# Table of Contents

1 Introductory Materials ................................................................. 1
1.1 Executive Summary ................................................................. 1
  1.1.1 Need for the project ......................................................... 1
  1.1.2 Project Activities ............................................................ 1
  1.1.3 Final Results ................................................................. 1
  1.1.4 Recommendations for Follow-on Work ....................... 2
1.2 Acknowledgement ................................................................. 2
1.3 Problem Statement ............................................................... 2
1.4 Operating Environment ......................................................... 3
1.5 Intended Users, Intended Uses ............................................... 3
  1.5.1 Intended Users ............................................................. 3
  1.5.2 Intended Uses ............................................................. 3
1.6 Assumptions and Limitations .................................................. 3
  1.6.1 Assumptions ............................................................... 3
  1.6.2 Limitations ............................................................... 3
1.7 Expected End Product ............................................................ 4

2 Analog Implementation ............................................................. 5
2.1 Design objectives ................................................................. 5
2.2 Functional requirements ....................................................... 5
2.3 Design constraints ............................................................... 5
2.4 Research Approach .............................................................. 5
2.5 System Design ................................................................. 6
2.6 PSpice Simulation ............................................................... 7
2.7 Implementation ................................................................. 7

3 Digital Implementation ............................................................ 9
3.1 Algorithm Selection .............................................................. 9
  3.1.1 Adaptive Control Filters ............................................... 9
  3.1.2 Algorithms ............................................................... 10
3.2 DSP Board Selection ........................................................... 10
  3.2.1 Requirements ............................................................ 10
  3.2.2 Boards Considered and Rejected ................................. 10
  3.2.3 Texas Instruments – TAS3004/3002 Evaluation Module .... 11
  3.2.4 Texas Instruments – TAS3103 Evaluation Module .......... 12
  3.2.5 Motorola – DSP56364 ............................................... 13
  3.2.6 Analog Devices – ADSP-BF533 ................................. 14

4 Testing ....................................................................................... 15
4.1 Lab Testing ........................................................................... 15
4.2 Other Tests ........................................................................... 16
  4.2.1 Human Test ............................................................... 16
  4.2.2 Outdoor Test ............................................................ 16
4.3 Results .................................................................................. 16
  4.3.1 Analog System ........................................................ 16
  4.3.2 Digital System ......................................................... 18

5 Resources and Schedule .......................................................... 20
5.1 Individual Effort ................................................................. 20
List of Figures
Figure 2.1 - ANC Block Diagram....................................................................................... 6
Figure 2.2 - Mono Three-stage Amplifier Circuit .............................................................. 6
Figure 2.3 - Final Analog System....................................................................................... 7
Figure 3.1 - Digital Feedback Control System ................................................................. 9
Figure 3.2 - TAS3004 Schematic...................................................................................... 12
Figure 3.3 - TAS3103 Schematic...................................................................................... 13
Figure 3.4 - ADSP-BF533 ................................................................................................ 14
Figure 4.1 - Testing Arrangement..................................................................................... 15
Figure 4.2 - Analog Circuit Frequency Response............................................................. 17
Figure 4.3 - Analog Circuit Noise Reduction ................................................................... 18
Figure 4.4 - Matlab Simulation of LMS Algorithm.......................................................... 19
Figure 5.1 - Fall Semester Schedule ................................................................................. 23
Figure 5.2 - Spring Semester Schedule............................................................................. 24
Figure 7.1 - Full Stereo Analog Circuit ............................................................................ 30
Figure 7.2 - PSpice Circuit............................................................................................... 31
Figure 7.3 - 20 kHz Transient Response of Input Amplifier (1st Stage).......................... 32
Figure 7.4 - 20 kHz Transient Response of Inverting Amplifier (2nd Stage)............... 33
Figure 7.5 - 20 kHz Transient Response of Output Amplifier (3rd Stage)................... 34
Figure 8.1 - Fall Semester Schedule ................................................................................. 35
Figure 8.2 - Spring Semester Schedule............................................................................. 36
List of Tables

Table 5.1 - Individual Effort ........................................................................................................ 20
Table 5.2 - Revised Individual Effort .......................................................................................... 20
Table 5.3 - Actual Individual Effort ............................................................................................ 21
Table 5.4 - Estimated Other Costs .............................................................................................. 21
Table 5.5 - Revised Estimated Other Costs .................................................................................. 21
Table 5.6 - Actual Other Costs ..................................................................................................... 21
Table 5.7 - Total Financial Resources .......................................................................................... 22
Table 5.8 - Revised Total Financial Resources ............................................................................ 22
Table 5.9 - Actual Total Financial Resources .............................................................................. 22
Table 6.1 - Statement of Work ..................................................................................................... 25
List of Definitions
ANC – Active noise control
DSP – Digital signal processor
Outside Signal – Signal from outside source such as radio or CD player
FIR filter – Finite impulse response filter
IIR filter – Infinite impulse response filter
LMS – Least mean square
1 Introductory Materials
This document will outline the current statues of the design of two active noise control (ANC) systems, one analog and one digital, as implemented by the May21-04 senior design team.

1.1 Executive Summary
This project deals with the design of an active noise control system that will cancel ambient noise in a laboratory environment.

1.1.1 Need for the project
Active noise control is a widely-needed technology in many industries. Specifically, Caterpillar wanted a system that would reduce the amount of noise their workers were exposed to while working with heavy machinery. Originally, the team expected to work on a solution for this problem, but further communication with Caterpillar revealed that they submitted the problem to the Senior Design course as a learning experience for students; Caterpillar has a team of engineers working on implementing a specific solution for their company

This aside, there is still a valid reason to study active noise control. When implemented in the form of a headset, it can be used by anyone in a noisy environment: a plane, a bus, or a noisy room. The world is a noisy place, and many people can benefit from this technology.

