

# Octave Keyboard with Autoplay

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The goal of this project was to create a simple one octave keyboard mapped to buttons with the additional capability to autoplay “Kids” by MGMT when a switch is turned on. When the buttons corresponding to notes are pressed, the appropriate notes are played through the speaker, and LEDs which correspond to the keys light up. The LEDs can be disabled using a switch.

This project was created by Vivian Hu and Daniel Chen in Summer 2014 at Dartmouth College for the Digital Electronics (ENGS031/COSC056) course. This report goes over the implementation, design, and usage of the final product, which implements all of these features.

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# 1 Introduction: The Problem

The problem that this project solves is the creation of a one-octave keyboard, and the ability to produce certain sounds through circuit logic. An additional issue is representing the song that will be autoplayed.

## 2 Design Solution

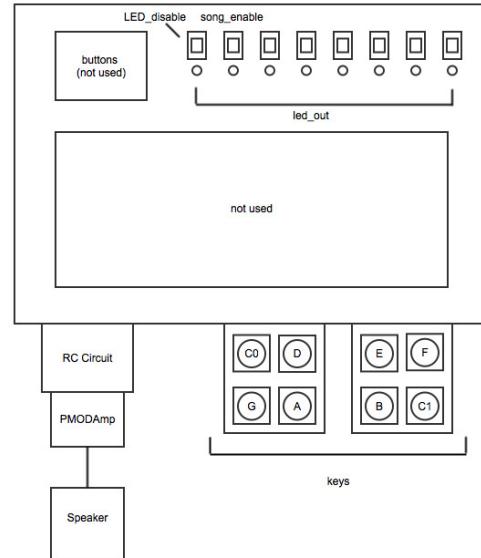
### 2.1 Specifications

The inputs to this circuit are:

- 8 Buttons that map to the notes to play (bottom right of image to the right).
- An LED disable switch which disables LED output.
- An AutoPlay switch which enables the playing of “Kids” by MGMT.

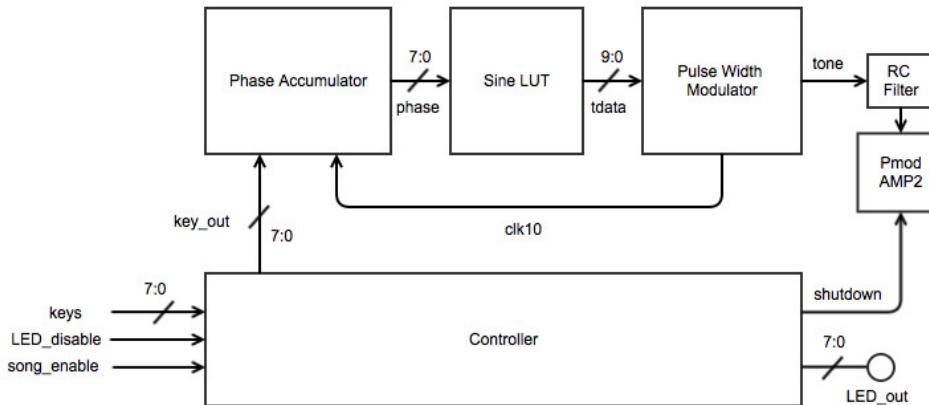
The outputs to the circuit are:

- 8 LEDs which correspond to the notes being played.
- A speaker which outputs the notes appropriate to the song or specified by the keys.



The picture shown below displays the datapath and control of the circuit. The controller (a finite state machine) takes in all of the inputs and outputs the LEDs. It emits a signal corresponding to the note that needs to be generated (a copy of the LED output) which is used to obtain the appropriate increment value for each key. The phase accumulator increments with this value, and the register output value is then used as an index into the SineLUT. The wave samples obtained from the SineLUT are passed to the pulse width modulator (PWM) to produce square wave pulses at the desired frequency. The RC filter then smooths out the wave pulses to produce the note we pressed!

For more information on how the circuit works, see section 2.3 “Theory of Operation.”



