

# Colorful Spectrum Analyser

Final Project Report

December 11th, 2009

E155

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## Abstract

*One common 'extra' seen on stereo systems is the graphical equalizer: columns of lights that move up and down based on the frequency content of the music. This final project is a similar type of display. The system takes in the audio output of an iPod, and displays the frequency content of eight different frequency on an  $8 \times 8$  grid of colored LEDs. It uses eight bandpass filters, which are implemented on the FPGA as 256-tap digital FIR filters. The bands range from 0 to 4000 Hz, and are geometrically spaced such that each band is approximately  $1.7 \times$  the size of the previous band, which allows for greater resolution at lower frequencies. The resulting output is smoothed to make it visually appealing, and is clearly visible even in a well-lit room.*

## Introduction

The goal of our MicroP's project is to create a device that can take in an audio signal from a source such as an iPod, and have a colorful illuminated display that represents the frequency content of the incoming music. The information is conveyed in a set of columns, which light up with the height of illumination determined by the magnitude of content in that frequency band. This project was designed to operate on a limited frequency range, with 8 different frequency bands displayed. This display is reminiscent of the "graphic equalizers that are often seen on stereo systems. The project will also allow for an application of the signal processing techniques developed in the Advanced System Engineering class (E101), with the use of digital filters to determine the frequency content.

## Project Overview

In order to display the frequency content of the incoming signal, several high-level tasks need to be accomplished. The incoming audio, in the form of a voltage signal, needs to be sanitized in the analog domain, and then converted into digital data. This digital signal then needs to be processed to determine the content in each of the desired frequency bands. Finally, this information is used to control a column-based output display. This gives the four main sections of the project: the analog signal conditioning, the PIC, the FPGA, and the output LEDs. Data flows linearly through each stage, as seen in figure 1. Input audio signals enter the system at the analog signal conditioning circuitry, and the LEDs light up as the output to the viewers. If a headphone splitter is used at the audio source, then the audio can be listened too as well as viewed on the system display.

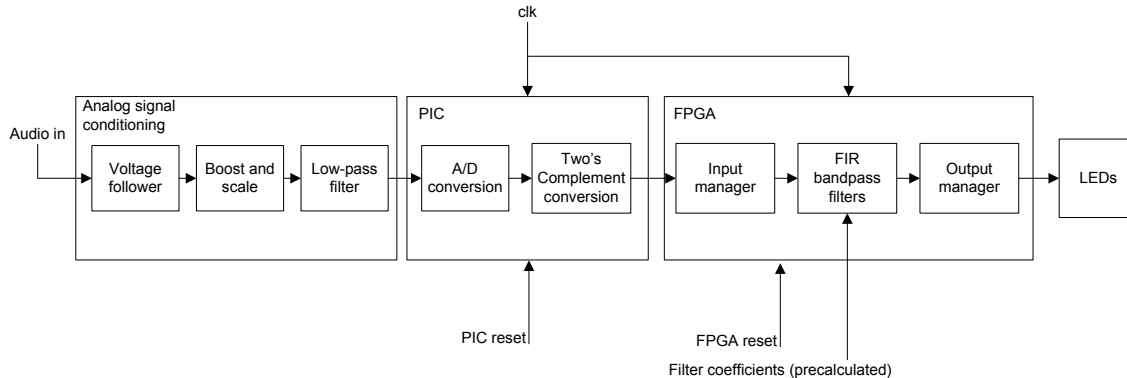


Figure 1: Data flow through the system

In designing this project, the two most important decisions were what frequency ranges to use for the analysis, and what method to use to calculate the signal content. The maximum frequency examined was set at 4000 Hz, which is high enough to capture at least the first harmonic of most musical sounds for example, the highest note on a piano, C8, just above 4000 Hz [1]. The method of analysis chosen was one that would be the most straightforward to implement on our available hardware: a series of digital Finite Impulse Response (FIR) bandpass filters spread out from 0 to 4kHz. The bands were spaced logarithmically, with the lower bands being smaller, to better reflect the distribution of musical content.

The entire system was implemented around a central breadboard. The LED array and signal conditioning circuitry were both implemented on daughterboards that plugged into the main

breadboard, to make the system modular. The overall system requires power for the Harrisboard (3.3 V minimum, usually 5 V), a ground, and power for the op-amps ( +5V and -5V). The initial signal conditioning requires power inputs of +5V, -5V, ground, and a 1/8 inch audio plug for signal input. It puts out a single output to a pin on the PIC. The LED output display has 8 data inputs to determine the height of a column, and 8 control inputs to determine which column is active, as well as a common ground. A schematic for the entire project can be seen in Figure 3.

