In-Room Noise Cancellation with Wall-Transmission Detection

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I. INTRODUCTION

There has been a substantial increase in construction at Tennessee Technological University [1]. This has come with a substantial increase in noise. In order to alleviate this increase, this project proposes an Active Noise Control solution. Active noise control is a heavily researched area of acoustics and signal processing. A great example is the noise-canceling functionality of modern headphones. In order to cancel the sounds from outside the classroom, this project will focus on the noise that is transmitted through the walls of that room. This project proposes using laser position-sensoring technology. It can be precise and when the displacement is measured over time and can get an accurate analog of the sound carrying through that wall. Combining these concepts, this project proposes a new approach to noise-canceling for use in classrooms.

II. THE PROBLEM

Studies have shown that many schools, especially those in urban environments, are exposed to heavy noise regularly. Construction and road traffic grow as cities urbanize, and so does the noise generated. More consistent noise such as the high hums of AC systems can also be distracting. Not only are they distracting but some studies have even shown that constant noise exposure in classrooms can have long-term effects on the learning trajectory of primary school-aged children [2]. According to a small poll of electrical and computer engineering students and faculty at Tennessee Technological University, the recent increase in on-campus construction has led to a higher rate of self-reported distraction in the classroom. Other environmental sounds such as the AC/heater system and students in the hall were also mentioned as usual distractions, though not as often. Several solutions to high noise exposure exist. Passive solutions such as sound-proofing walls can quickly get expensive but also cannot adapt to ever-changing soundscapes. In order to implement an adaptable noise control system, three issues will have to be solved: the basic implementation of ANC (Active Noise Control) systems, obtaining precise sound input data to which to apply the system, and using effective adaptive algorithms.

A. Background

1) Basic Principles of Noise Control: There are two common methods for implementing noise control: passive and active noise control. Both of these methods are effective but have differing functionalities. Passive noise control is executed through the use of sound-dampening materials that block out certain frequencies of noise. This could be foam coverings on walls or headphones that block sound by creating a seal around ones ear so as to not let the noise pass through. Active noise cancellation works in a different way. Instead of isolating your ears from ambient noise, ANC uses technology to reverse and cancel out various noises. Through an active noise cancellation device, sounds are filtered through a digital signal processor and replayed back through a speaker with equivalent magnitude/strength but opposite phase. By fully reversing the phase of the noise and emitting it at the same strength, a net zero signal is created, effectively canceling out the noise. This is called generating anti-noise [3].

To understand Active Noise Control it is important to note the different ways in which it is implemented. For the case of this design, both a feed-forward and feedback implementation has been examined. For a feed-forward ANC system, sound is picked up by a reference sensor, and then the sound correction is based on that reference signal [4]. Figure 1 shows a single channel feed-forward ANC system. The primary noise feeds into the reference microphone which then goes through the controller and out the speaker.

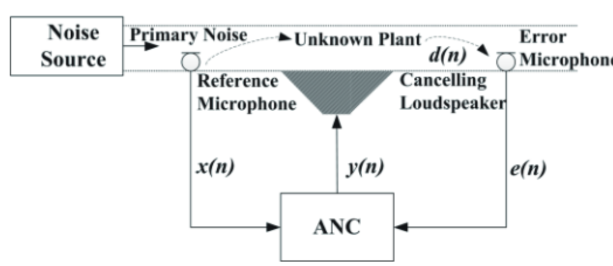

Fig. 1. Single channel feed-forward system [4]

With this type of system, the signals follow a direct path through the system and does not self-correct based on error. It does, however, pick up sounds earlier on, giving it more time to respond and generate an anti-noise. A disadvantage of a feed-forward system is that it doesn't hear the anti-noise that it is producing. This runs the risk of producing a wrong output that does not attenuate the noise. This system also works with a smaller range of frequencies so it will block out some types of noise but not others. A feed-forward system also works to reject noise disturbances before they have a chance to affect the output. A feedback control system differs in that it feeds a feedback/error signal back into the system which acts as a secondary input to help the system correct itself [5]. Figure 2 shows a single channel feedback system. As shown there is no reference microphone and instead just an error microphone based on the noise from the loudspeaker. Feedback focuses on

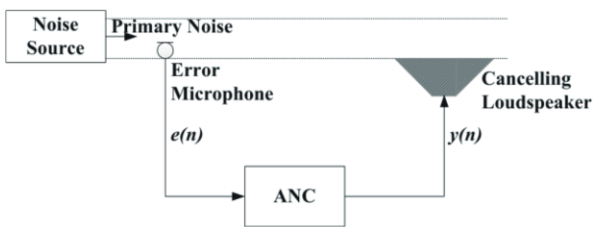

Fig. 2. Single channel feedback system [4]

the output of the system rather than the input, meaning it can detect more errors than a feed-forward system could. One of the disadvantages to this method is that by sending feedback in as input, one runs the risk of the system trying to correct its own anti-noise.