## 2.2 Operating Instructions

### Set up Circuit

To set up the one-octave keyboard circuit, you will need:

- Xilinx ISE Design Suite 14.4
- Digilent Adept
- The source code or the programming file
- 1 x Digilent NEXYS 3 Spartan 6 FPGA
- 2 x 4 button Digilent Button Module
- 1 x Digilent PmodBB
- 1 x Digilent PmodAMP2
- 1 x Speaker

Here are the steps to get the circuit running:

1. (If no bit file) Open the project in Xilinx, generate the programming file.
2. Plug in FPGA (NEXYS 3 Spartan 6) into computer.
3. Insert Digilent Button Modules in the top of JA1 and the top of JB1 on the NEXYS 3.
4. Insert the Digilent PmodBB into JD1.
5. Insert the PmodAMP2 into the top of J4 on the PmodBB.
6. Connect the speaker to J2 on PmodAMP2.
7. Set up the RC circuit on the PmodBB.
8. Open Digilent Adept, select bit file to program the FPGA.

### Playing notes

To play notes, press the buttons on the FPGA corresponding to the notes that you want to play. There are two rows of four buttons. The top four buttons represent low c, d, e and f, while the bottom four buttons are g, a, b and high c.

Only one note can be played at a time (first note pressed takes priority), and user-inputted notes only play when the auto-play switch is off.

### **Auto-play “Kids” by MGMT**

To play “Kids” by MGMT, simply flip the AutoPlay switch on. You cannot create additional notes at this time using the buttons.

### **Disable LEDs**

To disable the LEDs that light up corresponding to the notes that are pressed, simply turn on the LED disable switch.

## **2.3 Theory of Operation**

The key component of our keyboard project is the generation of sine waves of varying frequencies using a technique called direct digital synthesis (DDS). To implement this, we use a combination of a phase accumulator and a sine wave lookup table (LUT) to produce wave samples of specific frequencies. In the place of a digital-to-analog converter, we use a pulse width modulator (PWM) to convert these sine wave samples to audio.

The controller of our program is a finite state machine. The controller takes in the user’s input and turns it into a single-note output for the Phase Accumulator and the LEDs. It uses the note that was input first. If two notes are both initially pressed at the same exact time, the lower note is used. When the autoplay switch gets turned on, the state machine moves into hard-coded states that play MGMT’s “Kids.” The song only starts if the user is not currently pressing a key. The song consists of a large number of states that output a time that corresponds to the length of the note or the rest, and waits for either the switch to be turned off (at which point it goes to idle) or for the beat counter to reach its max (at which point it moves to the next note or rest).

The song itself consists of 3 snippets, which repeat in a particular fashion. Given that the three parts are A, B, and C, the song is a repetition of ACACBCBC. To keep track of this, an additional counter is used to determine whether to go to A or B at the end of C. See the appendix for detailed state diagrams related to the controller.

8 different buttons (button module extensions on the FPGA), or “key” serve as the main “playable” interface of the keyboard. In VHDL, the keys are represented as an 8-bit bus input to the controller, where each bit represents a different note. Because our keyboard is monophonic, the controller checks each bit in succession from low to high C and outputs the first note it detects to the FreqLUT. As a result, only one bit in the 8-bit key\_out vector received by ToneFreq-LUT should be high at a time; otherwise, when no button is being pressed, all bits are ‘0’. This prevents conflicts when multiple buttons are pressed at once. The

controller also takes in an LED\_disable input that disables the LEDs and a song\_enable that automatically plays back a pre-programmed song (here “Kids” by MGMT).

Key\_out is then used as an index of sorts into the ToneFreq-LUT, which contains the pre-calculated phase increment values for each note, which is related to the desired frequency in the following way where N represents the bit size of the accumulator and fclk is the frequency of the clock. We use N=13 here. This increment value is then passed on to the phase accumulator.

The phase accumulator is essentially an incrementer composed of an adder and a register which increases by the increment value every clock cycle. However, although the system is running at a frequency of about 50MHz in order to reduce noise, in actuality the phase accumulator is updating at a frequency of around 10kHz, at the clk10 signal given by the PWMCounter. As a result, clk10 here serves as an enable. The phase produced by the accumulator is then passed as an input address to the SineLUT. However, because our SineLUT only takes an 8-bit phase, only the 8 most significant bits are used.

To obtain wave samples, this value is then used as an index into a SineLUT supplied by the Xilinx Core Generator. Rather than having to generate all the samples of a waveform everytime, the values of a  $2^M$  (where M is the bit size of our phase) sample wave are simply stored in block memory (BRAM) for easy access. The SineLUT generates a 10-bit sample for conversion by the PWM.