1.1.2 Project Activities
The team first decided on how to implement an active noise control device. Of the two basic implementations (free-standing speakers or a headset) the headset was chosen because it was deemed to be more realistic for the team in terms of scope.

After deciding on the overall implementation scheme, the team decided to pursue two different methods to control noise using a headset. The first is a traditional analog circuit; the second is by using a DSP board to run an adaptive algorithm.

The team then divided the two semesters into three phases: research, implementation, and testing. During the research phase the team found a circuit schematic for the analog that would accomplish the desired effect. In addition, the team researched adaptive algorithms to implement on the DSP board, finally deciding on the LMS algorithm. Finally, the team researched DSP boards, deciding on the Analog Devices ADSP-BF533 board. During the implementation phase, the team built and debugged the analog circuit and began writing the C++ code to implement the LMS algorithm on the DSP board. Finally, the testing phase involves testing both systems in the laboratory and gathering results.

1.1.3 Final Results
As of this writing, the team is not finished with the project. The LMS code needs to be completed and the testing of both systems is on hold until the equipment needed to analyze the circuits becomes available.
1.1.4 Recommendations for Follow-on Work
Active noise control is a useful technology that need not be limited to one individual’s use via a personal headset. For example, an ANC system could be implemented in the ALC of Coover Hall to eliminate the noise made by the fans in that room. A system could also be implemented aboard Cy-Ride buses to reduce the noise level inside the bus. The team recommends that these options be looked into as possible projects in future senior design courses.

1.2 Acknowledgement
Thanks to Ken Gihring and Bill Allen at Caterpillar for the project idea as well as guidance. Also thanks to our advisors Clive Wood and Zhengdao Wang.

1.3 Problem Statement
The problem statement, as originally defined by Caterpillar, is to “design, implement, test, and demonstrate an active noise cancellation system, possibly using cab-mounted speakers or a headset.” The problem Caterpillar operators face is that noise impairs the operator’s ability to hear two-way radio communications. A system is needed that can dampen ambient noise without limiting the operator’s ability to hear radio communications.

After communicating with Bill Allen about Caterpillar’s expectations for the product, it was determined that the main focus of Caterpillar was not specifically to come up with a solution for their operators. Rather, Caterpillar’s intent is to fund the team’s research as an educational endeavor; their expectation is that we design a prototype for a system that will perform well in a laboratory setting, as opposed to a designing a device to be used by a Caterpillar. Various factors influenced their decision, including the operator’s unwillingness to wear a headset and the strict standards that an electronic device must meet in order to be allowed to be used in a Caterpillar: standards which are far beyond the scope of a senior design project.

After some preliminary time calculations, the team determined that both a digital solution and an analog system should be fabricated. This way, the overall effectiveness of both solutions can be weighed, thereby giving a more complete analysis of active noise control implementation.

The two fundamental physical mechanisms of sound control are destructive interference and impedance coupling. Firstly, a sound field is composed of high and low pressure areas called compressions and rarefactions, and when “the high-pressure part of one wave lines up with the low-pressure part of another wave, the two waves interfere destructively and there is no more pressure fluctuation (no more sound)” [1]. Secondly, if the actuator – the device which produces the controlling wave – is near the disturbance source, then the controlling wave can be thought of to change the input impedance of the disturbance. When this is the case, the controller doesn’t only change the disturbance signal at a reference point, but instead it changes how the disturbance signal “looks”. This type of system has both physical mechanisms.
Systems with both mechanisms are common when the disturbance signal is propagating in one dimension, as is common in problems with ventilation fans in ducts, as well as in problems with engines where the sound is propagated through definable passageways. Alternately, if it is not possible to reduce the wave structure to this level of simplicity, active noise control can be implemented with headphones. It is systems like these in which the disturbance signal is only controlled at a local point or points, and thus only utilize destructive interference. The team has chosen the latter approach.

1.4 Operating Environment
As per Bill Allen’s suggestions, the operating environment that the system must work in is a controlled laboratory setting.

1.5 Intended Users, Intended Uses
The team has determined the intended users of the ANC systems, as well as what uses these users will have for the systems.

1.5.1 Intended Users
The system will simple enough for people to use without extensive background with electronic equipment. If a user knows how to operate a portable CD player, he/she should be able to intuitively know how to use this system.

1.5.2 Intended Uses
The system should be quite versatile with regards to the type of noise it will attenuate. Obviously, its basic purpose is to eliminate background noise, and since different environments have different types of noise, the system should perform equally well with a wide variety of test noise.

1.6 Assumptions and Limitations
The team has made several assumptions for this project. The scope of the project will also be limited by several factors.

1.6.1 Assumptions
These are the assumptions the team has made in designing the ANC systems.

- Testing environment for both systems will be in a small, enclosed space
- Operating environment for both systems will be normal indoor laboratory conditions (no extreme moisture or temperature)
- Both systems will be portable: 12” by 6” by 3” or smaller
- Both systems will be DC powered by no more than two 9-volt batteries

1.6.2 Limitations
These factors limit the scope of the team’s design.

- Noise to be attenuated can only be low in frequency
- System can be limited by availability of funds
1.7 Expected End Product

The team expects to deliver two prototypes that will attenuate low frequency noise in a headset. One prototype will be based on analog circuitry; the other will be designed using DSP principles. Two microphones will be used; they will be on the outside of the earpieces of the headset, near the ear canal. An input for an outside signal such as a CD player or a two-way radio will also be included.
2 **Analog Implementation**
This section will discuss the analog implementation of the ANC system, while Section 3 will discuss the digital implementation.

