ECEn 390
Milestone 2 Report
Chase Dietz and Evan Nuss

Introduction:

The objectives of this Milestone are to (1) design 10 bandpass filters, (2) design a decimating system and analyze noise aliasing, and (3) analyze the full system with noise. This will be done using data gathered using our receiver PCB and MATLAB scripts we will write for filtering, plotting, decimating, etc.

Task 1:

Summary:

In this task we created 10 IIR bandpass filters of length 11. They were centered at the player frequencies with a bandwidth of 50Hz. We plotted the frequency response of each of those filters and within the necessary range, there was no overlap of our filters, which was one of the specifications. We passed a square wave for each of the player frequencies through the 10 IIR filters and used the equation for calculating the energy of a discrete signal to make sure only the corresponding player frequency was registered by the filters. This was successful, which means we can use these filters to identify which player a registered hit comes from.

Specifications:

- Butterworth IIR bandpass filter configuration with center frequencies of each player
- Filter length of 11
- Equal filter bandwidths for all 10 filters
- Attenuation of adjacent player frequency <-20dB
- Player frequencies: 1471, 1724, 2000, 2273, 2632, 2941, 3333, 3571, 3846, and 4167 Hz.
- Pulse length 200ms

Design:

The filter coefficients for each of the 10 filters are shown in the tables below.

Table 1: Denominator Coefficients (IIR Filter A)

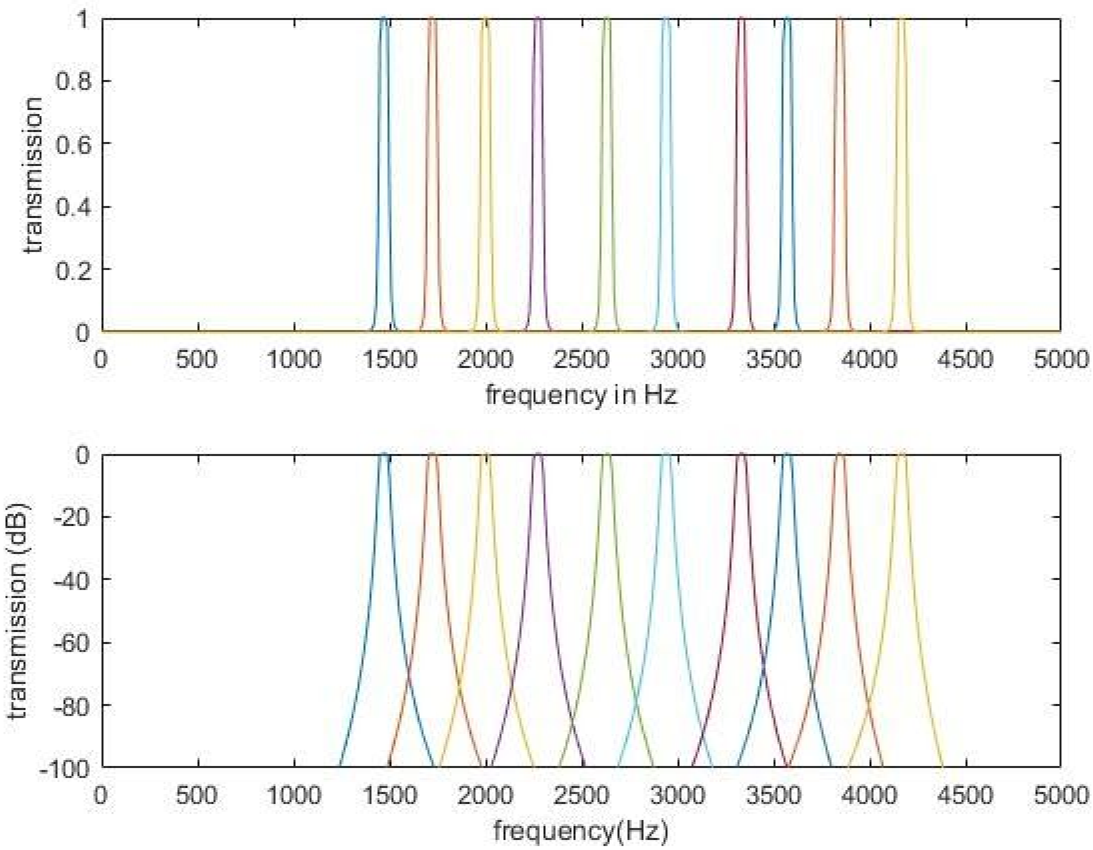
Filter 1	1	-5.9638	19.1253	-40.3415	61.5375	-70.0197	60.2988	-38.7338	17.9935	-5.4979	0.9033
Filter 2	1	-4.6378	13.5022	-26.1560	38.5897	-43.0390	37.8129	-25.1136	12.7032	-4.2755	0.9033
Filter 3	1	-3.0591	8.6417	-14.2788	21.3023	-22.1939	20.8735	-13.7098	8.1304	-2.8202	0.9033
Filter 4	1	-1.4072	5.6904	-5.7375	11.9580	-8.5435	11.7173	-5.5088	5.3537	-1.2973	0.9033
Filter 5	1	0.8201	5.1674	3.2580	10.3929	4.8102	10.1837	3.1282	4.8616	0.7560	0.9033
Filter 6	1	2.7081	7.8319	12.2016	18.6515	18.7582	18.2761	11.7154	7.3684	2.4965	0.9033
Filter 7	1	4.9480	14.6916	29.0824	43.1798	48.4408	42.3107	27.9234	13.8222	4.5615	0.9033
Filter 8	1	6.1702	20.1272	42.9742	65.9580	75.2304	64.6304	41.2616	18.9361	5.6882	0.9033
Filter 9	1	7.4093	26.8579	61.5788	98.2583	113.5946	96.2805	59.1247	25.2685	6.8305	0.9033
Filter10	1	8.5743	34.3066	84.0353	139.2851	163.0512	136.4815	80.6863	32.2764	7.9045	0.9033

