Cochlear Implant Project

Phase 3: Final Product

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Introduction

In Phase 3, the goal was to create the final design for the cochlear implant that scored the highest with the evaluation metric created in phase 1. This was done by taking the initial design of the system created in phase 2, and iterating on the design to create a better sounding system.

First Design Results

The initial filter design described in Phase 2 of the report was evaluated using the metric created in Phase 1. However, feedback from the teaching team prompted the adjustment of the order of the filters, which was changed from 40 to 4 to improve performance. Each of the test cases recorded in Phase 1 were evaluated according to the three scoring methods. The average score of each subtest was then weighted to create a final score out of 100. To get a baseline measurement for the evaluation system, the original input file was evaluated using the metrics described in Phase 1. This allows for each test to be compared against the baseline, and accounts for anomalies in the input files that may skew testing.

Table 1, 2 and 3 below show a sample test, which was an evaluation of the “regular voice, no background noise” audio files run through the first iteration of the filter design. For each design, the average between each test type was taken as a final result. This value was used to compare between iterations, allowing for evaluation of each design. The full evaluation of the first design can also be seen in the appendix.

Table 1: Conversation Scoring Sheet (regular voice, no background noise)

Criteria	**Score (1-5)**	**Weighting (%)**
Vocal Clarity (How well can you understand the conversation)	4.5	**90%** x 60%
Vocal Distinction (Can you tell the difference between voices)	3.5	**70%** x 15%
Inflection Perception (How well can you identify inflections and their meanings)	4	**80%** x 10%
Conversation Isolation (How well is the conversation isolated from the background sound stage)	5	**100%** x 15%
	Total:	**87.5%**

Table 2: Input/Output Evaluation Scoring Sheet (regular voice, no background)

How well does the output signal retain:	**Score (1-5)**	**Weighting (%)**
Vocal Clarity	4.5	**90%** x 50%
Vocal Distinction	4	**80%** x 25%
Inflection Perception	4	**80%** x 10%
Pitch	4	**80%** x 15%
	Total:	**85%**

Table 3: Total Scoring Table (regular voice, no background)

Words identified	**14** out of 15 = **93%**
Conversation Score	**87.5%**
Input/Output Evaluation Score	**85%**
Total	**93** % × 0.3 (Weighted Word Percentage) +**87.5** % × 0.5 (Weighted Conversation Percentage) + **85** % × 0.2 (Weighted Input/Output Evaluation Percentage)
	= **89%**

Design Iterations

The iterative process was based on the performance of each design using the evaluation method described in Phase 1. To analyze the effect of changing different parameters of the filter bank design, each parameter would be adjusted individually, keeping all other parameters constant. Once the parameter was changed, the output was compared to the previous design. If an improvement was shown, the parameter would be permanently changed to the new value. If no improvement was shown, the parameter was kept at its previous value, and a new parameter was chosen to modify. Some of the parameters changed included filter order, filter types of both the bandpass and lowpass filter, number of bands and cutoff frequency of the lowpass filter.

To allow for faster iterations through the designs, only 4 test cases were used to score each changed design iteration. If the weighted score of the new design showed an improvement over the existing design, the change would be implemented. The final score of each iteration is shown in Table 4, while the full scoring table showing the tabulated results of each evaluation can be seen in the Appendix in Table 5.

Table 4: Iteration Table

Iteration	Parameter Altered	Value of Parameter	Score	Better or Worse
1	Defaults	Defaults	84%	n/a
2	Bandpass Filter Order	10	78%	worse
3	Number of Bands	25	63%	worse
4	Lowpass Filter cutoff	300Hz	62%	worse
5	Lowpass Filter cutoff	600Hz	61%	worse
6	Filter Type FIR	Equiripple	0%	worse
7	Bandpass Filter Type	Chebyshev 1	80%	worse
8	Bandpass Filter Type	Chebyshev 2	0%	worse
9	Bandpass Filter Type	Elliptic	80%	worse
10	Lowpass Filter Type	Chebyshev 1	78%	worse
11	Lowpass FIlter Type	Elliptic	76%	worse

Each parameter affected the output audio differently, which had to be taken into consideration when iterating through each design. The effect of changing each parameter is discussed in detail below.

By increasing the order of the filter, the rolloff at each cutoff frequency becomes much sharper. In theory, this should lead to less bleed between bands, causing less noise to be present in each band. However, upon experimentation, the background noise seemed to be more prominent when higher order filters were applied. Additionally, increasing filter order greatly increased computation time. Since the implant needs to be able to process audio in real-time, an increase in computation time is undesired.