2.1 **Design objectives**
- System must be fairly robust. The circuit components will be housed in a hard box to make the system durable.
- System must be easy to operate. Knobs, switches, and various inputs will be accessible on the housing box.

2.2 **Functional requirements**
- System must achieve greater noise reduction than passive headphones at low frequencies.
- System will allow for an auxiliary input (e.g. CD player or two-way radio).
- Volume controls will be available for the auxiliary and noise inputs.

2.3 **Design constraints**
- System must be portable. Approximate dimensions are 3”x 4”x 2” and weighs under one pound.
- System must be low cost. Materials for system will total to approximately $20.

2.4 **Research Approach**
For the research phase of our project, the team used the internet to find possible active noise control designs that would meet the requirements. The team found a simple analog circuit using three op-amps that would meet the requirements. The schematic for this circuit can be found in Appendix A.

The team decided to build the circuit described on the website. This decision was made after careful consideration of several factors.
- Instructions on how to build the circuit were outlined on the website
- List of parts was included on the site (parts list included in Appendix A)
- Comments of other people who built the circuit were on the website, describing the circuit as reliable and effective
- Circuit components were all familiar to the team
- Parts could be quickly delivered (within a week of placing order)
- Parts are very inexpensive

All other sources the team researched were lacking in practical implementation. Books and online sources contained discussions on the theory behind active noise control, but did not include precise instructions or an actual circuit that the team could build. Most of these sources were also concerned with only digital solutions and their corresponding algorithms.
2.5 System Design

The noise cancellation circuit works by detecting the noise of the surrounding environment using a microphone attached to the earpieces of the headset. Once this noise is detected, it can be inverted and added to a desired signal (such as music from a CD player or a two-way radio communication). This is done in the active noise control block shown in Figure 2.1. Since the output of this block is the signal and the inverted noise, the incoming noise from the surrounding environment will add to this and leave just the desired signal for the user to hear.

![Figure 2.1 - ANC Block Diagram](image)

Figure 2.2 shows the noise cancellation block from Figure 2.1 as a simplified mono three-stage amplifier circuit. As can be seen, the noise is inverted and amplified while the desired signal is only amplified.

![Figure 2.2 - Mono Three-stage Amplifier Circuit](image)

The final stereo circuit along with the exact parts list can be viewed in Appendix A.

The circuit will be soldered onto a pc-board and placed into the housing box with two 9-volt batteries. As can be seen in Figure 2.3 below, the box will have several user controls. A microphone level knob can be turned to adjust to the appropriate level of “anti-noise”. The auxiliary level knob works to control the volume of the outside signal. The phase switch allows for the user to amplify background noise rather than reduce it.
Before constructing the actual circuit, PSpice circuit analysis software was used to model the circuit’s behavior. The results of the PSpice simulation encouraged the team to build the circuit and test its behavior in the lab. PSpice showed an inverted, amplified sinusoidal output when the circuit was given a sinusoid as input. Plots of these results can be seen in Appendix A.

2.7 Implementation
As an intermediate stage to the final product, the circuit was constructed on a breadboard so the team could test the circuit’s effectiveness. This test was performed before the specific circuit components were ordered; hence the intermediate circuit was built using the combined lab kits of the team members. Since microphones were not available to input noise into the circuit, a function generator was used to input a sinusoid and an oscilloscope was used to measure the output.

Initially, the circuit failed to output a correct waveform. A binary search was performed to determine the cause of the problem. The sequential testing of the binary search led to a problem in the first op-amp. The op-amp was then replaced and the entire circuit worked
as expected. The output sinusoid was an amplified and phase-inverted version of the input sinusoid.

The circuit was then assembled on a printed circuit board. At first, the entire circuit was exposed, as we had not yet mounted it in its housing box. This led to many problems. Weak solder joints and the poor quality of the actual circuit board led to numerous problems that prompted the team to re-solder several problem areas on the board. Once this was completed, the circuit performance improved, at which point the entire circuit was mounted in plastic case.

A second problem was encountered when the circuit began “motorboating.” A low frequency buzz could be heard in the headphones whenever the circuit was set to inverting mode. To fix the problem, capacitors were added to the circuit to cancel this frequency. The circuit performed well after this problem was taken care of. No further modifications have been made to the circuit.
3 Digital Implementation
The team dealt with two major issues in the digital implementation of the ANC system: determining the relevant algorithms, and choosing the DSP board.

3.1 Algorithm Selection
A digital system for feedback control is represented in Figure 3.1 below [2].

In Figure 3.1 above:
- $d(n)$ represents the noise that is being cancelled out
- $e(n)$ is the error signal gathered by the microphones between the user's ear and the speaker
- $x(n)$ is the signal approximation of the noise $d(n)$
- $y(n)$ is the signal that cancels the noise

The block diagram above describes the dataflow for the team's LMS algorithm. The LMS component continuously updates the coefficients for the 20-order FIR filter $W$, which then generates $y(n)$ from $x(n)$. Below is a more detailed discussion on filters and the LMS algorithm.

3.1.1 Adaptive Control Filters
The finite impulse response (FIR) filter, also called a transversal filter or a tapped delay line, has an output which decays to zero. It uses open loop control – meaning that there is feedforward, but no feedback, control – and is ideally suited to tonal noise problems.

The infinite impulse response (IIR) filter uses closed loop control in conjunction with feedforward control. It is inherently unstable, converges more slowly, and is more sensitive to abrupt change in input. However, it is the only type of filter that can control a signal composed of broadband noise. Additionally, a control system with an error microphone requires feedback, and thus IIR filters are required.
Both of these filters work by placing weights on the different sampled values of the reference signal, and the IIR filter will also apply weights to the sampled values of the error signal.