Table 2: Numerator Coefficients (IIR Filter B)

Filter 1	9.0929e-10	0	-4.5464e-09	0	9.0929e-09	0	-9.0929e-09	0	4.5464e-09	0	-9.0929e-10
Filter 2	9.0929e-10	0	-4.5464e-09	0	9.0929e-09	0	-9.0929e-09	0	4.5464e-09	0	-9.0929e-10
Filter 3	9.0929e-10	0	-4.5464e-09	0	9.0929e-09	0	-9.0929e-09	0	4.5464e-09	0	-9.0929e-10
Filter 4	9.0929e-10	0	-4.5464e-09	0	9.0929e-09	0	-9.0929e-09	0	4.5464e-09	0	-9.0929e-10
Filter 5	9.0929e-10	0	-4.5464e-09	0	9.0929e-09	0	-9.0929e-09	0	4.5464e-09	0	-9.0929e-10
Filter 6	9.0929e-10	0	-4.5464e-09	0	9.0929e-09	0	-9.0929e-09	0	4.5464e-09	0	-9.0929e-10
Filter 7	9.0928e-10	0	-4.5464e-09	0	9.0928e-09	0	-9.0928e-09	0	4.5464e-09	0	-9.0928e-10
Filter 8	9.0930e-10	0	-4.5465e-09	0	9.0930e-09	0	-9.0930e-09	0	4.5465e-09	0	-9.0930e-10
Filter 9	9.0927e-10	0	-4.5463e-09	0	9.0927e-09	0	-9.0927e-09	0	4.5463e-09	0	-9.0927e-10
Filter 10	9.0906e-10	0	-4.5453e-09	0	9.0906e-09	0	-9.0906e-09	0	4.5453e-09	0	-9.0906e-10

The frequency-domain transfer function plots for each of the 10 filters are shown in Figure 1, with the top plot having linear scaling and the bottom plot having logarithmic scaling (in dB).