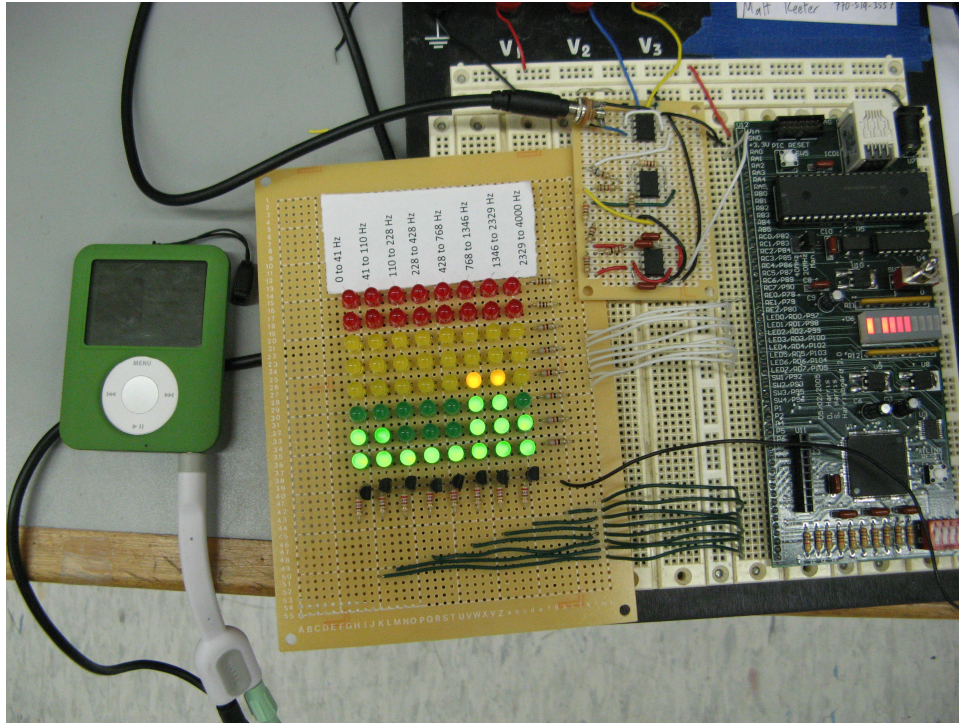


Figure 2: Frequency Analyzer in operation

### Analog Front End

The analog front end (AFE) consists of a series of conditioning circuits to prepare the music for sampling by the A/D converter. The three components of this system are a voltage follower (buffer), a booster/scaler, and a low-pass filter. These can be seen in Figure 4. Each stage uses a 741-series op-amp, which receive power at +5 and 5 V. When a stereo audio input is used, the left and right channels are shorted together by the 1/4 audio jack which was used to interface with the audio cable. This combined signal is the input voltage, while the signal's ground was tied to the common ground on the breadboard.

The voltage follower circuit, at the top of Figure 4, is fairly simple, consisting of just the op-amp and wire, with no other components. The purpose of the voltage follower is to isolate the audio source's output from the rest of the conditioning circuitry for example, to prevent excessive current draw on the device. While not initially anticipated, the need for this circuit was determined experimentally when attaching an iPod directly to the rest of the AFE led to a loss of signal. Once the voltage follower was included in the circuit, all of the components performed as expected.

The booster/scaler circuit is the middle block in Figure 4. This circuit's purpose is to take the input voltages, which cover a range of positive and negative values, and then shift and scale them to maximally fill the range from 0 to 3.3 V. This final range was chosen because it is the input

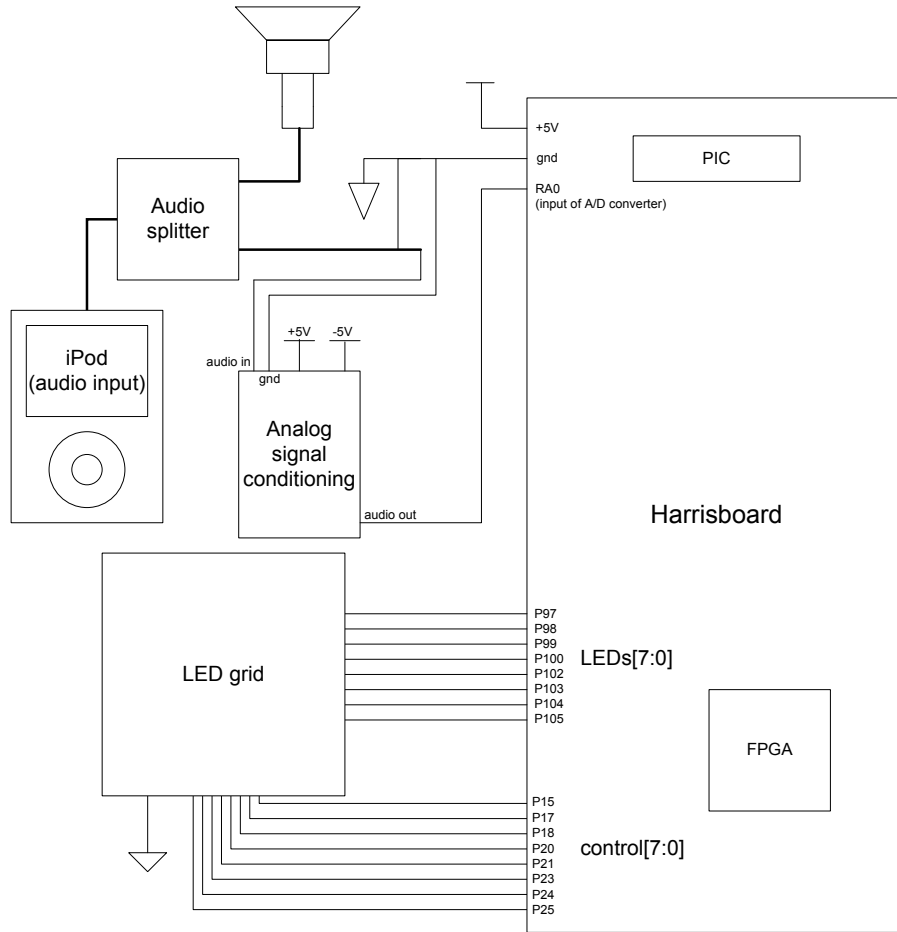


Figure 3: Schematic of overall project

range of the PIC's A/D converter. After using an oscilloscope to measure the output for an iPod at full volume, we found that the input voltages were in the range of  $-1.17\text{ V}$  to  $1.17\text{ V}$ . The desired output is a signal between  $0$  and  $3.3\text{ V}$ . Based on this, the desired scaling factor for the scale portion of the circuit is  $1.4\times$ . We selected resistor values of  $680\ \Omega$  and  $1\text{ k}\ \Omega$  to achieve this scaling.

The boost portion of the circuit is designed to raise the mean value of the signal from  $0\text{ V}$  to  $1.65\text{ V}$ . This was done by adding a DC offset using the same circuit. The exact value of the voltage needed was determined to be  $0.65\text{ V}$ . Resistors were chosen to create a voltage divider that changed  $5\text{ V}$  into the required voltage, which was placed across the second terminal of the op-amp. The end result of the components is a circuit which can take in voltages ranging from  $-1.17$  to  $1.17\text{ V}$  and linearly transform them into voltages ranging from  $0$  to  $3.3\text{ V}$ .