### 3.1.2 Algorithms

Both FIR filters and IIR filters normally use a *least mean squares* (LMS) algorithm. ‘Least mean squares’ is a mathematical method of measuring the strength (often power) of a signal. LMS can be implemented with only feedforward control, only feedback control, or a hybrid of the two.

Traditionally, hybrid control systems keep the feedforward (reference) control separate from the feedback (error) control. The “feedforward part will cancel those parts of the error signal that are correlated with the reference signal, while the feedback part will act on all periodic components of the noise at the error sensor, whether or not they are correlated with the reference signal” [3]. So not only is the algorithm computation for the two parts of the control system enacted separately, but they depend on disparate signals. A successful control design will depend upon fine tuning these internal balances against the balance between the parts.

### 3.2 DSP Board Selection

The team researched several different options from three different manufacturers for the DSP solution. This section outlines the requirements that the DSP board needed to fill. A discussion will be presented for each board considered, weighing the advantages and the disadvantages.

#### 3.2.1 Requirements

The DSP board that the team will use must:

- Have at least four signal inputs (two stereo analog inputs)
- Have at least two outputs for stereo headphones (one stereo output)
- Be fully programmable
- Have some kind of PC interface
- Include a software package to implement ANC algorithms

The team believes that these are the minimum requirements needed to correctly implement an effective ANC solution.

#### 3.2.2 Boards Considered and Rejected

The team considered five DSP boards from three different manufacturers:

- Texas Instruments – TAS3004/3002 Evaluation Module
- Texas Instruments – TAS3103 Evaluation Module
- Motorola – DSP56364
- Analog Devices – ADSP-BF533
This section will discuss each board’s advantages and disadvantages. The technical specifications and descriptions of each board are adapted from each company’s respective website.

3.2.3 Texas Instruments – TAS3004/3002 Evaluation Module
The TAS3004 is a flexible DSP specifically tailored to audio applications. Features of the TAS3004 board include:
- 32-bit, 100 MIP digital audio processor
- Audio manipulation (mixing, filtering, parametric or graphical EQ, volume control, tone control, etc.)

The following is included with the purchase of the evaluation module:
- CD with data manuals and Reference Design Board User's Guide
- TAS3004/3002 Reference Design Board
- EQ Software Tools CD
- PC to IIC Interface Adapter Board (Paddle Board)

Figure 3.2 shows a schematic.
This board was initially very attractive to the team. The board is flexible and powerful enough to handle the DSP algorithms, and a software package is included. At $399, it was a very attractive option. Unfortunately, upon consulting the schematic, the team noticed that the required set of inputs was not available. A single un-amped mono input is not enough for the dual microphone design. The stereo input could have been used for the microphone, but then the outside signal would have to be a mono signal, which is undesirable for some applications. Ultimately, this board does not fulfill the team’s requirements.

3.2.4 Texas Instruments – TAS3103 Evaluation Module
This board was a very attractive option for the team. The board features can handle up to three analog stereo inputs and up to three analog stereo outputs, which more than meets our needs.

The following is included with the purchase of the TAS3103 Evaluation Module:
- Wall mount power supply
- DCT (TAS3103 GUI) Software
- ALE (Automatic Loud Speaker Equalizer) Software
- TAS3103 Data Manual
- Paddle board for allowing PC control of evaluation board
- Paddle board connection cable

Figure 3.3 shows a schematic.

This board more than fits the team’s needs. The three stereo inputs and outputs would be more than sufficient for our ANC system. The system is also fully programmable, as required. Unfortunately, the $799 price tag would nearly wipe out our budget, so this board was not chosen.

3.2.5 Motorola – DSP56364
The DSP56364 processor provides a low-cost, high performance solution. Features of the processor include:
- 100 Million instructions per second (MIPS)
- 6 serial data lines (4 selectable as receive or transmit and 2 transmit only)
- Low power (3.3 V) design

At a price tag of $250, this is the least expensive option the team considered. Unfortunately, the website was not very clear on the programmability of the board, and this is one of the most important requirements of the board. The team decided not to risk spending less money for a product that would not fit our needs.
3.2.6 Analog Devices – ADSP-BF533

The team selected the Analog Devices ADSP-BF533 Blackfin processor. Analog Devices offers this processor in a kit called EZ-Kit Lite. Figure 3.4 shows a picture of the board.

![Figure 3.4 - ADSP-BF533](image)

The board is quite versatile. It features:
- ADSP-BF533 Blackfin Processor
- 132 MB (16M x 16-bit) SDRAM
- 12 MB (512K x 16-bit x 2) FLASH memory
- 1 AD1836 96 kHz audio codec w/4 input and 6 output RCA jacks
- 1 ADV7183 video decoder w/3 input RCA jacks
- 1 ADV7171 video encoder w/3 output RCA jacks
- 1 Evaluation suite of VisualDSP++

The board includes video capabilities that the team will obviously not use. Other than that, the board matches the team’s requirements well. The package includes an evaluation copy of VisualDSP++, which includes a C/C++ compiler/debugger. This is an advantage, as the team already has experience in coding in C++. Finally, the board costs $295, which is well within budget.
4 Testing
The team has developed a testing procedure that will objectively determine the performance of the ANC systems in the designated operating environment. This section is divided into two sub-sections. In the first, the laboratory testing procedure will be discussed. In the second, additional testing ideas will be discussed; these will be implemented depending on the results of the laboratory tests.