Figure 1: Frequency-domain Transfer Functions



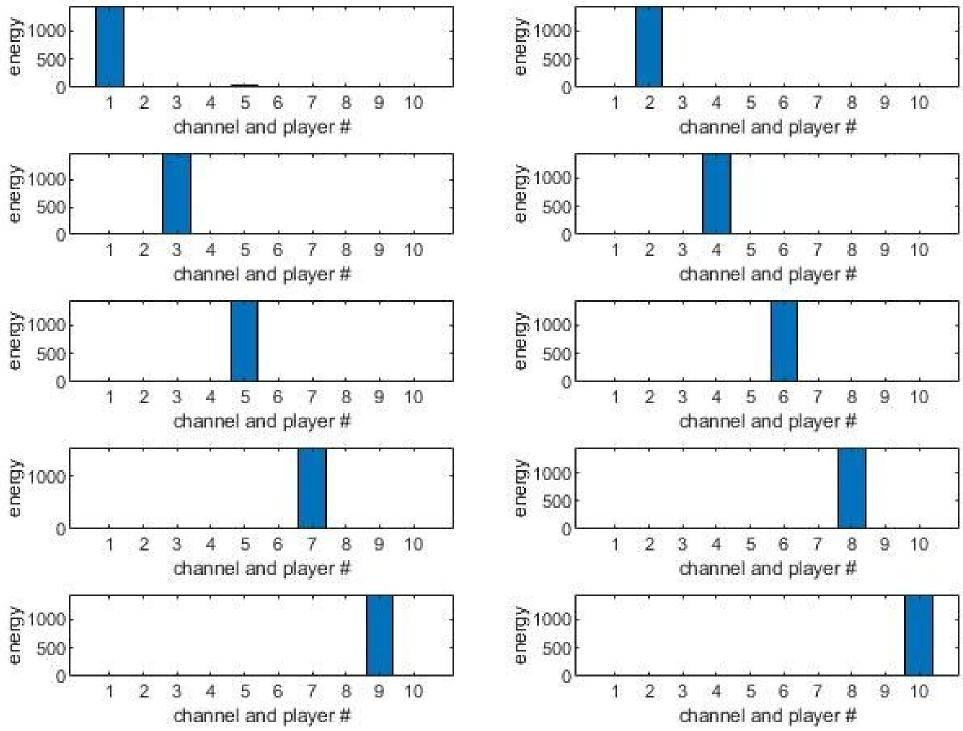
For each of these filters of order 10, we had a bandwidth of 50Hz. Due to this, we far exceed the specification of adjacent player frequency attenuation being less than 20dB.

The energy of a discrete set of data is calculated using the following equation:

$$E = \sum_{n=0}^{Length-1} |x[n]|^2 \tag{1}$$

After using the ‘square’ command in MATLAB to create 10 distinct square waves at each of the 10 player frequencies, we used Equation 1 to get the energies, as plotted in Figure 2 below.

Figure 2: Energy of Square Waves through Bandpass Filters



Player 1 has a single harmonic, so there is a nonzero value for the energy computed. But this is not a concern since the max energy corresponds to the appropriate player channel.

Task 2:

Summary:

In this task we created an FIR filter of length 81 with a corner frequency of 5.5kHz to act as an anti-aliasing filter for the decimated signals of the Laser Tag System. Applying a Hamming window, we achieved a max player variation of 0.603 dB and an out of band rejection of 54.39 dB.

Specifications:

- Anti-aliasing FIR filter
- Maximum filter length: 81
- Maximum player variation: 1dB
- Out of band rejection: 40dB
- Stopband: 10kHz < f < 50kHz

Aliasing Background:

Aliasing refers to the misidentification of a signal frequency after downsampling. In the context of this lab, that would mean a higher frequency of noise actually appearing after being downsampled in the frequencies we want noise to be completely filtered out. This phenomena is demonstrated by Figures 3 and 4 below.

