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HEARING AID REDESIGN

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ABSTRACT

The intent of this project is to design and deliver an optimized, rechargeable, ergonomic audio accessory that is appealing to both hearing and hard-of-hearing populations. The device should amplify and process sound, allow for rechargeable power, and be ergonomic and aesthetically appealing. This project hopes to de-stigmatize hearing aids as medical devices, and to provide the hard-of-hearing market with an alternative device with similar features in a new form. Based on test results, 92% of surveyed users identified the device as something other than a hearing aid; 91.8% of hearing users surveyed would use the device for Bluetooth capabilities or music listening. The project is to serve as an initial proof of concept for future MSD projects to focus more seriously on the sound processing and the electrical construction of the device. The On Semi RHYTHM R3910 Digital Signal Processor is suggested to replace the current Digital Signal Controller, which will help reduce the size of the product and allow for more advance sound processing techniques. Future students should also focus on Bluetooth integration.

INTRODUCTION AND BACKGROUND

A hearing aid is an electronic audio amplification device worn by hard-of-hearing individuals. According to the National Institute on Deafness and Other Communication Disorders (NIDCD) [1], only 1 out of 5 people who could benefit from a hearing aid actually wears one. The root cause of this statistic is unknown; based on preliminary research conducted by an RIT Industrial Design team during the Spring of 2012, one can argue that potential users fail to use the device due to price, unattractive visual design, or as a result of the stereotype associated with hearing aid use [2]. Designers Paula Garcia, Nick Kelemen, and Nanxi Yu, proposed an alternative design to the standard behind-the-ear style hearing aid device with the goal of redefining the visual presence of hearing aid technology, and to offer additional device functionality. The proposed design was intended to attract both hearing and hard-of-hearing users. By blending the user populations, the product will help destigmatize the device as a medical device and increase device acceptance as an attractive technology in society.

The industrial design product concept was approved as a multidisciplinary senior design project by the College of Engineering in the fall of 2012. The first iteration of the project is intended to serve as a proof of concept for future projects. The project goal was to deliver a working prototype that amplifies sound, includes a rechargeable power source, and incorporates an enclosure that is optimized based on ergonomics and user experience. The project was funded by a $5000 Effective Access Technologies Grant to cover design, manufacturing, and testing costs.

DESIGN METHOD

Assumptions & Constraints

This device should be competitive with current products on the market in cost and weight. The functionality of the device should include all major features found in current hearing-aid devices including the ability to amplify sound and control volume output. Due to the proprietary nature of the hearing-aid industry, little guidance is provided for the hardware and software product design. The team is also constrained by the size of the device. In order to maintain a competitive edge, the design of the product must be miniature. Due to monetary, skill, and time constraints, the delivered product may appear larger than ideal. Future iterations of the project should focus on optimizing and decreasing the size of the product while improving the performance and functionality.

A survey was conducted to gain user feedback on current hearing aid use [3]. There were a total of 21 responses; all individuals surveyed had more than 5 years experience with hearing aid use. The male to female percentage was from approximately 76 % to 23.8 %. Out of the 21 users, 52% wore a behind-the-ear hearing aid, while the remaining only wore a cochlear implant or none in the other ear. There was 85.7 % users who reported 10 hours or more of hearing aid use and 76.2 % overall satisfaction. When users ranked importance of features in hearing aids, performance (71.4%), and User friendly (61.9%) ranked highly followed by comfort (57%). Users were also surveyed for features taken into consideration when shopping for a new hearing aid. The results showed user friendliness (76.2%), performance (71,4%) and comfort (71.4%) were ranked highly and price (28.6%) ranked low. However, 68.4% of those surveyed preferred a "hidden" device less visible to the public. The customer needs and design was focused around the survey results; performance, user experience, and user comfort are the driving design constraints.