4.1 Lab Testing
To objectively determine how effective the ANC systems are, the team has come up with a set-up that will mimic a human head using two microphones and a mannequin head. A spectrum analyzer will run a frequency sweep from 50 Hz to 1000 Hz (this range of frequencies is the range for which the system is expected to reduce noise). Figure 4.1 shows this arrangement.

![Figure 4.1 - Testing Arrangement](image_url)
With this arrangement, the system’s performance can be safely tested without any risk of damaging a volunteer’s hearing. In addition, this arrangement allows the team to easily test passive noise reduction technology to compare our active system.

4.2 Other Tests
Depending on the system’s performance in the lab, the team may test the system in other environments, under different conditions. These tests will only be performed once the system has performed adequately in the laboratory, and only then if time allows.

4.2.1 Human Test
Every team member and several other students have tested the analog circuit in the ALC in Coover Hall. It was clear that the system was substantially reducing the loud fan noise, but a slight hiss from the circuit was also audible.

4.2.2 Outdoor Test
Once the system performs satisfactorily in the laboratory, the team may take the system outdoors to test how effective it is in eliminating normal outdoor noise pollution. Possible test sites include:

- Aboard a Cy-Ride bus
- Along a busy Ames street
- At a construction site on campus

4.3 Results
This section presents the results of the team’s testing of the end product. Both the analog and the digital system will be tested for their ability to reduce noise. We have tested the completed analog system. The digital system was simulated in Matlab.

4.3.1 Analog System
The analog system was tested in the Acoustics Lab of Howe Hall. The frequency response of the setup was obtained both when the ANC system was turned on and turned off. The resulting plot in Figure 4.2 shows the differing noise levels observed by a person wearing the headphones with the system turned on and off.
As can be seen from Figure 4.2, the ANC circuit is effective in the frequency region of 150 to 1000 Hz. The inability of the circuit to reduce noise at frequencies below 150 Hz can be attributed to the inability of our headphones to reproduce sound well at very low frequencies. Our circuit’s inability to reduce noise at high frequencies is expected, as all active noise control systems have trouble getting the inverted signal to be perfectly out of phase with the incident signal when the incident signal has a small wavelength.

Since passive headsets work best for high frequency noise, reduction of noise throughout the audible range could be achieved with a hybrid system of passive and active measures. An active system using headphones with good bass response could reduce noise in the 20 to 150 Hz range.

Figure 4.3 shows the reduction in noise achieved by our analog circuit. At best, the circuit reduces noise by 20 dB (420 to 590 Hz). The blue line is the measured response of the system and the green line is the moving average of the measured data.
4.3.2 Digital System

The digital system was not completed by the end of the semester. The team attributes this to an underestimation of the complexity of DSP programming, as well as a fundamental misunderstanding of the interface between the digital side of the system and the analog side.

Despite this, code was written for the LMS algorithm. This code compiled and ran on the board, which the team considers a success in and of itself. However, in order to prove the correctness of the algorithm, actual data had to be measured. To accomplish this, the team implemented the same algorithm in Matlab and ran a simulation. Using Matlab’s plotting capabilities, Figure 4.4 was generated. The red line shows a moving average of the actual error signal calculations. It is clear to see that a noise reduction of about 20 DB is achieved.
Figure 4.4 - Matlab Simulation of LMS Algorithm
5  Resources and Schedule

This section will revisit the original estimates the team made and present actual numbers of hours/dollars. Revised estimates and actual numbers are presented in adjacent tables.

5.1  Individual Effort

Table 5.1 shows the estimated personal effort contributed by each team member detailed in our Project Plan.

Table 5.1 - Individual Effort

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axel Aguado</td>
<td>50</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>210</td>
</tr>
<tr>
<td>James Bishop</td>
<td>50</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>210</td>
</tr>
<tr>
<td>Chad Raddatz</td>
<td>50</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>210</td>
</tr>
<tr>
<td>Tom Waite</td>
<td>50</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>210</td>
</tr>
<tr>
<td>TOTALS</td>
<td>200</td>
<td>240</td>
<td>160</td>
<td>240</td>
<td>840</td>
</tr>
</tbody>
</table>

Stage 1: Algorithm Development
  Active noise control of low frequencies within an enclosed space
Stage 2: Implementation
  Active noise control of low frequencies within an enclosed space
Stage 3: Algorithm Development
  Plug and play active noise control unit for headphones
Stage 4: Implementation
  Plug and play active noise control unit for headphones

Since drafting the Project Plan, the team has redefined the project into four different tasks. Accordingly, Table 5.2 shows a new, more accurate distribution of work hours.

Table 5.2 - Revised Individual Effort

<table>
<thead>
<tr>
<th></th>
<th>Task 1</th>
<th>Task 2</th>
<th>Task 3</th>
<th>Task 4</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aguado, Axel</td>
<td>15</td>
<td>10</td>
<td>40</td>
<td>70</td>
<td>135</td>
</tr>
<tr>
<td>Bishop, James</td>
<td>15</td>
<td>10</td>
<td>40</td>
<td>70</td>
<td>135</td>
</tr>
<tr>
<td>Raddatz, Chad</td>
<td>30</td>
<td>40</td>
<td>15</td>
<td>50</td>
<td>135</td>
</tr>
<tr>
<td>Waite, Tom</td>
<td>30</td>
<td>40</td>
<td>15</td>
<td>50</td>
<td>135</td>
</tr>
<tr>
<td>TOTALS</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>240</td>
<td>540</td>
</tr>
</tbody>
</table>

Task 1: Analog System
  Circuit research
Task 2: Analog System
  Circuit implementation
Task 3: Digital System
  Algorithm Research
Task 4: Digital System
  Programming DSP
Table 5.3 shows the actual personal effort contributed by each team member. Note that James Bishop left the team mid-year; therefore his hours are lower than the other team members.