2) Measuring the Transmission of Sound through Walls: Lasers can be used to measure sound by shining the laser on a reflective surface that covers the medium. Sound causes vibration in a medium which creates a displacement in the beam of a laser. This displacement can be measured by using a photo-diode which converts the laser light into an oscillating current. The oscillating current can then be converted into a voltage using specific electronic circuitry. This will allow the sound vibrations to be analyzed electrically [6]. A position-sensitive detector (PSD) works very similarly to a photodiode but is specially designed to measure the displacement of laser light with much higher accuracy. A PSD is essentially a P-N junction that creates a photo-current due to the photovoltaic effect. The two-dimensional PSD will be of the most interest. The two-dimensional PSD works by mapping the incoming signal to a set of 2D coordinates. The X and Y components of this set are formed by a pair of electrodes each. There are two main types of PSDs, lateral effect PSDs, and segmented PSDs [7]. The lateral effect PSD consists of planar photo-diodes that have no gaps and delivers an exact output of the displacement of the light. Light on the surface of the lateral effect PSD will generate photo-currents that travel from the resistive layer to the device's contacts. The segmented PSD consists of photo-diodes that are divided into two or four segments, which has a gap separating them. The segmented PSD has higher accuracy, but the trade-off is the light cannot be smaller than the gap between the segments [8]. The lateral type PSD is of most interest in this project due to its noise control capability [7].

The most important aspect of a PSD is position detection. The position of the light can be calculated by taking the photo-current removed from each electrode. If the light is directed towards the origin, the photo-currents from the electrodes are equivalent. Mathematically this can be represented by the following equation:

$$X_m = \frac{(I_{x_1} - I_{x_2})}{(I_{x_1} + I_{x_2})}(\frac{L_x}{2})$$

where X_m is the calculated position of the incident light on the $x-$axis. I_{x_1} is the output current from electrode x_1, I_{x_2} is the output current from the electrode x_2, and L_x is the resistance on the surface of the lateral effect PSD which will generate photo-currents that travel from the resistive layer to the device's contacts.

A couple of other quantities to note are X_i which is the actual position of the incident light, and $E = X_i - X_m$ which is the error of the PSD [9]. This is repeated for the $y-$axis.

3) Using Machine Learning to Create an Adaptable System: Machine learning is a wide branch of computer science and mathematics. Machine learning allows a computer to make decisions and recommendations based on data and statistics. The reason this is useful to apply to ANC is due to the inherent randomness of natural sound. Most sounds in real life are not simple cosine functions but instead have harmonics and distortion. In addition, most sounds are quick and random. Machine learning has shown promising results in alleviating this issue. Due to the vast nature of machine learning, many types of learning exist. On the simpler side is linear regression. Linear regression allows a computer to alter the parameters of a linear system in order to find a solution with minimal error. This is achieved through gradient descent. Gradient descent is an iterative optimization algorithm that searches for minima in a function [10]. In regards to linear regression, gradient descent changes the "weights" of input features, similar to coefficients in a linear equation. By following the partial derivative of the error function, it is able to decrease the error for a certain feature until the derivative equals zero. This is equivalent to finding a minimum of that feature's error function. It then iterates this for all features [11].

Another type of machine learning is reinforcement learning. Instead of using gradient descent in order to minimize error, reinforcement learning utilizes rewards and punishments. The computer interprets the environment and decides on an action. This action will affect the environment and depending on the effect, the computer will be rewarded or punished. This will affect future actions taken by reinforcing actions that lead to wanted results [12].

The final type of machine learning that is mentioned in this proposal is supervised deep learning. Supervised learning is shown models and told labels. Since the labels are known, the learning model is able to reduce error. Deep learning is an abstract type of machine learning and is based on the human mind. It is comprised of artificial neural networks. These are comprised of node layers that have a weight and threshold attached. If a node's output is above its threshold, it will activate and send its data. Each individual node acts as a linear regression model [13].