Figure 3: Plots of Raw Optical Noise Data
(the upper plot is in the time domain. The lower plot is in the frequency domain)

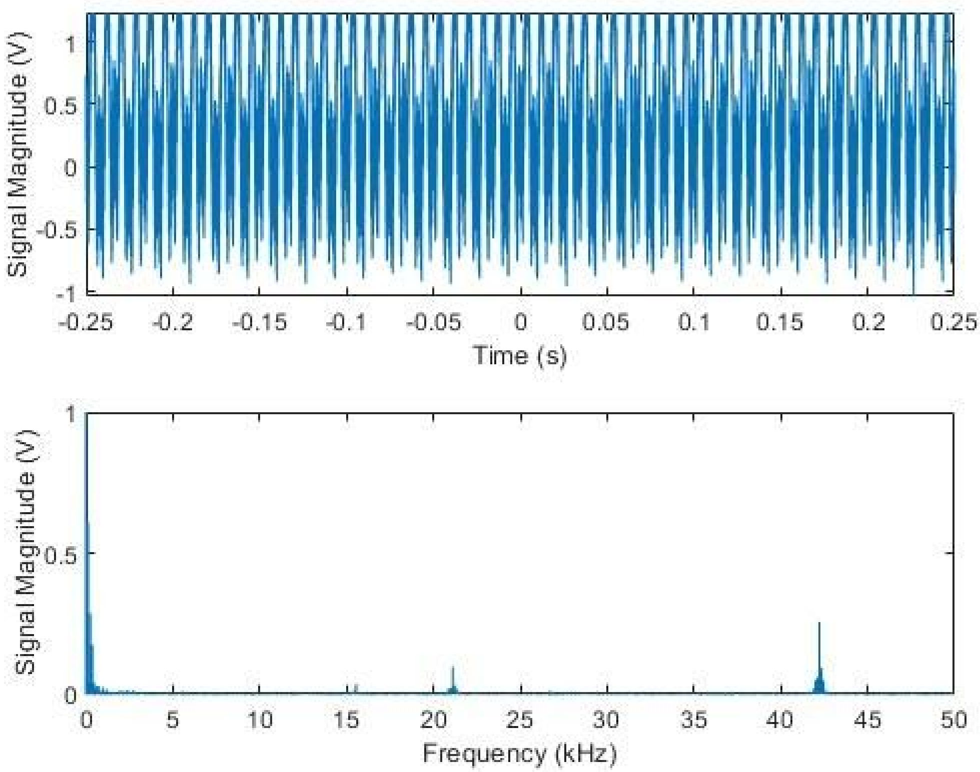
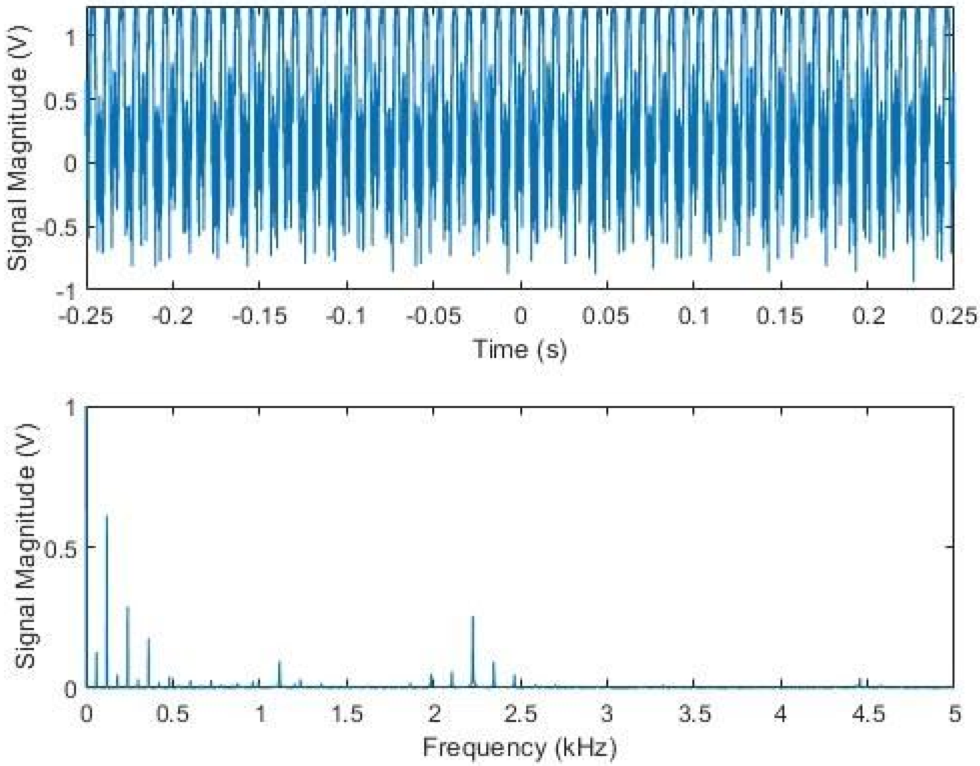