Table 5.3 - Actual Individual Effort

<table>
<thead>
<tr>
<th></th>
<th>Task 1</th>
<th>Task 2</th>
<th>Task 3</th>
<th>Task 4</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aguado, Axel</td>
<td>22</td>
<td>28</td>
<td>36</td>
<td>30</td>
<td>116</td>
</tr>
<tr>
<td>Bishop, James</td>
<td>18</td>
<td>31</td>
<td>38</td>
<td>0</td>
<td>82</td>
</tr>
<tr>
<td>Raddatz, Chad</td>
<td>35</td>
<td>49</td>
<td>23</td>
<td>10</td>
<td>117</td>
</tr>
<tr>
<td>Waite, Tom</td>
<td>33</td>
<td>46</td>
<td>24</td>
<td>12</td>
<td>115</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>108</td>
<td>154</td>
<td>121</td>
<td>47</td>
<td>430</td>
</tr>
</tbody>
</table>

5.2 Other Resources

Table 5.4 shows the estimated other resources which appeared in our Project Plan.

Table 5.4 - Estimated Other Costs

<table>
<thead>
<tr>
<th></th>
<th>Team Hours</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>0</td>
<td>$150.00</td>
</tr>
<tr>
<td>Acoustic Lab services</td>
<td>10</td>
<td>Donated</td>
</tr>
<tr>
<td>EE Lab services</td>
<td>50</td>
<td>Donated</td>
</tr>
</tbody>
</table>

Table 5.5 shows the revised estimated other resources which appeared in our Design Report.

Table 5.5 - Revised Estimated Other Costs

<table>
<thead>
<tr>
<th></th>
<th>Team Hours</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>0</td>
<td>$150.00</td>
</tr>
<tr>
<td>Acoustic Lab services</td>
<td>35</td>
<td>Donated</td>
</tr>
<tr>
<td>EE Lab services</td>
<td>20</td>
<td>Donated</td>
</tr>
<tr>
<td>Caterpillar money</td>
<td>0</td>
<td>$1,000</td>
</tr>
</tbody>
</table>

Table 5.6 shows the teams actual other resources.

Table 5.6 - Actual Other Costs

<table>
<thead>
<tr>
<th></th>
<th>Team Hours</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>0</td>
<td>$150.00</td>
</tr>
<tr>
<td>Acoustic Lab services</td>
<td>8</td>
<td>Donated</td>
</tr>
<tr>
<td>EE Lab services</td>
<td>36</td>
<td>Donated</td>
</tr>
<tr>
<td>Caterpillar money</td>
<td>0</td>
<td>$1,000</td>
</tr>
</tbody>
</table>

5.3 Financial Resources

Table 5.7 shows the overall financial resources as presented in the Project Plan.
Table 5.7 - Total Financial Resources

<table>
<thead>
<tr>
<th>Cost w/ Labor</th>
<th>Cost w/o Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$1,000</td>
</tr>
<tr>
<td>Acoustic Lab services</td>
<td>Donated</td>
</tr>
<tr>
<td>EE Lab services</td>
<td>Donated</td>
</tr>
<tr>
<td>Aguado, Axel (@$15/hr)</td>
<td>$3,150</td>
</tr>
<tr>
<td>Bishop, James (@$15/hr)</td>
<td>$3,150</td>
</tr>
<tr>
<td>Raddatz, Chad (@$15/hr)</td>
<td>$3,150</td>
</tr>
<tr>
<td>Waite, Tom (@$15/hr)</td>
<td>$3,150</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$13,600</td>
</tr>
</tbody>
</table>

Table 5.7 shows the updated overall financial resources as presented in the Design Report. The $1,000 dollar quantity is a ceiling measurement; the total cost for the project cannot and will not exceed the budget given by Caterpillar.

Table 5.8 - Revised Total Financial Resources

<table>
<thead>
<tr>
<th>Cost w/ Labor</th>
<th>Cost w/o Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$1,000</td>
</tr>
<tr>
<td>Acoustic Lab services</td>
<td>Donated</td>
</tr>
<tr>
<td>EE Lab services</td>
<td>Donated</td>
</tr>
<tr>
<td>Aguado, Axel (@$15/hr)</td>
<td>$2,025</td>
</tr>
<tr>
<td>Bishop, James (@$15/hr)</td>
<td>$2,025</td>
</tr>
<tr>
<td>Raddatz, Chad (@$15/hr)</td>
<td>$2,025</td>
</tr>
<tr>
<td>Waite, Tom (@$15/hr)</td>
<td>$2,100</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$8,175</td>
</tr>
</tbody>
</table>

Table 5.8 shows the updated overall financial resources as presented in the Design Report. The $1,000 dollar quantity is a ceiling measurement; the total cost for the project cannot and will not exceed the budget given by Caterpillar.

Table 5.9 - Actual Total Financial Resources

<table>
<thead>
<tr>
<th>Cost w/ Labor</th>
<th>Cost w/o Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$1,000</td>
</tr>
<tr>
<td>Acoustic Lab services</td>
<td>Donated</td>
</tr>
<tr>
<td>EE Lab services</td>
<td>Donated</td>
</tr>
<tr>
<td>Aguado, Axel (@$15/hr)</td>
<td>$1,740</td>
</tr>
<tr>
<td>Bishop, James (@$15/hr)</td>
<td>$1,230</td>
</tr>
<tr>
<td>Raddatz, Chad (@$15/hr)</td>
<td>$1,755</td>
</tr>
<tr>
<td>Waite, Tom (@$15/hr)</td>
<td>$1,725</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$6,450</td>
</tr>
</tbody>
</table>

Table 5.9 shows the actual overall financial resources.