The final component of the AFE is the low-pass filter. This filter is designed to attenuate the frequency components outside of the range which the analyzer is designed to work withnamely, all frequencies greater than  $4000\text{ Hz}$ . The filter was designed using a Sallen-Key topology configured as a Butterworth filter. To create this circuit, the two resistors were fixed to be the same value, and the grounding capacitor was fixed as  $0.1\ \mu\text{F}$ . Based on these constraints, along with a corner frequency of  $4\text{ kHz}$ , the bypass capacitor was found to be  $0.2\ \mu\text{F}$ , and the resistors as  $281\ \Omega$ . The resulting filter has a gain that is constant at  $0\text{ dB}$  until  $4000\text{ Hz}$ , then drops off at  $-40\text{ dB/decade}$ .

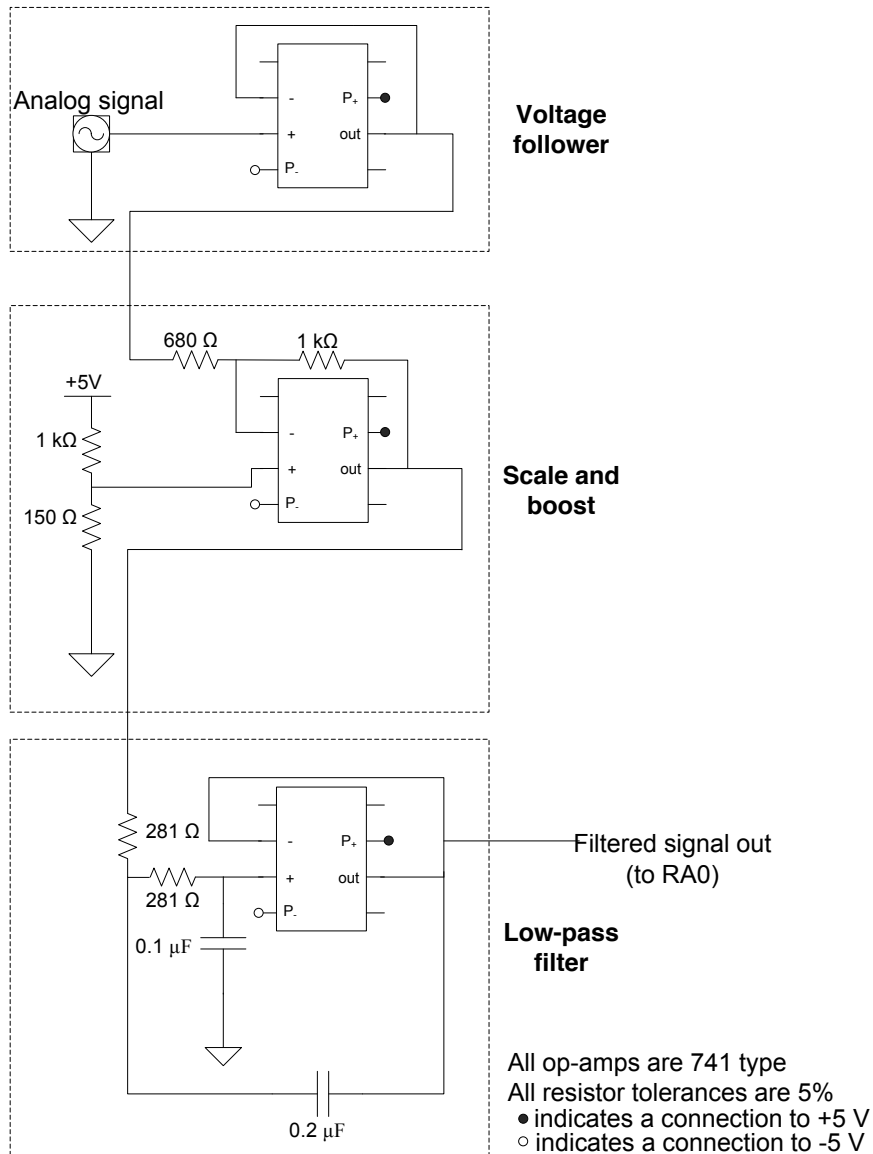


Figure 4: Analog Front End Schematic

## PIC

In this project, the PIC is used to sample analog data and pass the results to the FPGA. Since we chose to look at frequencies up to 4 kHz, the PIC must sample at above 8 kHz to avoid aliasing. We implemented code that causes the PIC to sample at approximately 9.6 kHz; this means that there is a Nyquist frequency of 4.8 kHz, and the lowest signal that could fold or alias into the bands of interest is 5.6 kHz. Thus, the analog low-pass filter has already been attenuating potential high-frequency noise for 1600 Hz before it could alias into the bands of interest. The PICs A/D converter takes in the output of the signal conditioning circuitry, and converts it into an 8-bit binary number, with 0 indicating 0V and 255 indicating 3.3V.

The PIC code runs by first initializing the A/D converter and Timer 0, with interrupts. The timer is set to trigger an interrupt every  $104 \mu\text{s}$ , corresponding to a frequency of 9.6 kHz. Whenever the interrupt for the A/D converter goes high, the system first takes this 8-bit value and subtracts 128 from it, converting from a 0-255 scale to a two’s-complement value between -128 and 127, which is expected by the FPGA. Then the PIC sets the 8 data bits to their desired values on the bus connecting the PIC to the FPGA. Then the PIC sets a separate “new data” bit high, signaling to the FPGA that the next data sample is ready to be recorded. The A/D converter is reinitialized to allow it to prepare for conversion. The PIC then continues to wait until the interrupt for Timer 0 goes off, indicating that the PIC should begin sampling the data again. It is at this point that the “new data” bit is reset back to 0, allowing the FPGA to detect when the next new set of data comes in. This process continues, allowing the PIC to sample the data at 9.6 kHz and send this data to the FPGA consistently. The C code which runs on the PIC can be found in Appendix A.