Figure 3 shows the data from the optical noise before downsampling, using a sampling frequency of 100kHz. And as we can see, there is basically no noise appearing in our essential frequency band of 1kHz and 5kHz. However, Figure 4 below shows that after downsampling using a sampling frequency of 10kHz, those higher frequencies from Figure 3 are aliased right into our essential frequency. This is exactly the type of aliasing we are trying to rectify with our FIR filter.

Figure 4: Downsampled Optical Noise Data
(the upper plot is in the time domain. The lower plot is in the frequency domain)



Design and Specification:

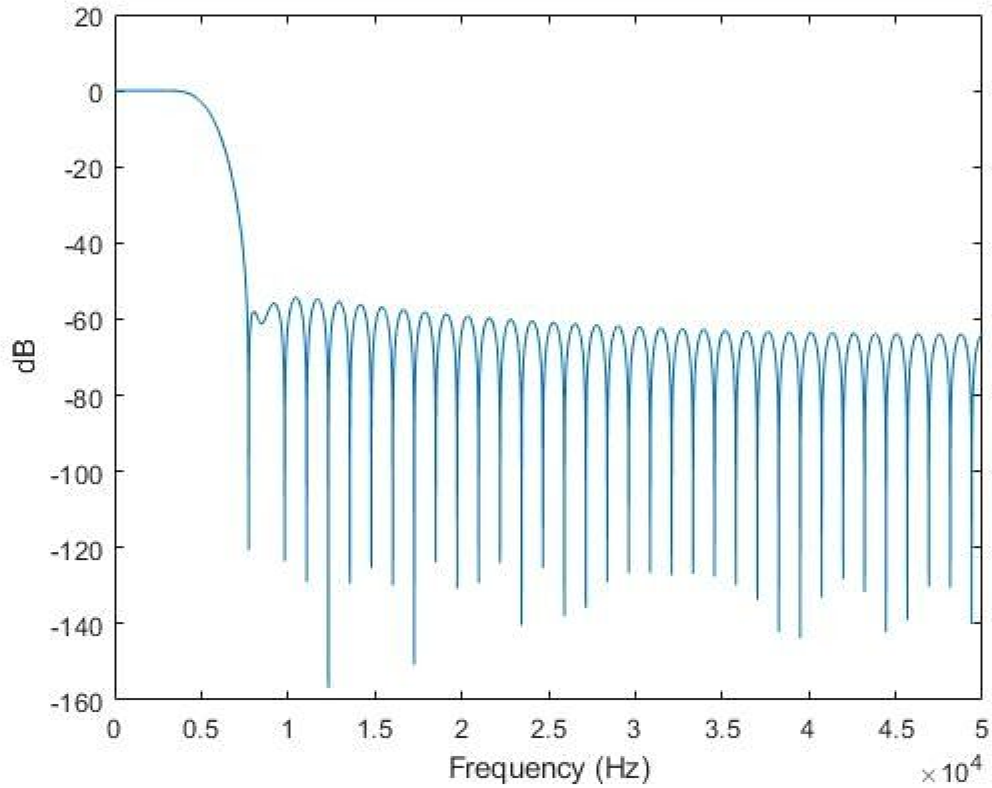
We decided to use a Hamming window with a bandwidth of 11kHz in our filter design. Our filter was of length 81 with the following B coefficients:

Table 3: Numerator Coefficients (FIR Filter B)