By increasing the number of frequency bands within the filter bank, the quality of the output signal could be improved. While in simulation there is no limit to the number of bands, the practical implementation of the cochlear implant must be considered as well when choosing band distribution. Cochlear implants only have a limited number of electrodes (usually 12-24 [1]), which needs to be considered in the design. Additionally, increasing the number of bands also increases the computation time, as the number of filters that need to be applied increases with the number of bands. Another consideration when choosing this value is the potential effect of the central frequencies of each band creating harmonics within the system, which may appear in the form of a sustained pitch being present within the signal. This was indeed observed during testing (for N=25), where the output signal was dominated by a sustained drone, drowning out the speakers in the conversation.

The cutoff frequency of the lowpass filter was also experimented with. Increasing the cutoff frequency of this filter allowed higher frequencies through, which increased the oscillations present in the envelope of the signal. This translated to a fuzzier audio output. A similar effect on the output was observed when lowering the cutoff frequency, as the small amount of oscillations in the signal lead to lower audio fidelity. Therefore, a value in between the extremes described here had to be chosen.

When selecting whether the filters should include feedback (IIR vs. FIR), the nominal filter order had already been selected. Since FIR filters require much higher orders to obtain the same amount of audio fidelity as an IIR filter, which works well at a lower order, IIR filters are ideal for this application. Therefore an IIR filter was chosen, due to its lower computation cost.

Finally, different types of IIR filters were tested on the lowpass and bandpass filters. These included Chebyshev 1, Chebyshev 2, and Elliptic filter types. The Chebyshev 2 filter was observed to not produce any kind of intelligible signal, and was therefore discarded. Elliptic and Chebyshev 1 produced better results, however they failed to exceed the performance of the original Butterworth filter. This is likely because of the ripple introduced by the Chebyshev 1 and Elliptic filters, which resulted in minor distortion in the signal output.

Final Design

After studying the effect of each parameter on the overall performance of the cochlear implant, many designs were created through iteration as described in the Design Iterations section. These designs were evaluated, and the best scoring design was chosen as the final product. Ultimately, as described in the Design Iterations section, every attempt to iterate the design by altering a parameter resulted in an overall degradation of quality, indicating that the initial parameters chosen as a starting point produced the optimal design. This, while slightly unexpected, is a result of initial parameters being chosen based on cochlear implant and audio filtering research. Therefore, the final design included 4th order filters with 20 logarithmically distributed frequency bands, a butterworth design for the lowpass and bandpass filters, and a lowpass cutoff frequency of 400Hz.

If this design were to be further improved, the selection method could be refined by adding to the evaluation criteria used to score each design. The evaluation methods used in this design were biased to designs which resulted in the highest possible output quality. The current evaluation methods do not account for some of the practical considerations that also play a role in a cochlear implant filter design. Some additional factors that could be considered include cost and size of hardware, battery life, and processing time. While these factors were taken into account when selecting the final filter design, most notably when choosing the number of passbands and filter order, the final design iteration could have been further optimized by quantifying these additional factors in the evaluation method.

References

[1] “Manufacturable 32-Channel Cochlear Electrode Array and Preliminary Assessment of Its Feasibility for Clinical Use” Accessed: Nov. 31, 2024. [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC8304779/#:~:text=The%20conventional%20multi%2Dchannel%20cochlear,deliver%20the%20corresponding%20sound%20frequency.

Appendix

Table 5: Full Results Table

Iteration	number of bands	filter order	Frequency cutoff	Lowpass filter type	Bandpass filter type	Criteria	No background			Street noise		Convo	
							Reg voice	high voice	low voice	**Reg voice**	low voice	**Reg voice**	
input signal (control)	n/a	n/a	400Hz	n/a	n/a	Vocal Clarity Retention	5	5	5	5	5	5	
						Vocal Distinction Retention	5	5	5	5	5	5	
						Inflection Perception Retention	5	5	5	5	5	5	
						Pitch Retention	5	5	5	5	5	5	
						Vocal Clarity (How well can you understand the conversation)	5	5	5	5	5	5	
						Vocal Distinction (Can you tell the difference between voices)	5	4	5	5	5	5	
						Inflection Perception (How well can you identify inflections and their meanings)	5	4	4	5	5	5	
						Conversation Isolation (How well is the conversation isolated from the background sound stage)	5	5	5	5	4	3	
						Words identified	15	13	15	15	15	15	Final Score:
						Total	1	0.935	0.99	1	0.985	0.97	0.98
1	20	4	400Hz	butterworth	butterworth	Vocal Clarity Retention	4.5	3.5	3	4.5	3	4	
						Vocal Distinction Retention	4	1	2	4	2	3	
						Inflection Perception Retention	4	2	3	4	3	4	
						Pitch Retention	4	4	2	4	3	2	
						Vocal Clarity	4.5	4	4.5	4.5	5	4	
						Vocal Distinction	3.5	1	3	3.5	1	3	
						Inflection Perception	4	2	3	5	4	3	
						Conversation Isolation	5	5	5	5	5	4	
						Words identified	14	10	14	14	14	14	Final Score:
						Total	0.8875	0.662	0.804	0.8975	0.82	0.793	0.81
2	20	10	400Hz	butterworth	butterworth	Vocal Clarity Retention				4		3	
						Vocal Distinction Retention				4		1	
						Inflection Perception Retention				4		3	
						Pitch Retention				4.5		4.5	
						Vocal Clarity				4		3	
						Vocal Distinction				4.5		1	
						Inflection Perception				4		2	
						Conversation Isolation				5		4.5	
						Words identified				15		14	Final Score:
						Total	0	0	0	0.8855	0	0.6715	0.78
3	25	4	400Hz	butterworth	butterworth	Vocal Clarity Retention				3		2	
						Vocal Distinction Retention				3.5		1	
						Inflection Perception Retention				4		3	
						Pitch Retention				3		1	
						Vocal Clarity				3		2	
						Vocal Distinction				4		1	
						Inflection Perception				4		3	
						Conversation Isolation				2		0.5	
						Words identified				15		14	Final Score:
						Total	0	0	0	0.739	0	0.5205	0.63
4	20	4	300Hz	butterworth	butterworth	Vocal Clarity Retention				2		2.5	
						Vocal Distinction Retention				2		2	
						Inflection Perception Retention				3.5		3.5	
						Pitch Retention				3		3	
						Vocal Clarity				2		3	
						Vocal Distinction				2.5		2.5	
						Inflection Perception				3.5		3.5	
						Conversation Isolation				1		3.5	
						Words identified				13		14	Final Score:
						Total	0	0	0	0.5595	0	0.687	0.62