By running the PIC in this manner, we make it easier for the FPGA to avoid any issues with metastable data. By using this method, the 8 data bits have all resolved before the FPGA tries to read them, as the FPGA does not attempt to record the data until it has received a separate signal which is sent after the data has long since resolved. If, on the other hand, the “new data” bit is changing when the FPGA tries to read it, one of two things will happen: either the FPGA will read it as a 1 and take in the already-resolved new data, or it will read it as a 0 and wait an extra cycle before reading a 1 and recording the data. As the data bits remain unchanging for a significant amount of time after the “new data” bit goes high, this slight delay will not cause a problem.

## FPGA

The FPGA performs three main roles: Storing the sampled data, applying bandpass filters, and controlling the LED array. The data storage system runs independently of the other two systems; the other two share certain timing signals. The overall flow of data through the FPGA can be seen in Figure 5

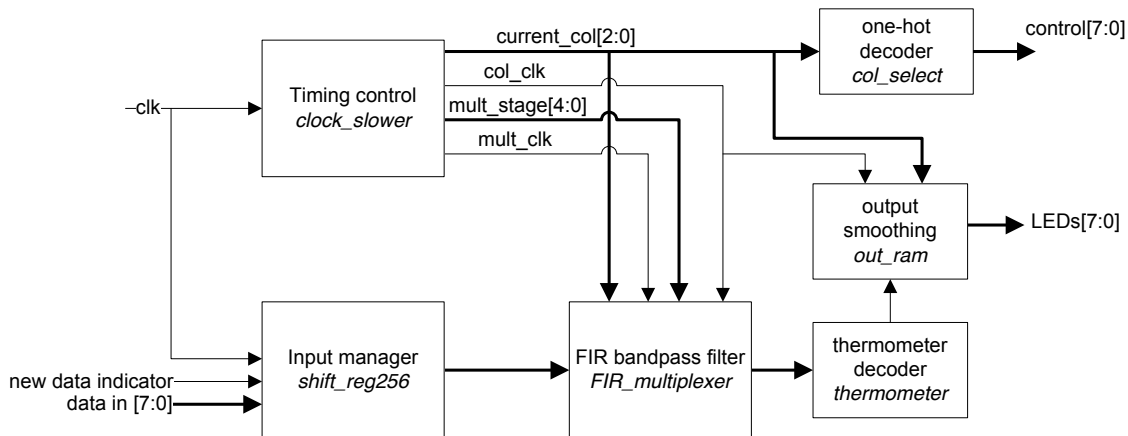


Figure 5: Data flow through FPGA

The FPGA’s first function is to store data from the PIC. This is done through the asynchronous interface described in the section above. When the “new data” bit goes from low to high, the FPGA adds the 8 bits of incoming data into a shift register at the next clock tick. This shift register is

2048 bits long, equivalent to 256 time-history values, each of which is 8 bits.

The next stage of data processing is applying the bandpass filters. This is synchronized such that only the bandpass filter for the active column is applied. We chose to use digital FIR bandpass filters [2]. To calculate the filtered output, the time history is multiplied with a pre-calculated set of coefficients, performing a calculation of the form

$$y = x_0c_0 + x_1c_1 + x_2c_2 + x_3c_3 + \dots x_nc_n$$

where the coefficients  $c_{1..n}$  are pre-calculated in Matlab using the code in Appendix C. These values are 8-bit integers, created using scaled versions of the "true" digital filter coefficients. These 2048 coefficients (256 coefficients at 8 bits each) were stored in one of the FPGA's block RAMs as a ROM created in CoreGen. The coefficients correspond to bandpass filters for the following bands: 0-41Hz, 41-110Hz, 110-228Hz, 228-428Hz, 428-768Hz, 768-1346Hz, 1346-2329Hz, and 2329-4000Hz. A plot of the bandpass filters used can be found in Figure 6.

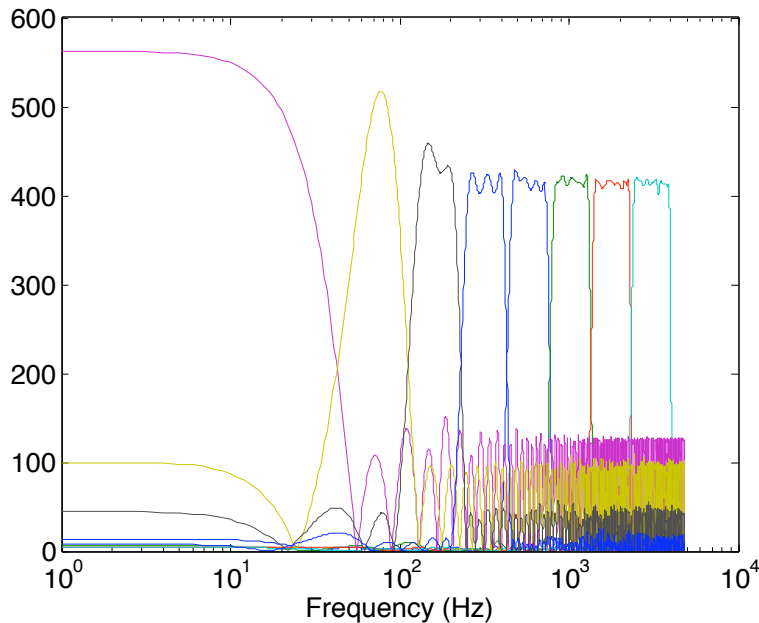


Figure 6: Plot of Bandpass FIR Filters (y axis is arbitrary units)

In order to create a 256-tap filter, the filter hardware (multipliers and adders) was time multiplexed. We created one module that behaved as an 8-tap filter, then used this filter 32 times over the course of the calculation, summing the results. Each calculation, new coefficients were read out of the block ram, and the sum was stored in a cumulative register. This time-multiplexing was necessary because there are not enough slices on the FPGA to create enough multipliers for this large of a digital filter. Instead, we chose to use the dedicated multipliers; however, this led to a second problem: the FPGA's dedicated multipliers share output circuitry with the block RAM. This limited us to eight multipliers, since we wanted to store the very large coefficients sets in block RAM for efficiency. The time multiplexing system uses the counter `mult_stage[4:0]`, which counts from 0 to 31 every time the current column increments by one (where the current column represents the filter band currently being calculated and displayed). The `FIR_multiplexer` block uses `mult_stage[4:0]` to select appropriate sections of the time history and coefficient ROM to send into the 8-tap filter block. This process is synchronized with `mult_clk`, which is a clock run-

ning  $32\times$  faster than the column clock. For more implementation details, the Verilog code used for the FPGA is in Appendix B.