The PWM maps the amplitude of the signal to a square wave pulse by comparing the sample value (which needs to be first converted from two’s complement to unsigned offset binary) to a counter value. When the count is less than the sample, the comparator output is a ‘1’; otherwise the output is a ‘0’. In order to send the clk10 enable to the phase accumulator at a 10kHz frequency, the PWM counter also generates a terminal count signal every 5,000 clock cycles.

The signal then passes through an off-board low-pass RC filter that reduces higher frequency signal noise before passing the tone through to the speaker. One importnat thing to note is that the Pmod we used had a ‘shutdown’ signal that had to be tied high in order to output sound.

Our circuit also features the additional functionality of automatically playing a pre-programed song when given the song\_enable signal. Most of this work is done by the controller state-machine (ie which note or sequence to go to next). However, in order to get the song to play at an appropriate speed, we implemented an additional BeatCounter that counts at a rate of about 240 beats per minute. When the signal to autoplay the song is given, the controller sends a count\_en signal and a number count\_to to the beat counter letting it know how long to “hold” the note before sending the terminal tc\_tick back to the controller to move on to the next note/state.

## 2.4 Construction and Debugging

To build the circuit, we began by building and testing the VHDL modules for the PWM. We designed the counter and the comparator and simulated the generation of wave “samples” with a separate counter in the place of our DDS module. In our testbench, we were able to observe the square wave pulses getting wider as the “sample” increased as expected. From there, we implemented the phase accumulator. Testing was simply a matter of assigning an arbitrary number to the increment signal and confirming the values were adding up correctly. The next step was designing a lookup table with phase increment information for each note frequency and mapping it via the top module to the phase accumulator. We did run into a slight problem here with integer arithmetic. When trying to calculate the increment (as in equation above), dividing the desired frequency by the clock frequency first would always yield 0. To account for this, we simply multiplied the desired frequency by the phase constant ( $2^N$ ) before dividing that product by the clock frequency.

Once the main components were built and mapped together, we implemented the FSM controller, which handled the key and led outputs. From there, using a PmodBB (breadboard), we built a small low-pass RC filter; we ran into a little bit of wiring trouble because we weren’t properly wired to ground, but it was pretty easily fixed. We then passed our tone through the RC filter and were able to display our sine waveforms on the oscilloscope. Our signal was definitely a sine wave, but we discovered that our desired frequencies were a power of 10 too large. It turned out this was because we had been testbenching our programs on a 10MHz clock, even though the FPGA was running at 100MHz. Adding a clock divider and clock buffer fixed this issue. After this, we were able to generate tones at the desired frequency, but we were getting a lot of residual high frequency noise. To counter this, we upped our system clock to 50MHz from 10MHz for a higher carrier frequency. This way, even though our PWMCounter was still only sending enable signals to the phase accumulator at 10kHz, the counter itself was running at 50MHz. Adding a larger capacitor helped to significantly reduce the noise, but also the volume of the keyboard itself. Although the noise is barely perceptible now, you can still hear it slightly.

We also ran into a bug where the keyboard would be playing normally and then suddenly everything would stop. We figured some kind of metastability was occurring because we were using switches as “keys”. We noticed that the keyboard would usually stop when we held a switch between ‘0’ and ‘1’. After switching over to buttons, the problem was still occurring, but we remembered that we had forgotten to add debouncers to our buttons. This resolved our issue.

At the very end, once our keyboard was completely playable, we decided to go back in and implement

the autoplay functionality. Most of that was done by simply adding more states to the controller. The only extra component we needed was a “metronome” of sorts in the form of our BeatCounter, which counted at a rate of 4 beats per second, or 240 beats per minute. Testbenching the counter was difficult because it took the simulator so long to generate a couple standard seconds as opposed to the usual nano- or micro- seconds, but we were able to observe terminal count ticks occurring at the right time. The major issue we ran into was that the first note of the song would sometimes be cut short or get dragged out. We resolved this by adding another “idle”-like state that only occurred when the song\_enable went from low to high.

### 3 Evaluation of Design

Our solution is a simple standard solution to a keyboard. Although we finished everything we set out to do, there are definitely things that could have been improved upon or added.

We far from maxed out the resources of the Nexys3. This leaves space for many things. We could have used a smaller frequency resolution to increase the note accuracy, added much more notes (potentially by using a switch for octaves), allowed sharps and flats, or allowed recording and playback.

General features that we speculated on but ended up not pursuing included adding a metronome and additional songs.