0.000605461382912526	0.000525071433152678	0.000384490912727015	0.000173986671979482	-0.000113604899349315	-0.000474881114786325	-0.000888138783562238
-0.00130826181783950	-0.00166636184969699	-0.00187557003663368	-0.00184323633288179	-0.00148842587217274	-0.000762255149246229	0.000332452491323848
0.00172625488025938	0.00327684187207442	0.00477448141465890	0.00596063178146703	0.00655914855665656	0.00631728702825865	0.00505164213245866
0.00269263889095544	-0.000679508088830152	-0.00481411000268887	-0.00928992006832306	-0.0135385959390865	-0.0168915878753250	-0.0186469849194417
-0.0181496978991236	-0.0148758769245867	-0.00851106085571505	0.000988489319273163	0.0133604211419479	0.0280333012910422	0.0441586685903126
0.0606764866428626	0.0764080626437003	0.0901668071129717	0.100874635255090	0.107670732078251	0.110000000000000	0.107670732078251
0.100874635255090	0.0901668071129717	0.0764080626437003	0.0606764866428626	0.0441586685903126	0.0280333012910422	0.0133604211419479
0.000988489319273163	-0.00851106085571505	-0.0148758769245867	-0.0181496978991236	-0.0186469849194417	-0.0168915878753250	-0.0135385959390865
-0.00928992006832306	-0.00481411000268887	-0.000679508088830152	0.00269263889095544	0.00505164213245866	0.00631728702825865	0.00655914855665656
0.00596063178146703	0.00477448141465890	0.00327684187207442	0.00172625488025938	0.000332452491323848	-0.000762255149246229	-0.00148842587217274
-0.00184323633288179	-0.00187557003663368	-0.00166636184969699	-0.00130826181783950	-0.000888138783562238	-0.000474881114786325	-0.000113604899349315
0.000173986671979482	0.000384490912727015	0.000525071433152678	0.000605461382912526			

The frequency response of our filter is shown below in Figure 5.

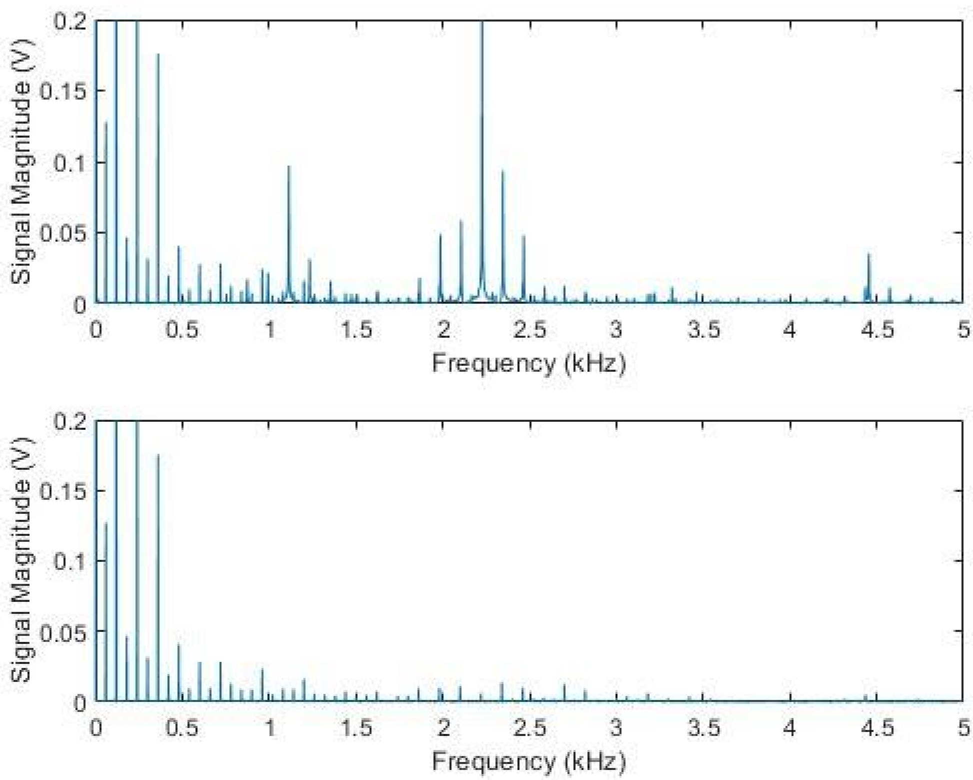
Figure 5: Frequency Response of Low-pass Filter



Analysis of this plot showed us that the minimum out of band rejection (at 10.45kHz) is 54.39dB, which is well above the desired specification of 40dB, thus showing our filter is more than sufficiently filtering the higher frequencies.