Needs & Specs

The primary function of the device is the ability to amplify and modify sound for high quality output. Due to the proprietary nature of the hearing-aid industry, no preliminary code was available to verify the complexity of sound processing and amplification. Initial hearing aid research and testing was conducted by using a MatLab program that simulated a digital hearing aid. The MatLab simulation amplified sound and reduce noise for a user with “ski-slope” hearing loss, a common form of hearing loss – the inability to hear high frequencies [4]. The program initializes a frequency shaper to break the users hearing loss profile into a set of piecewise functions and calculates the required gain for each section. A Fourier Transform moves the input signal from the time to frequency domain, where the calculated gain is added. An Inverse Fourier Transform returns the signal to the time domain. An amplitude shaper removes noise and confirms the adjusted signal is in within an acceptable (safe) range. Figure 1 displays the difference between an unaltered signal and the adjusted signal. The success of this simulation confirmed the team’s ability to create program that would successfully process and amplify signals captured by the device.

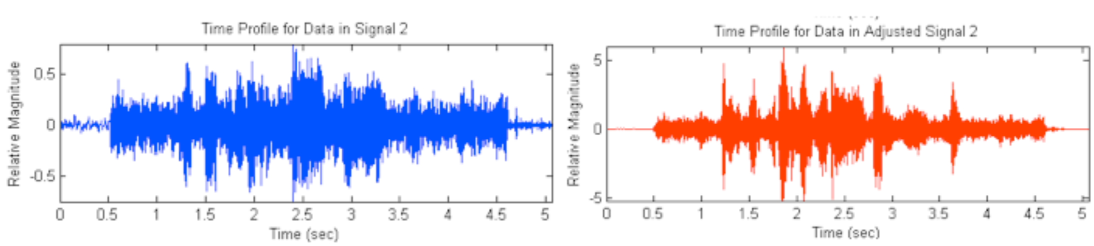

Figure 1: Original Signal (Blue), Adjusted Signal (Red)

The device should detect a minimum of 30dB of sound, the lowest decibel level on the range of normal hearing. The device should amplify all frequencies between the 85 and 8000 Hz. To comply with the customer safety needs, the maximum amplification allowable is 90dB. Additionally, the range of volume adjustment should be controlled to protect the user. To do this, the “normal” volume level as determined by the users audiologist, will be the median volume level and the amplification program will allow the user to adjust 5 steps above and below this level. The outer temperature of the device must not exceed 95 degrees Fahrenheit.

The design of the audio device must include the ability to recharge the device power source through USB 2.0 port. This need is validated by customer feedback preferring rechargeable power options to disposable batteries used in current product designs. The time to charge the device from zero percent power should be less than thirty minutes. The life of the battery must be no less than 48 continuous hours.

In order to deliver a successful product, the device must be appealing to both hearing and hard-of-hearing populations. Additionally, the device should not draw attention to the user as a hard-of-hearing individual. These needs will be verified through a series of user focus groups and customer feedback surveys. Of the surveyed population, eighty percent should identify the device as something other than a hearing aid (such as a Bluetooth or wireless headset); seventy-five percent should show a preference for the new device over the behind-the-ear style hearing aid; and seventy percent should confirm that they would use the device for a function other than sound processing and amplification, such as answering phone calls or listening to music. User comfort and interaction with the device is also a key area of interest in the design of the product. The device must fit users between the 10^{th} and 90^{th} percentiles. The weight of the earpiece should not exceed 12 grams when fully assembled.

In order to maintain a competitive edge in both the audio accessory and hearing aid industries, the cost of manufacturing should be examined. The cost of the device should not exceed one thousand dollars. The cost to manufacture will be estimated based on the components used in the prototype, assembly and manufacturing studies. Currently, digital hearing aids cost an average of $1500, with top of the line devices ranging from with top-of-the-line devices costing $3000-$5000 [5]. In order for this device to compete with the overall hearing aid market, the price should be relatively competitive with existing devices.

