$-	$-
A/D Converter	2	$-	$-
Microphone	44	$1.83	$100.52
Dynamat Sound Dampening Material	1	$21.64	$21.64
Mark III Robot	1	$98.00	$98.00
Mark III Robot Upgrade	1	$30.00	$30.00
LED Display	1	$3.24	$3.24
Piezo Buzzer	1	$3.24	$3.24
Flux	1	$2.70	$2.70
Cleaner w/ brush	1	$11.90	$11.90
Various Discrete Components	1	$4.82	$4.82
PCB Fabrication	1	$60.16	$60.16
PCB Fabrication	1	$76.34	$76.34
DIP Switch	1	$2.48	$2.48
10k Resistor Pack	2	$1.00	$2.00
Plexiglass	1	$4.00	$4.00
Various Discrete Components	1	$0.60	$0.60
Various Discrete Components	1	$3.91	$3.91
Ribbon Cables, etc.	1	$11.25	$11.25
Standoffs	1	$16.11	$16.11
Parallel Programming Cable & EEPROMs	1	$40.35	$40.35
Standoffs	1	$3.00	$3.00

Table 2: Budget Analysis

13 Conclusion

Our team felt this project implemented all aspects of engineering design. Further, this project required us to combine all of the knowledge we have gained throughout our undergraduate careers, from digital/analog design to programming. Although our robotic design does not perform optimally, our team feels that all of the primary design objectives and goals were met. Due to our inexperience with robotic applications and the many aspects of the design, our team failed to place proper emphasis on our microphone sensors, which ultimately did not perform optimally in a real world environment. Although the microphones operated correctly during design and testing, they did not meet our standards when they were fully implemented with the controller and robot. We also feel that if had we have secured better performing microphones, our design would have worked flawlessly. In spite of our non-optimal robotic performance, this design project culminated many years of learning and not only increased our understanding of computer systems design, but increased our confidence in our abilities as young engineers as well.

14 Design Validation

☐ In 360° environment, robot responds to a single generated tone.
☐ Robot moves directly toward or away from source of sound.
☐ Robot responds to both high and low frequency tones.
☐ Robot stops when sound source is inactive or turned off.
☐ Robot moves to sound source at 0° (directly above it).
☐ Robot moves to sound source at 45° (north-east of it).
☐ Robot moves to sound source at 90° (directly to the right of it).
☐ Robot moves to sound source at 135° (south-east of it).
☐ Robot moves to sound source at 180° (directly behind it).
☐ Robot moves to sound source at 225° (south-west of it).
☐ Robot moves to sound source at 270° (directly to the left of it).
☐ Robot moves to sound source at 315° (north-east of it).

Table 3: Design Validation Checklist

Table 3 is a list of checks to see if the robot responds to sound in every direction in a 360° environment. Once the robot successfully completes this task list then our design is correct and our project is complete.

15 Acknowledgements

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