The output control has three stages: thermometer-coding, smoothing, and time-multiplexing. In the first stage, three bits of the filtered signal are examined, and decoded to produce an 8-bit thermometer-coded value. These three bits were found by experimentation: they are the most significant bits that go high in the filtered output signal. This allows for the output display to be fully used, resulting in the best-looking results. This value is then passed on to the smoothing system.

The smoothing system prevents high-frequency flickering of the LEDs, which would otherwise be expected. The smoothing works as follows: there are 64 counters stored on the FPGA, one for each of the LEDs. When an input bit is high, meaning that a specific LED is supposed to be on, the corresponding LED's counter is set to `0xFF`; otherwise the counter reduces itself by one (minimum of zero) each time `col_clk` goes high. Each LED is turned on if the corresponding timer is nonzero. In other words, after the system calculates that an LED should be turned on, the output value for the LED is set to high for a minimum amount of time. This means that a rapidly flickering input bit will produce a constantly lit LED, which improves the visibility and visual appeal of the output.

Finally, the LED array is controlled by the FPGA. The FPGA turns on each column using the transistors tied to the column's common cathode. It cycles through the columns one at a time, at each column setting the appropriate values for the rows to illuminate the desired LEDs. The system cycles through all 8 columns, calculating and displaying the filtered output in each column so quickly that it appears that all columns are displaying data simultaneously.

## LED Array

The analog display consists of an  $8\times 8$  grid of LEDs. Each row of LEDs shares a anode, which is connected through a resistor to FPGA data output pins. These resistors are chosen based on the voltage drop across the LEDs to provide about 15 mA through each LED. Each column of the grid shares a cathode, which is connected through a transistor to ground. The row of transistors is enabled by the FPGA control output pins, connected through a resistor to limit the current output. This resistor was chosen to allow optimal transistor operation even if all 8 LEDs in a column were lit. The FPGA cycles through the columns, calculating and then displaying the correct values on the data output pins. A diagram of the LED grid is shown in Figure 7.

## Materials Used

The following materials were used in the project. Items without indicated prices were acquired from the Engineering department.

- 1 breadboard
- 1 Harrisboard
- 1 perfboard (\$4)
- 1 small perfboard (\$2)
- $\frac{1}{8}$ " connector plug (\$3 for 2 plugs)
- 1 audio cable (\$5.50)
- 64 LEDs: 16 red, 24 yellow, 24 green



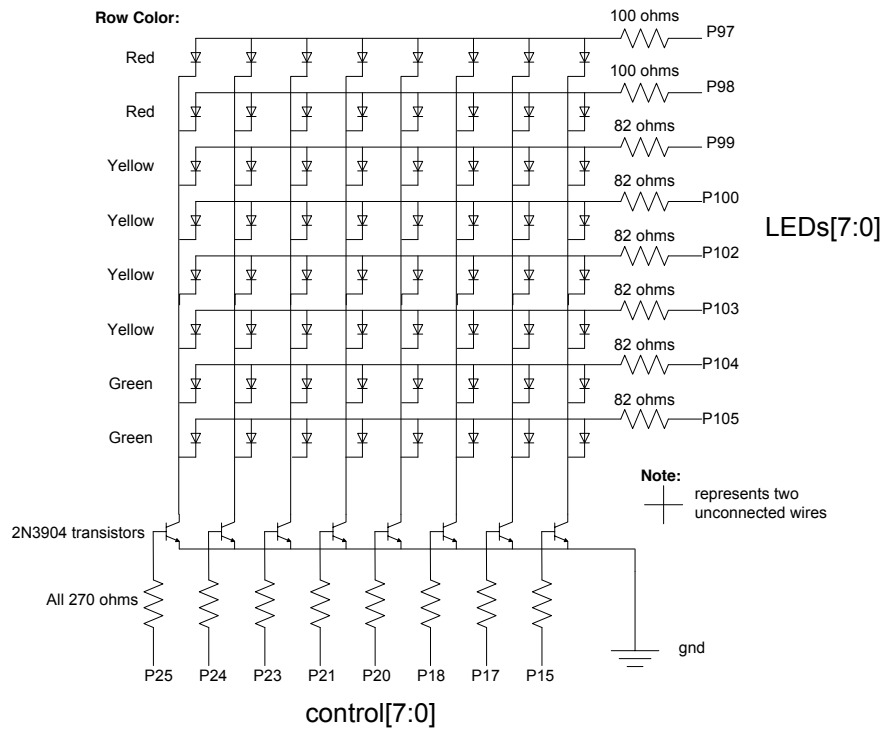


Figure 7: LED grid implementation

- 8 NPN transistors (2N3904)
- 3 741-type op-amps
- Various resistors
- Various capacitors
- Headphone splitter
- Speakers

## Results

The project was successful: an iPod could be plugged into the analog jack, and the LEDs lit up in synchrony with the song. The system was also tested using an audio file constructed in Audacity, which consisted of a series of pure sine waves at the center of each band played in succession. With each tone, the corresponding band lit up to the top. There was a small amount of spectral leakage noticeable in the lowest band. This is because this band occupies less than 1% of the total frequency range, so even with a 256-tap filter the cut-offs are not ideal (see Figure 6 for the frequency responses). The system also performed very well when given a regular song as input. By watching the LED output, it was possible to detect beats in the music. The 41-110Hz and 110-228Hz bands both exhibited large peaks following the primary "beat" of the music, to be expected

based on the low frequency instruments usually used to generate the sounds. Even with the  $8\times$  time multiplexing on the output display, the LEDs could be seen in a well-lit room; however, the effect was observed to be much more impressive in the dark.