DESIGN PROCESS

Enclosure Design

The enclosure is a three-piece system that allows the user to use the device in two different orientations (Figure 2). The primary orientation (Figure 2a) is considered to be when the user wears the round enclosure and battery enclosure. The combination of these parts allows the user to process sound and run the programs stored on the device. The intent of this design is to mimic wireless ear bud headphones. With the transfer module attached, Figure 2b, users are able to access Bluetooth functionalities. This iteration of the project is not required to deliver a device with Bluetooth integration; this functionality is intended for a future iteration of the project, but the physical representation transfer module is included to explore aesthetics, user acceptance, and assembly.


(a) (b)

Figure 2: (a) ear bud orientation, (b) transfer module attached

During the design process, the team met with several focus groups to gain feedback on potential designs, Figure 3. The feedback from the focus motivated the size, shape, and color. Additionally, user feedback inspired the need for user control of the device, such as adjusting the volume, profile setting, and power. Several switch options were explored and wireless control options were considered. In an effort to reduce the number of moving parts, a five-way switch was chosen. The switch was tested during a focus group to make sure it was comfortable, and easy to use. The pull out force of the transfer module was also considered during the design. With the use of a force gauge, the team tested the micro USB connection between the transfer module and the round enclosure to ensure that it did not exceed the strength of the user. Several materials were considered for the manufacturing of the device. The focus of the material search was to find a material that would provide enough strength to protect the electronics from external harm, a material that would not melt, and one that was easy to injection mold. Sabic's Cycolac acrylonitrile-butadiene-styrene (ABS) thermoplastic resin [6] was chosen based on these constraints.

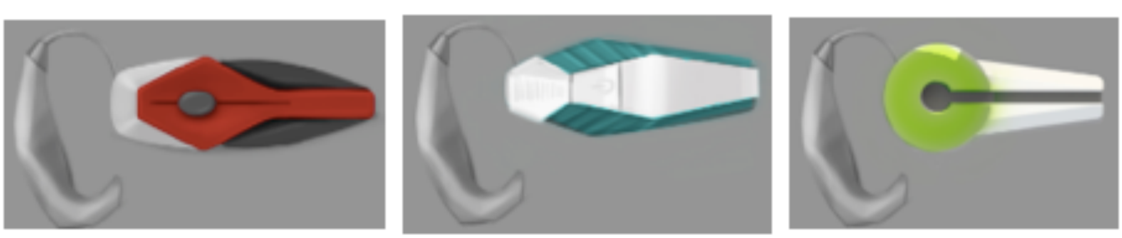

Figure 3: Focus Group Designs

Hardware Design

The electronic design was completed by breaking the product into a series of sub systems (input, pre-amplification, pre-filtering, processing, post-amplification, output, power), and optimizing the subsystem electronics based on size, monetary, and performance constraints. Allowable internal space motivated the removal of the some pre and post amplification electronics. Based on the frequency range required, and the orientation constraints allowing the capture and output of sound, the ES-21237 speaker, T0-24603 omnidirectional microphone, and TD-24618 directional microphone were chosen. Familiarity with a similar product and product performance inspired the need for using the INA333 instrumentation amplifier for pre-amplification. The ideal microprocessor for hearing-aid applications is the RHYTHM 3910 Digital Signal Processer based on its size, advanced functionality, and power consumption (655 micro-amps). A sixteen-week delivery time of this product made using it for this iteration of the project impossible. The Freescale MC56F8006 Digital Signal Processor was purchased. The MC56F8006 does not have an integrated digital-to-analog converter; therefore a DAC8311 DAC was added to compensate. Pre-filtering is intended to limit the amount of excess noise to the input of the microprocessor, without consuming additional power. A Bandpass filter configuration, using resistors and capacitors, was used to filter undesired signals from interacting with the microprocessor. The design of the system power was driven by the customer need to interface with USB 2.0. A micro USB connection was included in the design of the battery enclosure to allow power to flow into the system and recharge the batteries within.