We will now show the optical noise data when it has only been downsampled, then show the same data that has been downsampled *and* filtered (decimated) and demonstrate the anti-aliasing nature of our filter.

Figure 6: Downsampled and Decimated Optical Noise



As we can see, the filtering got rid of any noise within our desired frequency band between 1kHz and 5kHz.

The final specification we had to verify was the player gain variation, the maximum of which must be less than 1dB. Using the data in Table 4, we computed our maximum player variation to be $20\log_{10}(0.9356/1.0029)$ = 0.603dB, which is within spec.

Table 4: Player Variation Gains

Player 1	Player 2	Player 3	Player 4	Player 5	Player 6	Player 7	Player 8	Player 9	Player 10
1	0.9999	0.9999	1.0004	1.0017	1.0029	1.0004	0.9933	0.9754	0.9356

Task 3:

Summary:

For the third task we took the filters that we had designed for Tasks 1 and 2 and put together the process required to filter an actual signal to achieve the desired results. We did this by importing the coefficients for both of those filters into MATLAB. We then took a noise signal and added a square wave at the frequency of Player 1 to the noise. We then passed that through the low-pass anti-aliasing filter that was designed in task 2, then downsampled that from 100 kHz to 10kHz, taking one in every ten pieces of data. Afterwards, we then passed the downsampled signal through the 10 bandpass filters designed in task 1 and calculated the resulting energies from each of the 10 individual filters to determine which player shot.

Specifications:

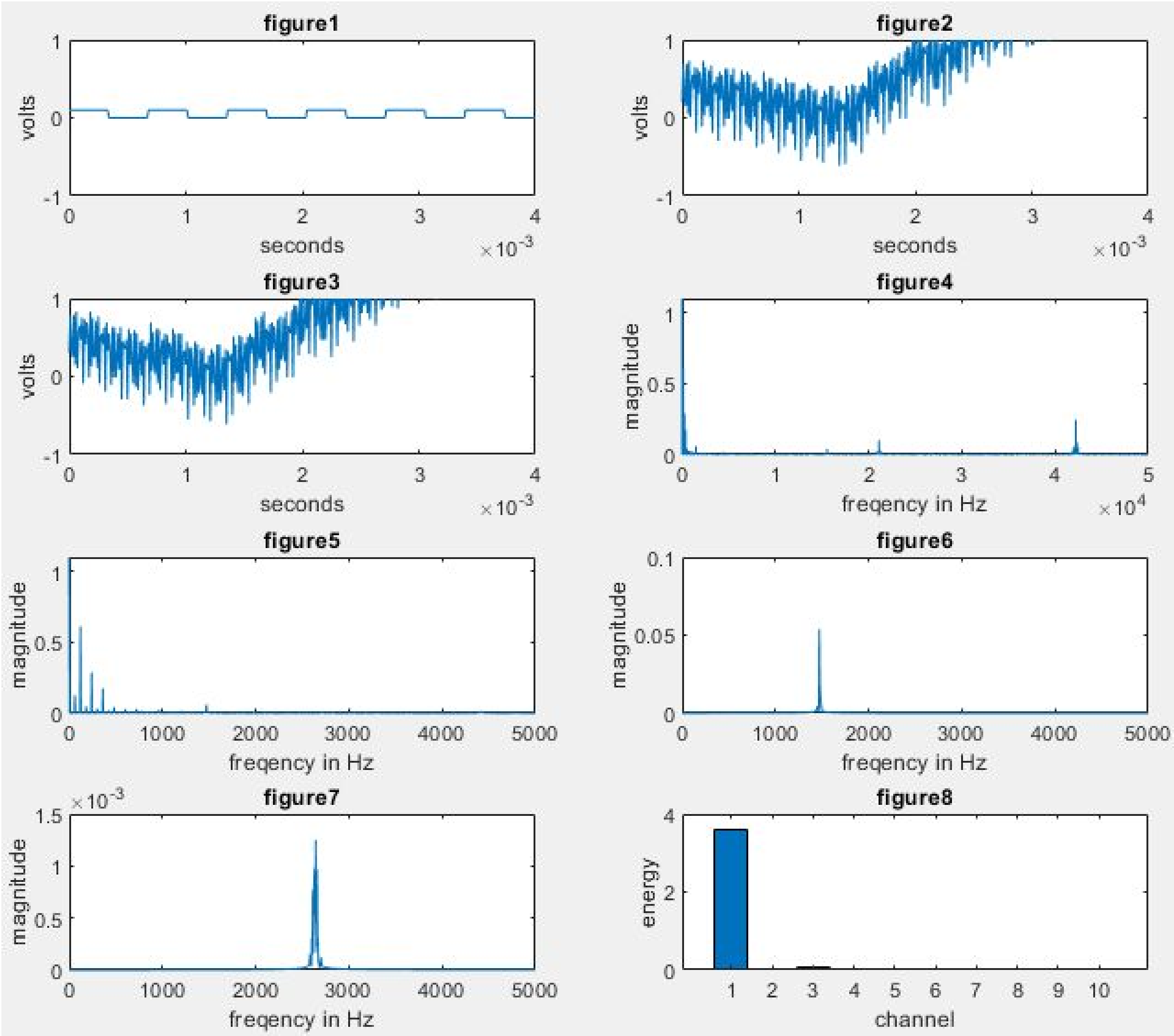
- Combined signal processing algorithm
- Anti-aliasing filter from Task 2
    - FIR Filter
    - 81 ‘b’ coefficients
    - 1 nonzero coefficient of 1 for ‘a’ coefficients
- Bank of bandpass filters from Task 1
    - IIR Filters
    - 11 ‘a’ and 11 ‘b’ coefficients
    - Center-of-passband frequencies are the 10 player frequencies