5	20	4	600Hz	butterworth	butterworth	Vocal Clarity Retention				4		1		
						Vocal Distinction Retention				3		2		
						Inflection Perception Retention				3		1		
						Pitch Retention				2		2		
						Vocal Clarity				3.5		1		
						Vocal Distinction				4		2		
						Inflection Perception				3		1		
						Conversation Isolation				3		1		
						Words identified				15		13	Final Score:	
						Total	0	0	0	0.779	0	0.431	0.61	
6	20	20	400Hz	butterworth	equiripple	Vocal Clarity Retention				0		0		
						Vocal Distinction Retention				0		0		
						Inflection Perception Retention				0		0		
						Pitch Retention				0		0		
						Vocal Clarity				0		0		
						Vocal Distinction				0		0		
						Inflection Perception				0		0		
						Conversation Isolation				0		0		
						Words identified				0		0	Final Score:	
						Total	0	0	0	0	0	0	0.00	
7	20	4	400Hz	butterworth	Chebyshev 1	Vocal Clarity Retention				4		4		
						Vocal Distinction Retention				3		3		
						Inflection Perception Retention				4		4		
						Pitch Retention				4		3.5		
						Vocal Clarity				4		3.5		
						Vocal Distinction				4		3.5		
						Inflection Perception				4		4		
						Conversation Isolation				3.5		3		
						Words identified				14		14	Final Score:	
						Total	0	0	0	0.8225	0	0.7745	0.80	
8	20	4	400Hz	butterworth	Chebyshev 2	Vocal Clarity Retention				0		0		
						Vocal Distinction Retention				0		0		
						Inflection Perception Retention				0		0		
						Pitch Retention				0		0		
						Vocal Clarity				0		0		
						Vocal Distinction				0		0		
						Inflection Perception				0		0		
						Conversation Isolation				0		0		
						Words identified				0		0	Final Score:	
						Total	0	0	0	0	0	0	0.00	
9	20	4	400Hz	butterworth	Elliptic	Vocal Clarity Retention				4		4		
						Vocal Distinction Retention				3		3		
						Inflection Perception Retention				4		4		
						Pitch Retention				4		3.5		
						Vocal Clarity				4		3.5		
						Vocal Distinction				4		3.5		
						Inflection Perception				4		4		
						Conversation Isolation				3.5		3		
						Words identified				14		14	Final Score:	
						Total	0	0	0	0.8225	0	0.7745	0.80	
10	20	4	400Hz	Chebyshev 1	butterworth	Vocal Clarity Retention				4		4		
						Vocal Distinction Retention				4		3		
						Inflection Perception Retention				4		3		
						Pitch Retention				4		2		
						Vocal Clarity				4		4		
						Vocal Distinction				3		3		
						Inflection Perception				5		3		
						Conversation Isolation				3		2.5		
						Words identified				14		13	Final Score:	
						Total	0	0	0	0.82	0	0.7465	0.78	
11	20	4	400Hz	Elliptic	butterworth	Vocal Clarity Retention				4		3		
						Vocal Distinction Retention				4		3		
						Inflection Perception Retention				4		3		
						Pitch Retention				4		2		
						Vocal Clarity				4		3		
						Vocal Distinction				3		4		
						Inflection Perception				4		4		
						Conversation Isolation				3.5		2		
						Words identified				14		14	Final Score:	
						Total	0	0	0	0.8175	0	0.704	0.76	