Software Design

The software portion of this project is intended to handle capturing and sampling of sound from the microphones, amplifying the sound data, and outputting the amplified sound through the speaker to the user. In order to avoid a time delay, or distortion, a strict timing requirement was desired during software development. Sampling occurred in interrupts during sound capture, which are designed to be as short as possible so that the captured data could be modified, and outputted, as quickly as possible to meet the strict timing requirements. The sampling and processing were conducted in an interrupt to ensure that when the samples needed to be taken they would be, then after that was done control was returned to the main method to continue monitoring the switch inputs to detect any user input to the device. The goal of the software was to implement basic digital sound processing, and also to try and leave room for any additional features that might need or want to be added in the future.

RESULTS AND DISCUSSION

Enclosure Design

The round enclosure (Figure 4) lives on the user's ear. The enclosure contains a round printed circuit board containing the electronics necessary for sound capture (microphones), sound processing (pre-filters, digital signal converter), and sound output (speaker). On the back of the round enclosure, the device interfaces with a standard ear tube. This tube allows the user to use a variety of ear molds, chosen based on user comfort preferences and the level of hearing loss. The five-way switch allows users to control volume (up and down), the profile setting (left and right), and the power status (in and out controls on and off). The surface of the round enclosure includes two cutouts for the microphones to capture sound. The top piece of the round enclosure includes a rotation feature, allowing the user to cover the micro USB when the transfer module is not attached.

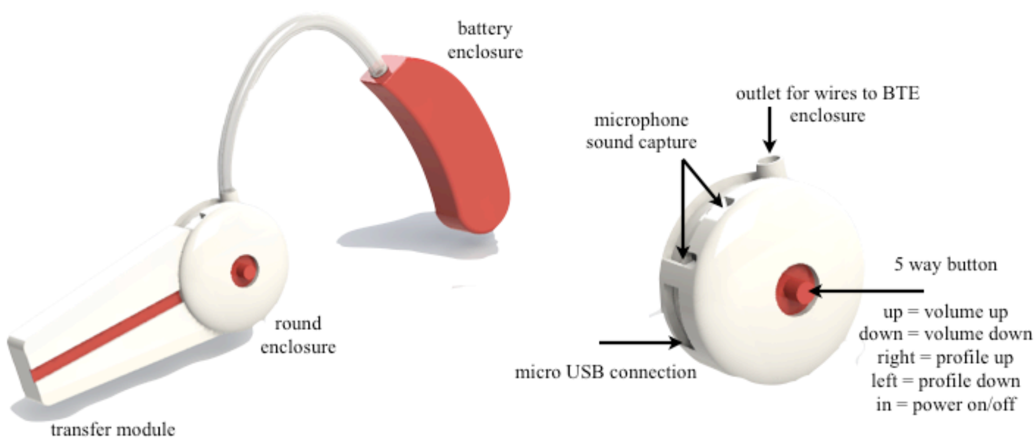

Figure 4: Round Enclosure

The battery enclosure, Figure 5, lives behind the users ear and contains the rechargeable batteries, battery charging printed circuit board, micro USB interface for battery charging, and a tube interface to protect the wires running between the round and battery enclosure. The top surface of the battery enclosure is removable for battery removal (users should expect to change batteries once a year based on the nature of rechargeable batteries).

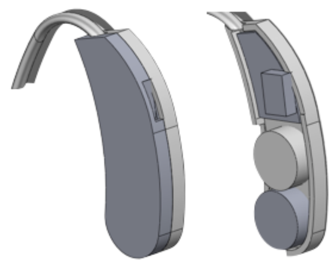

Figure 5: Battery Enclosure

Due to electronic need the final size of the device had to be increased. As a result, users were not satisfied with the comfort or feel of the device. Despite increasing the size, the team was able to meet the marginal weight spec of 15 grams. The largest space challenge resulted from the inability to accesses the On Semi DSP. The team was forced to use a Freescale chip that increased the diameter of the printed circuit boards and surround enclosure. An "ergonomic" model was created to display the intended dimensions of the device. This model is a scaled model of the final design and reflects the size allowable by the On Semi DSP. Approximately 61.63% of the 86 persons survey at Imagine-RIT recognized the device as a Bluetooth device and 69.7 % also recognized it as a hearing aid device. Overall, the number of people surveyed, expressed a high satisfaction for the shape, color, texture and ease of recharging. Based on the survey results, specifications 14-17 were meet.