B. Goal of This Project

The following is the main goal of this project:

– Attenuate outside noise by at least 10-20 dB in room 314 of Brown Hall at Tennessee Technological University with a "quiet zone" that encompasses the teacher's and students' desks.

C. Stakeholders

This project will have two main types of stakeholders: interior and exterior. Interior stakeholders will have access to the team's progress at their request along with access to the GitHub repository. Occasional meetings with management in the form of the project supervisor will be held. Another stakeholder will be the ECE department of Tennessee Technological University since it will be providing funding. Any request for funding will have to be signed off by the project supervisor.

- **Interior Stakeholders**
  - Project Team
  - Project Supervisor - Prof. Roberts
  - Funding - ECE Department

External stakeholders have been surveyed for specifications. They will also have access to progress if requested.

- **External Stakeholders**
  - Students of Brown Hall
  - Faculty of Brown Hall
  - Tutors that use Brown 314

D. Specifications

The following are specifications placed upon the design project by our stakeholders:

– Shall be easy to use. Since the system will be used by students and faculty alike, it should be easy to operate. In remedy, it should operate off of a simple on-off switch. It should also operate on the 120V outlets of the room.

– Shall not be a visual distraction. If the system is visually loud or bold, it could itself become a distraction. We want to limit this by having the system be as discrete as possible. This will be accomplished by mounting parts of the device high on the wall.

E. Constraints

The following are constraints placed upon the design project by our stakeholders:

– Shall not emit sounds that are harmful to the human ear. Noises above 90 dB can harm the human ear if played for extended periods of time, and sounds above 120 dB will immediately cause harm. With this in mind, the device will not be able to emit amplitudes of 90 dB for more than 2 hours at a time.

F. Standards

The following are potential standards and regulations to be followed:

Z136.1, American National Standard for Safe Use of Lasers - This standard sets regulations to ensure safety when utilizing a laser that operates between the wavelengths 180 nm and 1000 μm. This standard allocates different types of lasers by its possible ability to cause bodily harm. The classes that these types are allocated to are Class 1, Class 1M, Class 2, Class 2M, Class 3R, Class 3B, and Class 4. Class 1 is the least dangerous due to its inability to cause hazard, while class 4 requires strict controls in order to lower the risk of causing harm to skin and eyes [14].

Z136.5, American National Standard for Safe Use of Lasers in Educational Institutions - This is a standard pertaining to the usage of any lasers in an academic setting. The Z136.5 standard applies to public schools and ranges up to any usage of lasers at the college level. This standard was meant to apply to all levels of education except graduate level research laboratories. The wavelength ranges that are important with this standard are the ultraviolet, visible, and infrared regions of the electromagnetic spectrum. In more detail, the range from 0.18 μm to 1 mm. If at any point there is a laser in class 3B or 4B being used, there needs to be a designated Laser Safety Officer (LSO). All schools need to know if there is equipment that could potentially accommodate a Class 3B or Class 4 laser and extra precautions need to be made. Institutions need to have a plan of action prepared in case of any injury due to laser hazards. This standard knows that not all institutions have an assigned LSO but advises to have at least a teacher who has had some form of laser training present [15].

Z136.8, American National Standard for Safe Use of Lasers in Research, Development, or Testing - This standard's existence gives guidance for safe use of lasers in research, development, and testing environments, where safety controls common for a laser could be nonexistent or disabled. This standard notes that the schools laser safety training is nothing but an awareness step. Actual awareness comes from mentoring known as on-the-job training. It is important to document activities dealing with on-the-job training. Commercial lasers are not always used in research and the rejection of some of the commercial laser safety controls are justifiable by authorized and trained users [15].

OSHA – Occupational noise exposure 1910.95 - This sets a limit on the amount of exposure of decibels people can have based on an average 8-hour work day. OSHA's limit is 90 dBA for an 8-hour day. This will be important to note considering in a school setting, students and faculty can be in classrooms for several hours in a day. If the device is too close or exceeds the limit then the system could put several people in danger [16].

IEC 62368-1 - This standard is in relation with audio/video, information and communication technology equipment. This standard was made to give designers more versatility in designing the product by using hazard-based safety engineering principles. The principles reveal the potential hazards as energy sources capable of producing harm while finding ways to prevent it from happening [17].

IEC 60950-1 - This standard deals with the safety of information technology. The standard is used with wired or battery-powered machines with voltages not exceeding 600 V. This standard should help prevent injury to both people and property. Neglecting this may cause harm, electric shock, fire, and mechanical. instability [17].