Design:

We imported the ‘a’ and ‘b’ coefficients of the filters created in Tasks 1 and 2.

Verification:

First we created a square wave at frequency of 1471 Hz and an amplitude of 100mV as shown in figure 1 below. We also used a noise sample that was provided for us (figure 2) and added our square wave to that, resulting in figure 3. When contrasting figures 2 and 3, there is little difference from a noisy signal and a noisy signal with a player shot, as would be expected in a real game. The only noticeable difference is that in some places figure 3 is increased by a .1 V. The signal in the frequency domain is shown in figure 4. It can be seen that there are many lower frequency signals and a large noise signal at about 42 kHz. Most signals stay before the 2 kHz range
We then took that combination signal and passed it through the anti-aliasing FIR low pass filter. The frequency response of the results is shown in figure 5. It looks as it should, with the only signals we see are on the lower end of the frequency spectrum.
Afterwards, the signal was then passed through our IIR bandpass filters in attempt to isolate which player shot. Figure 6 shows the results after passing the signal through the channel 1 filter. It shows a magnitude of around 50mV at 1471 Hz, as expected. Figure 7 then shows the results of passing the signal through a different channel filter, here being channel 5. While there is an energy shown, it is miniscule, about a 1 mV. Lastly, we plotted a bar graph of the resulting energies calculated from each channel filter in figure 8. Here we can see that the channel 1 filter has far more energy associated with it than any other filter. The system was correctly able to detect a signal from player 1.



Conclusion:

This milestone was an exhaustive review of what we learned in ECEn 380 concerning the power of bandpass IIR filters, anti-aliasing FIR filtering of noise, and system analysis. It was extremely useful to review MATLAB and the procedure for filtering and downsampling, as well as how to plot in the frequency domain and time domain. The most interesting thing for us was to see the energy calculation plots which are really the confirmation that our overall system is working because it indicates what hit we are registering. We had some struggles with scaling and realizing what a plot was really telling us. But we learned the hard way to pay special attention to the axes and how they are scaled since we could be getting the right results even when it looks incorrect, or vice versa.