PCB Design

Two printed circuit boards are required for the performance of the device. The PCB located in the round enclosure is responsible for the sound capture, processing, amplification, and output. This PCB consists of two layers: top and bottom, 11 surface mount resistors, 2 surface mount capacitors, a DAC8311 digital to analog converter, an INA333 instrumentation amplifier, a TD-24618 directional electret microphone, a TO-24603 omnidirectional electret microphone, an ES-23127 speaker, a Freescale MC56F8006 Digital Signal Processor, and one micro USB connecter. The board connects to the battery enclosure through a set of four wires that connect through a clear tube that runs between both enclosures. Figure 7 represents the final circuit schematic used to manufacture the printed circuit board. The electrical team was not able to obtain a recordable waveform from the microphones, therefore the lowest level of sound detected (Spec 1) is unknown. The circuit was able to successfully filter signals using the bypass filter, some amplification was accomplished with the instrumentation amplifier.

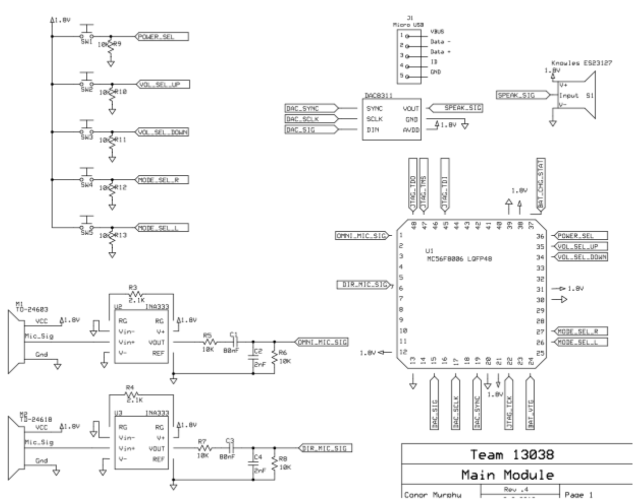

Figure 5: Round PCB Circuit Schematic

The battery enclosure contains a PCB responsible for accepting power from a micro USB connection, recharging batteries, and boosting the battery voltage from 1.2V to the 1.8V, as required by the DSC. This board consists of two layers, 14 surface mount resistors, 8 surface mount capacitors, 2 surface mount diodes, 2 surface mount transistors, 1 TPS61070 boost converter, 1 micro USB, and 1 BQ2000 battery charger. Figure 8 represents the final circuit schematic used to manufacture and print the battery charging PCB.

The battery charger circuit is designed to evaluate the power level of two nickel metal hydride batteries in the device and assess if they need to be charged. When the power is low, users may initiate the recharging process by connecting the circuit to a power source via the micro USB connection. The battery charger recognizes the user input of the power connection, checks the batteries, and enters charging mode if the batteries require power. The electrical team was not able to use the micro USB charging feature due to a flaw in the PCB. The time to charge the earpiece (Spec 5), and battery life at maximum amplification (Spec 12), could not be met. The most likely cause of failure is due to the modulation pin of the battery charger chip since it controls when the battery charger enters charging mode. To resolve this issue, a new PCB was created without the BQ2000 chip, removing the recharging capability. To recharge the prototype, users must remove the battery from the enclosure and charge using an external device.