IEC 60065 - This standard protects against fire, electric shock, and injury in respect to audio, video, and any other similar apparatuses. This should cover any potential harm coming from a power supply the group intends to use. There will be more provisions with respect to isolation, insulation, limiting current and voltage, and measures to increase resistance to fire [17].

G. Survey of Possible Solutions

1) Possible Solutions to Implement an ANC system: ANC works through the use of signal input, normally microphones, signal processing, normally through a DSP or equivalent chip, and signal output, normally speakers. The input signal is passed through a DSP that filters and processes the noise so that it can be reversed and played back through the speaker at an equal magnitude. The exact filter specifications are unknown while designing, which is why an adaptive algorithm called Least Mean Square (LMS) or Filtered-X Least Mean Square (FxLMS) is used. These algorithms update the constantly changing filter coefficients so that they can be reduced to a size where the error is as minimal as possible [18].

Since feedback and feed-forward ANC implementation both have their strengths and weaknesses, a hybrid ANC system is going to be used. The feed-forward system will be used to process the general noise of the room through the reference microphone, and the feedback part of the system will work to reduce the noise of random or unforeseen noises. By including both a reference and error microphone that both feed in to a controller, a more accurate anti-noise can be created [19]. An example of feed-forward and feedback systems being used can be seen in many of today's noise cancelling headphones. With feed-forward, the microphone is located outside the headphone and attenuates the incoming noise, while with feedback the microphones are inside the ear cup and attenuate based on the noise that the user is hearing. A hybrid noise cancelling headset will use both microphones to create the strongest noise cancellation, since all different sounds and angles are being accounted for [19].

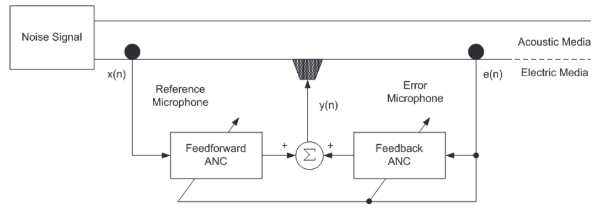

Fig. 3. Hybrid ANC system [19]

Figure 3 shows both a feedback and feed-forward system working together to create an anti-noise at the loudspeaker.

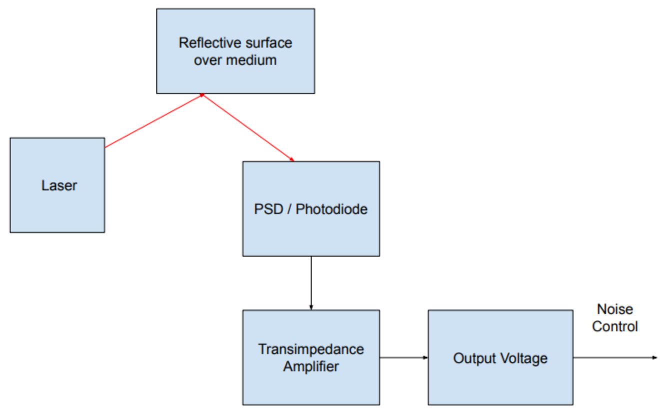

Fig. 4. Block Diagram of Laser Sound Measurement System

2) Using a Laser to Detect Noise Transmitted through a Wall: There are two solutions that have been researched in depth. The first solution is to shine a laser at a reflective surface onto a normal photo-diode. This photo-diode will be connected to a circuit referred to as a trans-impedance amplifier which is a circuit that changes a current to a voltage. The trans-impedance amplifier utilizes normal operational amplifiers. The exact configuration that will be implemented at this stage is still unknown, but most likely the configuration of the amplifier will be either inverting or differential [6]. The second solution is to utilize a PSD. This would be more expensive but lead to higher accuracy in the measurements along with the reliability of integrated circuitry from a respectable manufacturer.

3) Survey of Machine Learning: As stated earlier, the ability of an ANC system to adapt is important due to the inherent nonlinearities present in reality. Noise rarely presents itself as static white noise. A system has to be able to adapt when different frequencies begin to "overpower" other frequencies. One way of doing this is through the LMS and FxLMS algorithms. These algorithms could be classified as a type of linear regression model. These are easier to implement than more advanced types of adaptive noise control models and can be programmed directly on a DSP chip. A disadvantage appears as nonlinearity increases, however [20]. These algorithms are great for steady-state noises such as AC/Heater systems.