Additionally, the hardware is not the best for the project. Having the keys split into two rows is non-standard and makes the project unusable for most practical purposes.

If we were to start over on this project, we would do a better job testing each component before implementing them as part of the larger project. We ended up having to do a lot of debugging on issues that could have been picked out earlier by a more “unit tested” approach.

### 4 Conclusions and Recommendations

The original goal of our project was to simply make a one-octave keyboard that plays all the notes in C major. LEDs would light up when notes were played, unless an “LED disable” switch was turned on.

At the end, we were not only able to accomplish our original goal of the simple keyboard but also to add an additional autoplay feature that played “Kids” by MGMT.

For future groups looking to create this project, we would recommend that they really take the time to understand the operation of the circuit before jumping into the project. Another important consideration is to remember to synchronize the inputs and debounce the buttons throughout the project’s creation.

## 5 Acknowledgments

We would like to thank Eric Hansen and Dave Picard for their support and mentorship throughout not only this project but also the course. We would also like to thank the other students of Digital Electronics as well as the TAs. We'd also like to thank MGMT for an awesome song that conveniently contains itself to a single octave.

5.1 and 5.2 list the contributions for each partner. Although both partners had their hands in most aspects of the project, some components generally had one partner who was more involved in its creation.

### 5.1 Vivian's Contributions

- Circuit Design
- DDS, PWM, FreqLUT, PlayCount
- RC Circuit
- Block Diagrams

### 5.2 Daniel's Contributions

- Majority of the controller, including auto-play
- Design and creation of song auto-play, state diagram
- Top level
- Diagrams
- LaTeX for report
- Git creation/management

## 6 References

- [1] Cordesses, Lionel. "Direct Digital Synthesis: A Tool for Periodic Wave Generation." *IEEE Signal Processing Magazine*. IEEE, July 2004. Web.
- [2] Hansen, Eric. *Lab Assignment 1*. N.p.: ENGS128 - Advanced Digital System Design, Spring 2011. PDF.
- [3] *Introduction to Direct Digital Synthesis*. San Jose: Intel Corporation, June 1991. PDF.
- [4] Palacheria, Amar. *Using PWM to Generate Analog Output*. N.p.: Microchip Technology Inc., 1997. PDF.

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## 7.1 System level diagrams