## References

- [1] “Piano key frequencies.” Wikipedia 11 Dec. 2009. <[http://en.wikipedia.org/wiki/Piano\\_key\\_frequencies](http://en.wikipedia.org/wiki/Piano_key_frequencies)>
- [2] Bright, Anthony. Class Lecture. Advanced Systems Engineering. Harvey Mudd College, Claremont CA. 14 Oct 2009.

## Appendix A: C code

```
/*
A_D_convert.c
Chris Ferguson & Matt Keeter
cferguson@hmc.edu
mkeeter@hmc.edu

Code to take in Analog sound input and convert it to
8-bit digital signal at a specific sampling rate,
sending the converted values through PORTC
to an FPGA listening for a "new data" bit on PORTE[0].

*/

#include <p18f452.h>

void main(void);
void isr(void);

//goes to actual interrupt program upon interrupt
#pragma code high_vector=0x08
void high_interrupt(void){
    _asm
        GOTO isr
    _endasm
}

//creates the main program to setup everything and loop
#pragma code
void main(void) {

    //We want global and peripheral interrupts on
    INTCONbits.GIE=1;
    INTCONbits.PEIE=1;
    PIE1bits.ADIE=1;
    //Now turn on Timer 0 interrupt
    INTCONbits.TMROIE=1;

    //Configurations
    /*Timer0 or TOCON
    7:TMROn = 1
    6:T08BIT = 0 (16-bit mode)
    5:T0CS = 0 (internal clock)
    4:T0SE = 0 (doesn't matter)
    3:PSA = 1 (no prescaler!)
    2: = 0
```

```

1:      = 0      (don't care)
0:      = 0
*/
TOCON=0b10001000;

//TOCON=0b10000111; Used for slow register updating
/* A/D Converter: ADCON0
7-6:ADCS = 10    set A/D clock
5-3:CHS   = 000   read channel A[0]
2: Go/~Done = 0    Don't start yet
1:      = 0      unimplemented
0:ADON    = 1     turn on converter
*/
ADCON0=0b10000001;

/*A/D Converter: ADCON1
7:ADFM    = 0     left-justify
6:ADCS    = 0     sets A/D clock
5-4:      = 00    unimplemented
3-0:      = 1110 sets only A[0] as analog
*/
ADCON1=0b00001110;

//Setupt inputs/outputs
TRISA = 0xFF; //All inputs

TRISC = 0;    //All of these are outputs of PIC
TRISE = 0;    //

PORTC = 0;
PORTE = 0;

//set timer value
TMROH=0xFE;
TMROL=0x0C;

//MAIN CODE LOOP. Put interesting stuff here if we want to do any of it
while(1) {};

}

//Interrupt code
#pragma interrupt isr
void isr(void){

```

```
if(INTCONbits.TMROIF){
    INTCONbits.TMROIF = 0; //reset
    ADCON0bits.GO=1; //Start A/D converter
    PORTE=0; // valid bit low
    TMROH=0xfe; // reset timer
    TMROL=0x0c;
}
else if (PIR1bits.ADIF) {
    PIR1bits.ADIF=0; //reset
    PORTC=ADRESH; //Get Data
    PORTC=PORTC - 128; //Convert to two's complement
    PORTE=0x01; //valid bit high
}
}
```

## Appendix B: Verilog code

```
//////////////////////////////////////////////////////////////////
// Matt Keeter & Chris Ferguson
// mkeeter@hmc.edu
//
// spectrum_v3: performs bandpass filtering on an input signal,
// displaying the output on a grid of LEDs
//
//////////////////////////////////////////////////////////////////

module spectrum_v3(
    input      initb,
    input      clk,
    input  [7:0] data_in,
    input      new_data,
    input      music_mode,
    output  [7:0] LEDs,
    output  [7:0] control
);

    wire reset;
    assign reset = ~initb;

    // we're using a 256-tap filter, with 8 bits of data for each tap
    wire [2047:0] time_data;

    // this keeps track of the current column
    wire [2:0] current_col;

    // this is the output of the FIR filter
    wire [23:0] filtered_time;

    // these are various wires used to time-multiplex the multipliers
    wire mult_clk;
    wire col_clk;
    wire [4:0] mult_stage;

    // this block slows down the clock in various amounts, to set up
    // the output multiplexing and the multiplier multiplexing
    clock_slower timing_control(clk, reset, current_col,
        col_clk, mult_stage, mult_clk);

    // one-hot decoder of current_col
    col_select column_control(current_col, control);

    // manage the asynchronous input and store time data
```

```

shift_reg256 time_history(clk, reset, data_in, new_data, time_data);

// the actual FIR filter
FIR_multiplexer bandpass(time_data, current_col, mult_stage,
    mult_clk, reset, filtered_time);

// thermometer decoding
wire [7:0] therm;
thermometer display_control(filtered_time, current_col,
    music_mode, therm);

// output system that smooths out high-frequency flickering
out_ram outram(col_clk, reset, therm, current_col, LEDs);

endmodule

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
//
// module that takes in a fast clk (20 MHz), and outputs a slower counter
// that cycles from 0 to 7 and then overflows
//
// Also outputs mult_stage, which cycles from 0 to 3 with every counter tick,
// and mult_clk, which is a clock that switches with every tick of mult_stage
//
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////

module clock_slower(input clk, reset,
    output [2:0] current_col,
    output col_clk,
    output [4:0] mult_stage,
    output mult_clk);

// timer constantly counts up
reg [13:0] timer;

always @(posedge clk, posedge reset)
begin
    if (reset) begin
        timer = 14'b0;
    end
    else begin
        timer = timer + 1;
    end
end