5.4 Schedule

The team’s schedule is divided into two parts. The first part spans the first (fall) semester, from August to December. The second part spans the second (spring) semester, from January to April. Figure 5.1 shows the schedule for fall semester. Figure 5.1 is reprinted larger in Appendix B for clarity.
As of April 6th, the team is on schedule. We are in the process of programming our DSP board, as well as further testing of the analog system.

Figure 5.2 shows spring semester’s schedule. Again, Figure 5.2 is reprinted larger in appendix B for clarity.
Figure 5.2 - Spring Semester Schedule

The major goal for the team to accomplish before the end of the year will be to finish coding the DSP system. Then the team will be able to test the digital system’s effectiveness in the same manner the analog system was tested.
6 Closure Materials
In this section, a summary of the project is presented, as well as contact information for everyone involved.

6.1 Project Evaluation
In order to objectively evaluate the success of the project, a number of milestones were defined in the project plan. The milestone will be evaluated according to the following criteria from the Project Plan.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) greatly exceeded</td>
<td></td>
</tr>
<tr>
<td>(2) exceeded</td>
<td></td>
</tr>
<tr>
<td>(3) met</td>
<td></td>
</tr>
<tr>
<td>(4) almost met</td>
<td></td>
</tr>
<tr>
<td>(5) partially met</td>
<td></td>
</tr>
<tr>
<td>(6) did not meet</td>
<td></td>
</tr>
<tr>
<td>(7) did not attempt</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 shows the project’s milestones and their respective grades.

Table 6.1 - Statement of Work

<table>
<thead>
<tr>
<th>Task 1 – Problem Definition</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtask 1a – Determine operating environment</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 1b – Determine final product</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 1c – Determine technologies used</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 1d – Determine constraints</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 1e – Determine end users, uses</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 2 – Technology Considerations and Selection</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtask 2a – Research DSP boards</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 2b – Research DSP algorithms</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 2c – Research analog solutions</td>
<td>2</td>
</tr>
<tr>
<td>Subtask 2d – Research passive control as a benchmark</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 2e – Research selection criteria</td>
<td>5</td>
</tr>
<tr>
<td>Subtask 2f – Research time commitment</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 2g – Select technology</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 3 – End-Product Design</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtask 3a – Determine functional requirements</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 3b – Determine non-functional requirements</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 3c – Write DSP algorithm in MatLab or similar software</td>
<td>5</td>
</tr>
<tr>
<td>Subtask 3d – Design analog system schematic</td>
<td>3</td>
</tr>
<tr>
<td>Subtask 3e – Document design process</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 4 – End-Product Prototype Implementation</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtask 4a – Build analog prototype</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 6.1 shows that nearly all of the project's milestones have been met or exceeded. There are however some notable exceptions that should be explained. End product testing is not yet complete at this point but is expected to be completed by the end of the semester. Similarly, end-product demonstrations have not been conducted yet since the team has not conducted the final meeting with Caterpillar nor has it presented to the Industrial Review Panel, both of which are expected to happen before the end of the term. Also, end-product documentation has been deemed unnecessary since it would duplicate already existing documentation. Overall, the team has almost met the milestones defined at the beginning of the term and as such the project will be a success once the final milestones are met.

### 6.2 Commercialization
The project was defined as a learning experience by Caterpillar and as such, the team sees no potential commercialization for this project.

### 6.3 Recommendations for Additional Work
As stated in the executive summary, additional senior design projects could be developed to incorporate ANC technology. An ANC system could be implemented in the ALC of
Coover Hall to eliminate the noise made by the fans in that room. A system could also be implemented aboard Cy-Ride buses to reduce the noise level inside the bus. Basically, any noisy environment could benefit from the inclusion of an ANC system; however, the scope of the project would possibly be too large for a year-long assignment, an ongoing assignment would be more appropriate.

6.4 Lessons Learned
A number of things went well in this project, notably the development of the analog circuit. The team located schematics for a circuit designed to do exactly what was needed. This allowed the analog circuit design and implementation to proceed much faster than expected.

There were also some difficulties encountered, such as the project being poorly defined, and losing a team member. Both difficulties slowed progress but were not detrimental to the success of the project.

The project provided an opportunity for the team to learn about various Active Noise Control algorithms, including analog phase inversion, and Least Mean Square. The analog circuit provided lessons in electrical circuit debugging. The digital system required learning how to use a DSP evaluation board and IDE. If the project were done over again, the team would begin work on the digital system sooner so as to better understand the interface between the analog world and the digital board.

6.5 Possible risks and risk management
If a member of the design team were to leave the project for some reason, the team would ask him to submit any useful notes pertaining to the project. If the leaving team member completed an investigation or experiment on his own, he would tell the others what he did and what he learned. The remaining team members will proceed to the best of their abilities to accomplish all of the goals originally planned for the entire team to complete.

If the project becomes too complex for the team’s current expertise, more research will be needed. This added research time would cut into the time required to further refine the prototype. If a certain part of the prototype is impossible to design in the time allowed, purchase of an existing part may be required.

The team did encounter the loss of a team member. However, the team had maintained good communication throughout the project so that the loss did not result in a great setback. The team was successful in managing this risk.

An unanticipated risk was the performance of our DSP board. We did not expect to have such problems implementing the digital solution. To handle this risk, the team focused on Matlab as a means of proving that the algorithm we had developed worked correctly.