Since the main category of noise we are trying to control is construction — which tends to be harsh and jarring — slower adapting is not the correct approach. More complex models through deep learning are the most promising solution. Supervised deep learning through CRNs (Convolutional Recurrent Networks) is capable of modeling very complex nonlinear relationships. This even allows the system to be trained to attenuate a noisy voice signal and allow just the voice to come through. It also excels in modeling quiet zones as opposed to spatial points [21]. This level of complexity comes at the cost of high latency and high amounts of memory. However, the paper by Hao Zhang and DeLiang Wang uses delay-compensated training. This means that the model can "predict" future input frames by comparing the current input to future-related inputs. In order to model a system that complex, we would have to use parallel computing or a computer cluster in order to have the information processed in a reasonable amount of time.

In order to tackle both changes in steady-state and complex irregularities, a hybrid approach has also been suggested [22]. Since FxLMS can be directly programmed into the DSP, it can be used to adapt to a change in steady-state, such as the sound of rain, which is a new noise but manifests over long periods. A less complex deep learning model is also implemented to assist with complex irregularities such as the irregular sounds of an excavator. These are then combined. This offers lower latency and better response times. It still requires lots of memory and data to train but does not have to train as much or as frequently as a solely deep-learning ANC system.

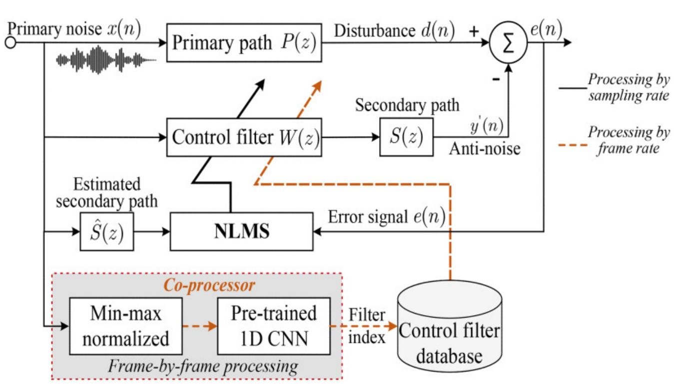

Fig. 5. Block Diagram of a Hybrid SFANC-FxNLMS ANC system [22]

Figure 5 is the block diagram of a hybrid deep-learning and LMS-type algorithm by Z. Luo, D. Shi and W. -S. Gan. The general diagram will apply to our project but with different algorithms.

H. Challenges

Certain challenges are apparent from the start: lack of experience of the team, limited time, limited budget, and small team size. Other less obvious challenges also will arise. Powering the system without distorting any signals will be a challenge.

I. Summary

In summary, this problem of reducing the outside noise in room 314 has 3 main components. The basic implementation of an ANC system, a method of measuring the transmission of sound through exterior walls, and creating a system able to adapt. This must be done while meeting the specifications and constraints given by the stakeholders. In addition, the solution must also meet standards and regulations.

III. Looking Toward a Solution

A. Unknowns

A big component of the noise the device will reduce is nearby construction sounds outside of Brown 314. During the timeline of this project, the construction sounds may change or move elsewhere, which will make testing the device difficult. Another unknown is access to circuit-testing equipment. While the group plans on using a nearby laboratory in Brown, the room is not always open to public access and is occasionally occupied.

B. Existing Solutions

One example of an ANC device was showcased using a system that worked for an individual sitting in a chair. This system required lasers pointing inside reflective tape inside a person's ear. This design was able to attenuate human voice frequencies by 10 to 20 dB [23].

Another solution to distracting sounds is to implement a speaker system as part of a window to play anti-noise to attenuate the constant sounds heard when near or in a city. The most effective frequencies it was able to create anti-noise for was between 300 to 1000 Hz. This process focuses on reducing constant sounds like cars' engines instead of random construction and other ambient sounds our device will reduce [24].

One solution involves using a large ANC device directly at the source of sound. ANC devices can be placed on large construction machinery exhaust outlets to reduce the sound they emit. Low frequency machinery such as this have had noise attenuation by up to 20 dB [25].