```

```

        end
    end

    assign current_col = timer[13:11];
    assign col_clk = ~timer[10];
    assign mult_stage = timer[10:6];
    assign mult_clk = timer[5];

endmodule

////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
//
// module that multiplexes an FIR filter block to increase the number of
// coefficients. The FIR block is intended to use 8 coefficients; this
// module multiplexes it 32 times to make a 256-tap filter
//
////////////////////////////////////
module FIR_multiplexer( input [2047:0] time_history,
                       input [2:0] current_col,
                       input [4:0] mult_stage,
                       input mult_clk, reset,
                       output [23:0] y_abs);

    reg [63:0] current_x;
    wire[63:0] current_c;
    reg signed [23:0] y;

    // select the correct section of time-history to put into the filter
    // (this part should synthesize to a mux)
    always @(*)
    begin
        case(mult_stage)
            0: current_x = time_history[63:0];
            1: current_x = time_history[127:64];
            2: current_x = time_history[191:128];
            3: current_x = time_history[255:192];
            4: current_x = time_history[319:256];
            5: current_x = time_history[383:320];
            6: current_x = time_history[447:384];
            7: current_x = time_history[511:448];
            8: current_x = time_history[575:512];
            9: current_x = time_history[639:576];
            10: current_x = time_history[703:640];
            11: current_x = time_history[767:704];
            12: current_x = time_history[831:768];

```



```

13:  current_x = time_history[895:832];
14:  current_x = time_history[959:896];
15:  current_x = time_history[1023:960];
16:  current_x = time_history[1087:1024];
17:  current_x = time_history[1151:1088];
18:  current_x = time_history[1215:1152];
19:  current_x = time_history[1279:1216];
20:  current_x = time_history[1343:1280];
21:  current_x = time_history[1407:1344];
22:  current_x = time_history[1471:1408];
23:  current_x = time_history[1535:1472];
24:  current_x = time_history[1599:1536];
25:  current_x = time_history[1663:1600];
26:  current_x = time_history[1727:1664];
27:  current_x = time_history[1791:1728];
28:  current_x = time_history[1855:1792];
29:  current_x = time_history[1919:1856];
30:  current_x = time_history[1983:1920];
31:  current_x = time_history[2047:1984];
    default: current_x = 128'b0;
    endcase
end

// block ROM generated using coregen stores the coefficients
coeffmem256 memory(mult_clk,{current_col, mult_stage}, current_c);

wire signed [18:0] filter_output;

FIRfilter8 filter(current_x, current_c, filter_output);

// register to store sum of multiple filter iterations
always @(posedge mult_clk, posedge reset) begin
    if (reset) begin
        y = 24'b0;
    end
    else if (mult_stage == 3'b0) begin
        y = filter_output;
    end
    else begin
        y = y + filter_output;
    end
end

// take the absolute value of y to prevent some output flickering
assign y_abs = y[23] ? ~y[23:0]+23'b1 : y[23:0];

endmodule

```

```

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
// modified 11/21/09
//
// FIRfilter
// Takes in a set of 8-bit input values, and a set of 8-bit coefficients,
// then multiplies each input by its coefficient and sums the results
//
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
module FIRfilter8(input [63:0] x,
                  input [63:0] c,
                  output signed [18:0] y);
    wire signed [15:0] xc1, xc2, xc3, xc4, xc5, xc6, xc7, xc8;
    mult mult1(x[7:0], c[7:0], xc1);
    mult mult2(x[15:8], c[15:8], xc2);
    mult mult3(x[23:16], c[23:16], xc3);
    mult mult4(x[31:24], c[31:24], xc4);
    mult mult5(x[39:32], c[39:32], xc5);
    mult mult6(x[47:40], c[47:40], xc6);
    mult mult7(x[55:48], c[55:48], xc7);
    mult mult8(x[63:56], c[63:56], xc8);
    assign y = xc1+xc2+xc3+xc4+xc5+xc6+xc7+xc8;
endmodule

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
// Matt Keeter
// Chris Ferguson
// cferguson@hmc.edu
// modified 11/22/09
//
// shift_reg256
// Module to take act as a shift register for the 256 most
// recent inputs
//
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
module shift_reg256(
    input          clk,
    input          reset,
    input          [7:0] data_in,
    input          new_data,
    output reg     [2047:0] stored_data
);
    reg take_new; //wire to only take data once per new input

always@ (posedge clk, posedge reset)
    begin

```



```

        7:    columns=8'b10000000;
        default: columns=8'b00000000;
    endcase
end
endmodule

////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
// modified 12/5/09
//
// thermometer
// module to take in a input value and output an 8-bit thermometer style display
//
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
module thermometer(
    input [23:0] x,
    input [2:0] col_select,
    input music_mode,
    output reg [7:0] therm
);

reg [2:0]    y;

// to make music more interesting, pick different bits of
// outputs based on column
always @(*) begin
    if (music_mode) begin
        case (col_select)
            0: y = x[14:12];
            1: y = x[14:12];
            2: y = x[14:12];
            3: y = x[14:12];
            4: y = x[14:12];
            5: y = x[14:12];
            6: y = x[14:12];
            7: y = x[14:12];
        endcase
    end else begin
        y = x[14:12];
    end
end

//now decode into thermometer mode
always @(y)
    case (y)
        0: therm = 8'b00000000;

```

```

        1: therm = 8'b00000001;
        2: therm = 8'b00000011;
        3: therm = 8'b00000111;
        4: therm = 8'b00001111;
        5: therm = 8'b00011111;
        6: therm = 8'b00111111;
        7: therm = 8'b11111111;
        default: therm = 8'b0;
    endcase
endmodule

////////////////////////////////////////////////////////////////////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
// modified 12/2/09
//
// out_ram
// stores the output, and smooths out high-frequency blinking in the LEDs
//
// column_ram
// stores the outputs for one column
//
// LED_fadeaway
// manages the behavior of one LED
//
////////////////////////////////////////////////////////////////////////////////////////////////////
module out_ram(input clk, reset,
              input [7:0] data_in,
              input [2:0] current_col,
              output [7:0] data_out);

    wire [7:0] col_en;
    col_select onehotdecoder(current_col,col_en);
    wire [7:0] out1, out2, out3, out4, out5, out6, out7, out8;

    column_ram col1(clk,reset,col_en[0],data_in,out1);
    column_ram col2(clk,reset,col_en[1],data_in,out2);
    column_ram col3(clk,reset,col_en[2],data_in,out3);
    column_ram col4(clk,reset,col_en[3],data_in,out4);
    column_ram col5(clk,reset,col_en[4],data_in,out5);
    column_ram col6(clk,reset,col_en[5],data_in,out6);
    column_ram col7(clk,reset,col_en[6],data_in,out7);
    column_ram col8(clk,reset,col_en[7],data_in,out8);
    mux8 outmux(current_col,out1,out2,out3,out4,out5,out6,out7,out8,data_out);
endmodule