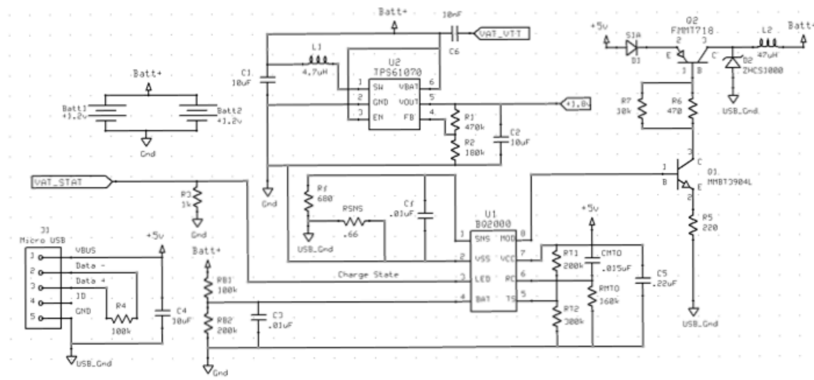

Figure 6: Battery Charging Circuit Schematic

Sound Amplification Code

The MatLab simulation used during the design processes helped to influence the software design that would be implemented in the prototype on the Freescale MC56F8006 Digital Signal Controller. The software design for the prototype samples signals input to the Analog to Digital converter (ADC) of the DSC. The sound samples are converted to digital values in the ADC. The sound is amplified in the digital form by multiplying a gain value to the time domain signal. Filtering is possible in this system by passing the digital values through an FIR filter. The FIR filter coefficients determine what part of the sound is kept, and which is filtered. Different hearing modes are possible by changing the coefficients of the filter. Processing was done in the time domain instead of the frequency domain in an effort to reduce complexity and ensure that the sound processing delay was minimal. The digital samples are then put through a digital to analog converter, and driven into a speaker in the users ear. The graph in Figure 5 displays the input and amplified waveforms in the digital domain, before being sent to the Digital to Analog converter.

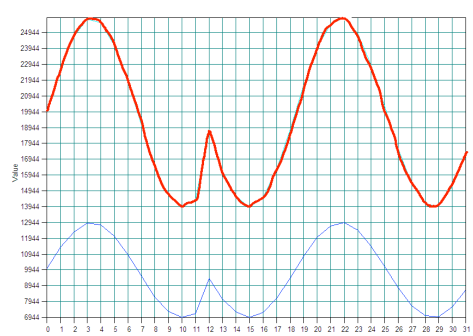

Figure 7: Input and Amplified Input Waveforms, 3 KHz sine wave, Gain = 2

Manufacturing (and cost)

In order to manufacture the device at a cost less than $1000, PCB and Rapid Prototyping must be out-sourced. The projected lead-time based on the production of 5000 units was estimated to be 15 weeks. The process for manufacturing the device will begin with CAD drawings being sent to Shapeways, Inc. for rapid prototyping of the enclosure as well as PCB layouts will be sent to PCB Express. After the enclosures and PCBs are manufactured, the parts are ready for assembly. PCBs must be trimmed prior to mounting electrical components in order to to fit the round enclosure's inner diameter. Once all the PCB's are trimmed, all electrical components such as microphones, speakers, etc will be mounted and the enclosures will have go through a drilling/grinding process to remove excess flanges and add vents/openings. After the PCB's are mounted with electrical hardware, the integration of the hardware to the enclosure pieces will proceed and a sealing/finishing process will take place. During the sealing and finishing process, the enclosure will be sealed with a solvent bonding adhesive and the overall device will be buffed and shined. The final process, quality and testing check will take place to ensure device meets cosmetic criteria and ANSI test protocols. Projected cost to manufacture is approximately $415 if manufactured in Rochester, NY.