6.6 Caterpillar Contact
Bill Allen
Phone: 309-578-6584
6.7 Faculty Advisors
Clive Woods
Phone: 515-294-3310
Email: cwoods@iastate.edu
Address: 2128 Coover Hall, Ames, IA 50011-3060
Zhengdao Wang
Phone: 515-294-8362
Email: zhengdao@iastate.edu
Address: 3134 Coover Hall, Ames, IA 50011-3060

6.8 Team Members
Axel Aguado – Computer Engineering
Email: aaguado@iastate.edu
James Bishop – Electrical Engineering
Email: jdbishop@iastate.edu
Chad Raddatz – Electrical Engineering
Email: craddatz@iastate.edu
Tom Waite – Electrical Engineering
Email: twaite@iastate.edu

6.9 Conclusion
When the team first signed on for this project, an assumption was made that the system designed would be specifically designed for Caterpillar. After corresponding with our contacts at Caterpillar, however, we were informed that the system did not necessarily have to be so specific to their business, and in fact, was intended to be an exercise in research and lab work. The project has been a great learning experience for all team members. The team gained new technical knowledge such as noise control techniques, as well as non-technical knowledge such as project management.

The team was successful in designing, implementing, and testing the analog solution to the ANC problem. The digital solution was not completed because of interfacing issues with the selected analog devices board, but the algorithm was written and simulated and Matlab and it works correctly. Both systems provide significant reduction in background noise.

Ultimately, the team’s recommendation to Caterpillar is to implement an analog solution similar to what we have described in this report. Digital solutions to ANC are appropriate for complicated systems in large spaces, where many computations must be made to correctly cancel noise, but DSP is inappropriate for solving the headset problem. The low cost, simple implementation and good performance of the analog system far outweighs the digital solution, which is cumbersome, expensive, and difficult to implement.
Appendix A - PSpice Simulation Results
The result of the PSpice Circuit simulation is included in this appendix.

Here is the full parts list for the circuit:
- R1 – 4.7Kohm
- R2, R3 – 2.2Kohm
- R4, R5 – 1M
- R6, R7 – 1Kohm
- R8, R9 – 33Kohm
- R10-13, R15-18 – 10Kohm
- R14, R23 – 100Kohm pot, dual-gang, linear taper
- R19, R20 – 100Kohm
- R21, R22 – 47 ohm
- IC1-3 – NE5532 dual audio op-amp
- C1 – 33uF, 25WVDC, electrolytic capacitor
- C2, C3 – 0.01uF Mylar capacitor
- C4, C5 – 10uF, 25 WVDC, electrolytic capacitor
- J1-3 – Audio jacks, 1/8-inch, stereo
- S1, S2 – DPDT toggle switch
- B1, B2 – Battery, 9 volt
- Microphones – Digi-Key P9967-ND or similar

For the purposes of the PSpice simulation, only one half of the circuit was tested. Figure 7.2 shows this circuit that was tested. It is one half of the full stereo circuit shown, so this circuit is only a mono circuit. For the purposes of the simulation, this will be sufficient to judge the performance of the full circuit.

For clarity, the plots and circuit diagrams are all shown in landscape format. Here is a list of the figures included in this appendix:
- Figure 7.1 - Full Stereo Analog Circuit
- Figure 7.2 - PSpice Circuit
- Figure 7.3 - 20 kHz Transient Response of Input Amplifier (1st Stage)
- Figure 7.4 - 20 kHz Transient Response of Inverting Amplifier (2nd Stage)
- Figure 7.5 - 20 kHz Transient Response of Output Amplifier (3rd Stage)
Figure 7.1 - Full Stereo Analog Circuit
Figure 7.2 - PSpice Circuit
Figure 7.3 - 20 kHz Transient Response of Input Amplifier (1st Stage)
Figure 7.4 - 20 kHz Transient Response of Inverting Amplifier (2nd Stage)
Figure 7.5 - 20 kHz Transient Response of Output Amplifier (3rd Stage)
8 Appendix B – Team Schedule

Figure 8.1 - Fall Semester Schedule
Figure 8.2 - Spring Semester Schedule
Appendix C – Matlab LMS Code

clear all; close all;

order = 20; % filter order
N = 2000; % simulation length
DELAY = 20;
a=randn;
b=randn;
c=randn;
desired = zeros(1,N);

output = zeros(1,N);
error = zeros(1,N);

noise = zeros(1,N);
for i = 1:(N)
    noise0(i) = a*sin((100*pi/N)*i) + b*sin((125*pi/N)*i) + c*sin((95*pi/N)*i); % create noise
end
noise(DELAY:N) = noise0(1:N-DELAY+1); % delay the noise
mu = .05/(a^2+b^2+c^2);
w = 0.25*ones(1,order);
for i = order+1:N-1;
    output(i) = w(1:order)*((noise(i-order:i-1))');
    error(i) = desired(i) - output(i) - noise0(i);
    w(1:order) = w(1:order) + mu*noise(i-order:i-1)*error(i);
end;

% End of algorithm
% The rest of this is code to create the plot

error = 20*log10(abs(output+noise0));
for i=1:149
    avg_error(i) = mean(error(1:i));
end
for i=150:N
    avg_error(i) = mean(error(i-149:i));
end

figure(1);
plot(avg_error,'.r'); title('LMS Simulation');
hold on;
plot(error,'b');
axis([0 N -60 10]); xlabel('Samples'); ylabel('Error (dB)');
db=10*log10(sum(error(N/2:N).^2)/(sum(noise0(N/2:N).^2)))/sum(error(N/2:N).^2)/sum(noise0(N/2:N).^2))
10 Appendix E – Bibliography

Analog circuit:

DSP Board Information:
Texas Instruments
  TAS3004/3002 Evaluation Module
  TAS3103 Evaluation Module
Motorola
  DSP56364
Analog Devices
  ADSP-BF533