```

```

module column_ram(input clk, reset, en,
                  input [7:0] data_in,
                  output [7:0] data_out);
    LED_fadeaway LED1(clk,reset,en,data_in[0],data_out[0]);
    LED_fadeaway LED2(clk,reset,en,data_in[1],data_out[1]);
    LED_fadeaway LED3(clk,reset,en,data_in[2],data_out[2]);
    LED_fadeaway LED4(clk,reset,en,data_in[3],data_out[3]);
    LED_fadeaway LED5(clk,reset,en,data_in[4],data_out[4]);
    LED_fadeaway LED6(clk,reset,en,data_in[5],data_out[5]);
    LED_fadeaway LED7(clk,reset,en,data_in[6],data_out[6]);
    LED_fadeaway LED8(clk,reset,en,data_in[7],data_out[7]);
endmodule

```

```

module LED_fadeaway(input clk, reset, en,
                   input data_in,
                   output data_out);
    reg [15:0] countdown;
    // if the LED is lit, then start counting down
    // once the countdown hits zero, turn the LED off
    // (this smooths out high-frequency flickering)
    always @(posedge clk, posedge reset)
    begin
        if (reset) begin
            countdown = 16'b0;
        end
        else if (en) begin
            if (data_in) begin
                countdown = 16'h00FF;
            end else begin
                countdown = countdown - (countdown != 0);
            end
        end
    end
    assign data_out = |countdown;
endmodule

```

```

////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
// modified 12/2/09
//
// mux8
// chooses between 8 eight-bit inputs
//
////////////////////////////////////
module mux8(input [2:0] control,
            input [7:0] in1, in2, in3, in4, in5, in6, in7, in8,

```

```

        output reg [7:0] out);
always @(*)
    case (control)
        0: out = in1;
        1: out = in2;
        2: out = in3;
        3: out = in4;
        4: out = in5;
        5: out = in6;
        6: out = in7;
        7: out = in8;
    endcase
endmodule

/////////////////////////////////////////////////////////////////////////////////////////////////////////////////
// Matt Keeter
// mkeeter@hmc.edu
// Chris Ferguson
// modified 11/21/09*
//
// mult
// signed 8-bit multiplication
//
/////////////////////////////////////////////////////////////////////////////////////////////////////////////////
module mult(input signed [7:0] x,
            input signed [7:0] y,
            output signed [15:0] z);
    assign z = x*y;
endmodule

```

## Appendix C: Matlab code

Note: In the interest of space, we did not include the set of coefficients; however, the following Matlab code will generate them in a CSV file that can be imported into CoreGen's Memory Editor.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% findCoeffs.m
% Matt Keeter
% mkeeter@hmc.edu
%
% Matlab script to find the magic numbers that
% we need to plug into the FPGA to make it do
% digital FIR band-pass filters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Let's say that we want frequencies between 64 and 4000 Hz
display('Calculating band limits');
Fmin = 0;
Fmax = 4000;
Fs = 9620; % from PIC sampling rate

numbands = 8;

% generate bands such that each band is 1.7x larger than the previous
bands = (1:numbands);
logval = 1.7;
temp = fliplr(1./logval.^bands);
bandlimits = [Fmin cumsum(temp) .* (Fmax - Fmin) ./ sum(temp) + Fmin] ./ (Fs/2);
clear temp bands;

% and 256 taps
numsamples = 256;

display('Finding filter coefficients');
clear filtercoeffs;
filtercoeffs = zeros(numbands,numsamples);
for i=(1:length(bandlimits)-1)
    edge = (bandlimits(i+1) - bandlimits(i)) / (4);
    % special case for first band
    if (bandlimits(i) < edge)
        filtercoeffs(i,:) = firpm(...
            numsamples-1, [0 bandlimits(i+1)-edge/2 bandlimits(i+1)+edge/2 1],...
            [1 1 0 0]);
    % special case for last band
    elseif (bandlimits(i+1) + edge > 1)
        filtercoeffs(i,:) = firpm(...
            numsamples, [0 bandlimits(i)-edge/2 bandlimits(i) 1],...
            [0 0 1 1]);
    end
end
```



```

else
    filtercoeffs(i,:) = bandpass(...
        bandlimits(i)+edge/2, bandlimits(i+1)-edge/2, ...
        edge,...
        numsamples-1);
end
end

% digitize the values
filtercoeffsdig = round(filtercoeffs * 128 /max(abs(filtercoeffs(:))));

% convert negative values into two's complement
negatives = filtercoeffsdig<0;
filtercoeffsdig_tc = filtercoeffsdig;
filtercoeffsdig_tc(negatives) = 256 + filtercoeffsdig(negatives);

% print out the band limits
for i=(1:size(filtercoeffsdig_tc,1))
    fprintf('%d to %d Hz\n',...
        round(bandlimits(i)*Fs/2), round(bandlimits(i+1)*Fs/2));
end

% store the magic numbers in a csv file
memory = transpose(filtercoeffsdig_tc);
memory = memory(:);
saved = memory;
output = fopen('filtercoeffs.csv','w');
while (~isempty(memory))
    temp = transpose(memory(1:8));
    temp = fliplr(temp);
    temp = dec2hex(temp,2);
    temp = transpose(temp);
    temp = transpose(temp(:));
    fprintf(output,'%s,\n',temp);
    memory = memory(9:end);
end
fclose(output);

```