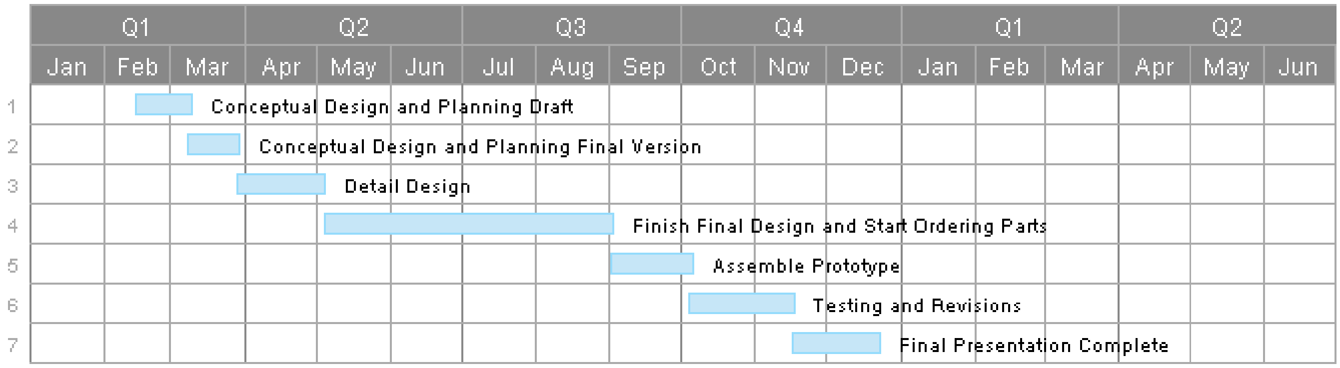

Fig. 6. Expected Timeline

C. Measures of Success

A measure of success will be the ability of our system to correctly process its inputs. This can be tested by measuring the output of the system and seeing if it equals the negative of the targeted frequencies of the input. If the output of the system is added with the input of the system, these signals should cancel out at the targeted frequencies. The team can use this fact to check if the transfer function of our system is operating correctly. The other measure of success will be the accuracy of the measurements using the PSD or photo-diode, which can be done by performing different experiments, taking an average, and eliminating discrepancies such as noise until we get a good R^2 value for the data. The last and most important measurement of success will be whether the goal is achieved. This will be done by measuring the level of sound right inside of the wall, and comparing that to the level of the sound at the noise-controlled areas, which will be a decent approximation to the attenuation due to our system.

D. Broader Implications, Ethics, and Responsibilities as Engineers

Since our system will be able to pick up all local sounds, special care will have to be taken in order to provide an ethical level of privacy. Since our system will involve the use of artificial intelligence, with the potential of being run through a separate machine, there is a concern that this sound information could be breached, allowing the unauthorized acquirement of personal information. The availability of this information to police through a court order should also be addressed [26] [27].

The accessibility of our system is also an ethical concern. The system should not cause any hindrance to people with or without disabilities.

IV. RESOURCES

A. Personnel and Skills

In order to successfully create an in-room noise cancellation device, skills with lasers, microphones, noise filtering, signal processing, and machine learning are required. Each team member has a similar set of basic skills involving circuit design and analysis. As the more specialized parts of the design are incorporated, each team member's specific skills, listed below, will be implemented to further the success of the project.

- Jalene Joyce
  - Transmission
  - Heat distribution
  - Power management
- Dylan Mitchell
  - Optoelectronics
  - Audio filtering
  - Soldering
- Carson Pope
  - Signal Processing
  - MATLAB
  - Machine Learning
- Caleb Turney
  - C++
  - Digital Logic Design
  - Power Management
- Jared Vega
  - Digital communication
  - Synchronous logic
  - Embedded Systems

B. Budget

Our estimated total cost will be between $300 - 350. Figure 7 shows an itemized list breaking down the total.

C. Timeline

The group expects to complete this project in about one year. Figure 6 displays the constant progress we expect to make. The group will start by considering specific designs to utilize, develop an intermediate build, and end with final adjustments and a deliverable product by December.

V. CONCLUSION

To combat distracting sounds coming from outside of Brown 314, the team proposes an active noise control device. The team proposes to create an easy-to-use device that reduces

Component	Price ($)
Wires	10
5 mW red laser	30
PSD (Position-Sensitive Detector)	80
Reflective Tape	10
OP Amp (UA741CP Qty. 5)	2
Microcomputer	50
Speakers	40
Small components	10
Microphone	45
Unknowns	50
Total	327

Fig. 7. Proposed Budget

outside noise. With information gathered from lasers, microphones, and processed with the aid of machine learning, the team believes a successful noise control solution can be implemented.

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