TEST RESULTS SUMMARY

Spec	Specification	Dir.	Units	Marginal	Ideal	Measured Value	Pass/Fail
S1	Lowest level of sound detected	min	dB	<60	<30	No recordable wave form obtained from microphones	N/A
S2	Frequencies amplified	max	Hz	300-7000	85-8000	200-8000	Pass
S3	Maximum amplification	target	dB	85-95	90	22 dB	Fail
S4	Levels of volume adjustment	max	levels	5	20	20	Pass
S5	Time to charge earpiece	min	minutes	<60	<30	Circuit incomplete	Fail
S7	Connects to standard USB 2.0	target	yes/no	yes/no	yes	yes	Pass
S8	Maximum temperature at outside surface of device	min	oF	98	110	Not Tested	N/A
S9	Range of adult ear size accommodated	max	percentile	25th-75th	10th -90th	15th to 90th	Pass
S10	Weight of earpiece	min	g	<15	<12	15	Pass
S12	Battery life at max. amplification	max	hours	>16	>48	3.5	Fail
S14	Percent of serveyed people who identify a picture of the device as something other than a hearing aid.	%	%	>60	>80	92.06	Pass
S15	Percent of surveyed hard of hearing people who prefer the form of the new device to standard behind the ear hearing aids	%	%	>50	>75	33	Fail
S16	Percent of surveyed hearing people who would use the device for Bluetooth or music listening	%		>50	>70	91.8	Pass
S17	Percent of surveyed people who feel the device is comfortable to wear	%		>60	>80	33	Fail
S18	Attaches to a standard ear tube and ear mold	yes/no	yes/no	yes	yes	yes	Pass
S19	Manufactured cost (estimated)	min	$	<2000	<1000	415	Pass

CONCLUSIONS AND RECOMMENDATIONS

The product vision was for an audio accessory that was to be optimized for both hearing and hard-of-hearing populations. In order to best utilize team resources (experience, time, knowledge), the project focus was refined to supporting the hearing aid device features including rechargeable power and sound processing and amplification. The design of the enclosure was designed around improving the behind-the-ear style hearing aid. Future iterations of this project should be encouraged to focus on refining the form of the device to better suit the lifestyle and function demands of hearing users, such as a detachable battery pack. The transfer module is currently designed to interface with the round enclosure through a micro USB port. In addition, the size of the transfer module was designed with Bluetooth chip and potential PCB dimensions in mind. Future iterations of this project should focus on the Bluetooth and smartphone integration.

One of the largest challenges during this project cycle was obtaining a micro controller, or digital signal controller, that met the designs' size and functionality constraints. The ideal chip for this project is the RHYTHM R3910 digital signal processor from ON Semiconductor [source]. This is a pre-configured DSP system for hearing aid applications as it is pre-loaded with features including environmental classification, adaptive noise reduction, and feedback cancellation. The DSP measures 5.59mm x 3.18mm, almost half of the size of the Freescale DSC used in the final product. The RHYTHM R3910 was not used in this iteration of the project because the lead-time for part deliver was sixteen weeks. If the department chooses to move forward with a second iteration of this project, this part should be ordered immediately. Due to the extensive lead-time, our team chose to use a digital signal controller from Freescale Semiconductor. The DSC is larger than ideal, forcing the design of the enclosure to grow unnecessarily. Additionally, the Freescale DSC limited the functionality of our device.

Many lessons can be taken away from this design challenge. Compromise between the mechanical and electrical designs was one of the most difficult challenges. The mechanical designers strove to make an aesthetic, small device that would satisfy the physical customer needs. Electrical and Computer engineers fought to have space added for ease of circuit board development and testing. For an early prototype, larger parts would have been easier for testing and debug. We suggest that future teams begin with building their designed circuit on a breadboard or with through hole components for testing. After a large working system has been created, the design can be miniaturized to meet mechanical specs. Additional tips include creating a Bill of Materials during MSD1 to help organize testing and development during MSD2. Customer feedback that was collected via focus groups and surveys was invaluable to the design iterations and evolution of the product.

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