### 7.1.1 Front Panel

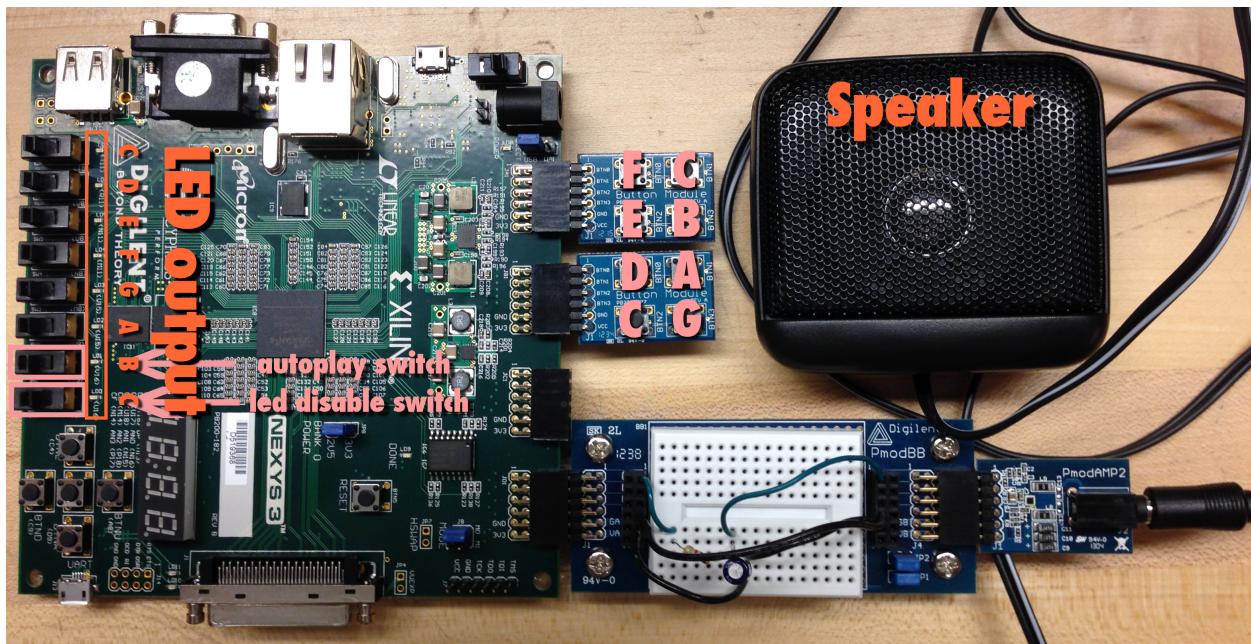


Figure 1: Annotated Digital Photo of Project

### 7.1.2 Block Diagram

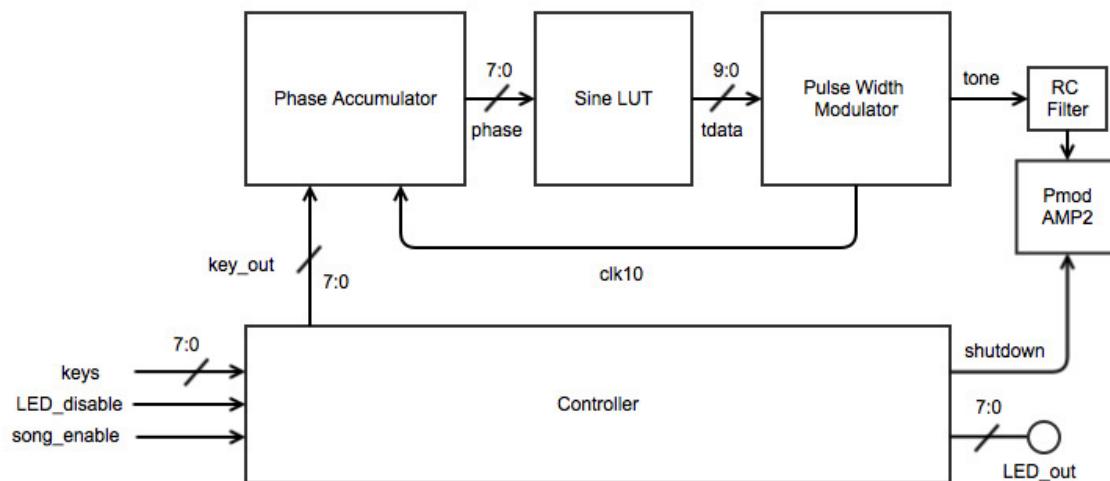


Figure 2: Basic Block Diagram of Keyboard

Keyboard Block Diagram

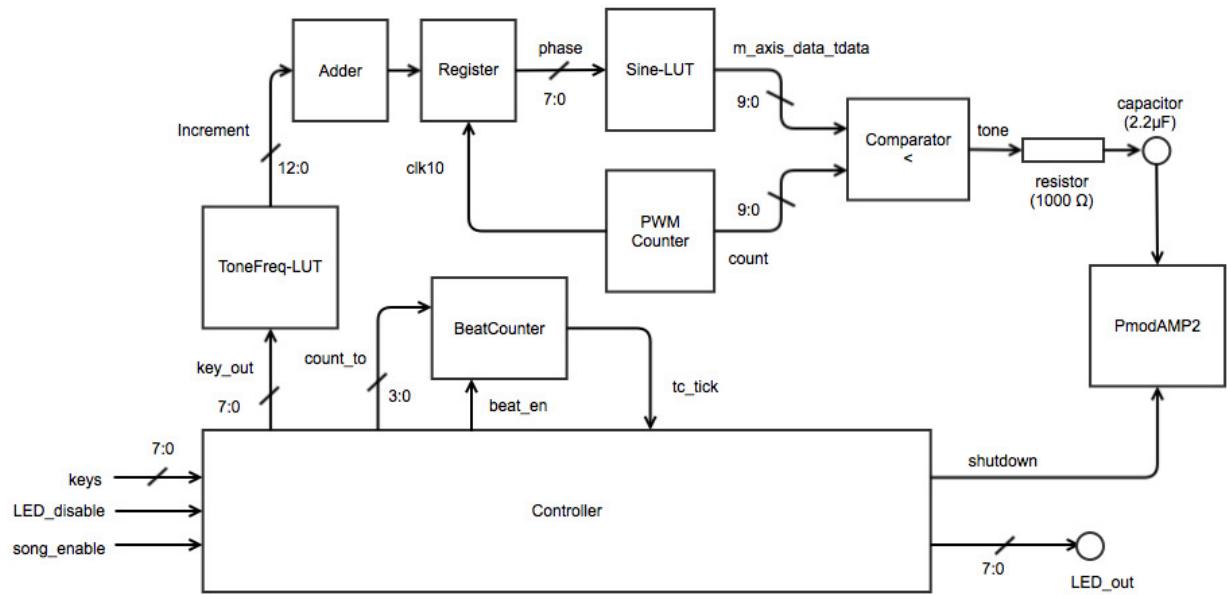


Figure 3: Advanced Block Diagram of Keyboard

#### 7.1.3 Schematic Diagram

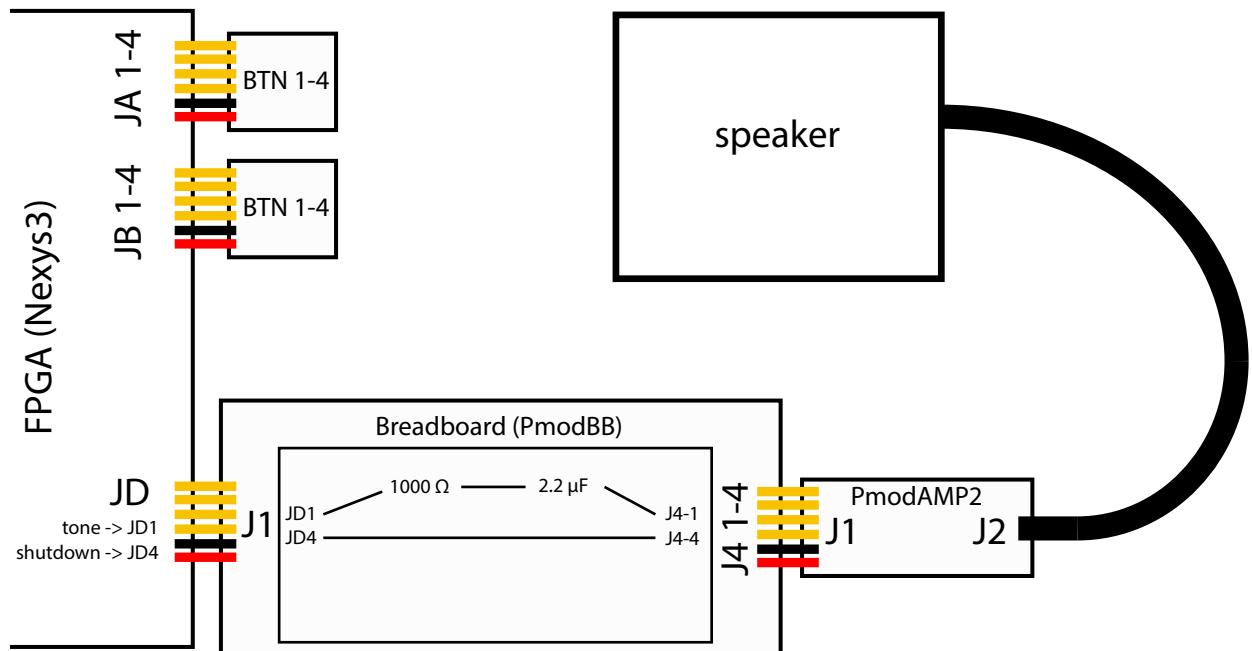


Figure 4: Schematic Diagram for the RC Filter

#### 7.1.4 Package Map

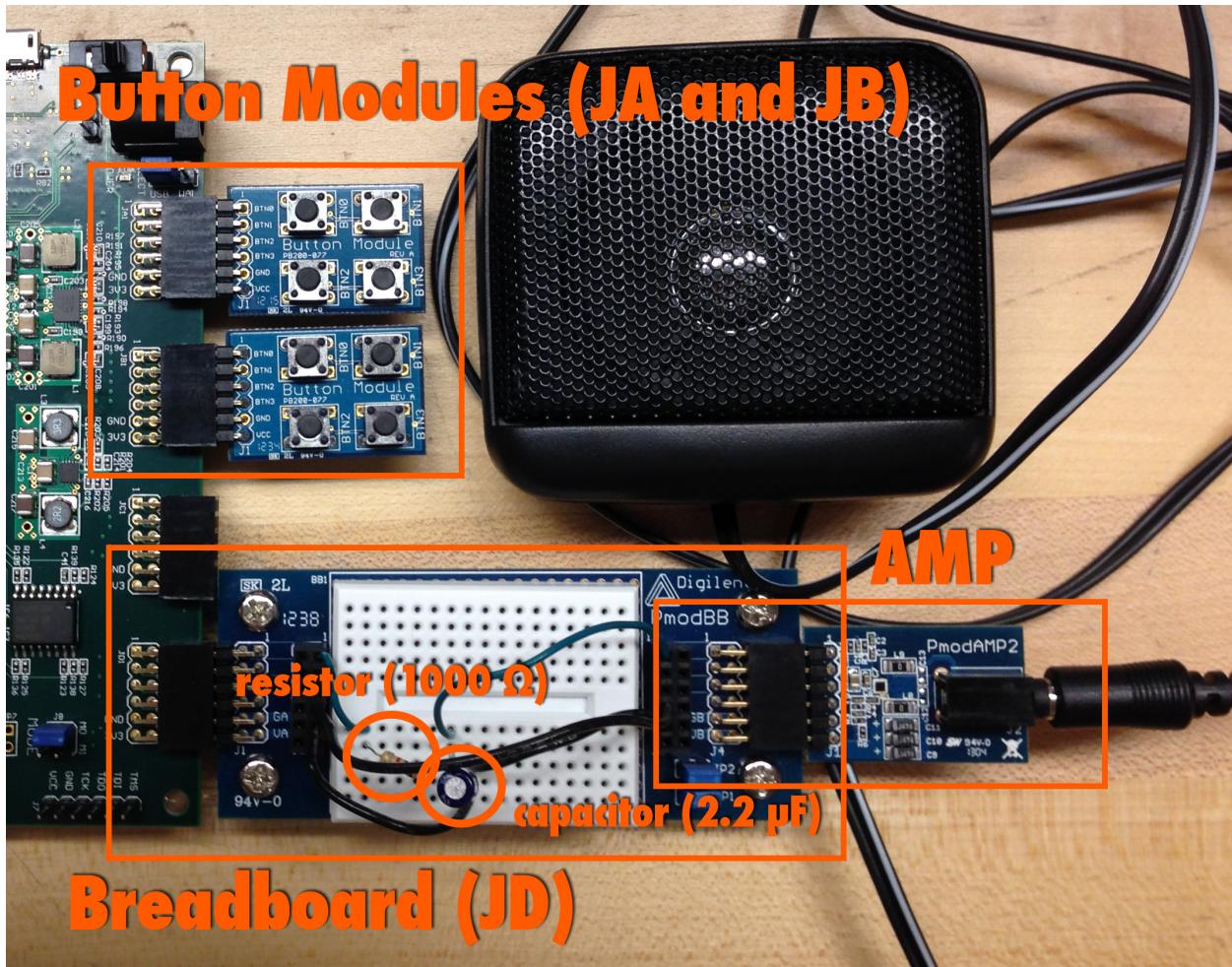


Figure 5: Package Map

#### 7.1.5 External Components

Table 1: Parts List

Reference	Quantity	Description
Nexys3	1	Digilent Nexys3 board
PmodBTN	2	Digilent PmodBTN Push Button. 4 buttons
PmodAMP2	1	Digilent Amplifier for monophonic output
PmodBB	1	Digilent Bread board
Speaker	1	Any generic speaker with standard input

## 7.2 Programmed Logic

### 7.2.1 State Diagrams

For simplicity, the state machine for this program is represented in two state diagrams. The first, “User Play State Diagram,” represents the state machine for when the user is given input through the buttons. The second, “Autoplay State Diagram,” represents the state machine when the autoplay mode is on. Both state diagrams share an idle state. If the song enable switch is off, the “User Play State Diagram” should be used. If it is turned on, the “Autoplay State Diagram” should be used.

The program starts at the idle state in the “User Play State Diagram.” If the song enable switch is turned on, the state jumps to autoidle in the “Autoplay State Diagram.” Otherwise, the state changes depending on the user’s input.

**Default Values if unspecified:**

```
next_state <= curr_state;
out <= (others => '0');
key_out <= output;
count_out <= "0001";
repeat_tick <= '0';
beat_en <= '0';
```

Figure 6: State Diagram Defaults

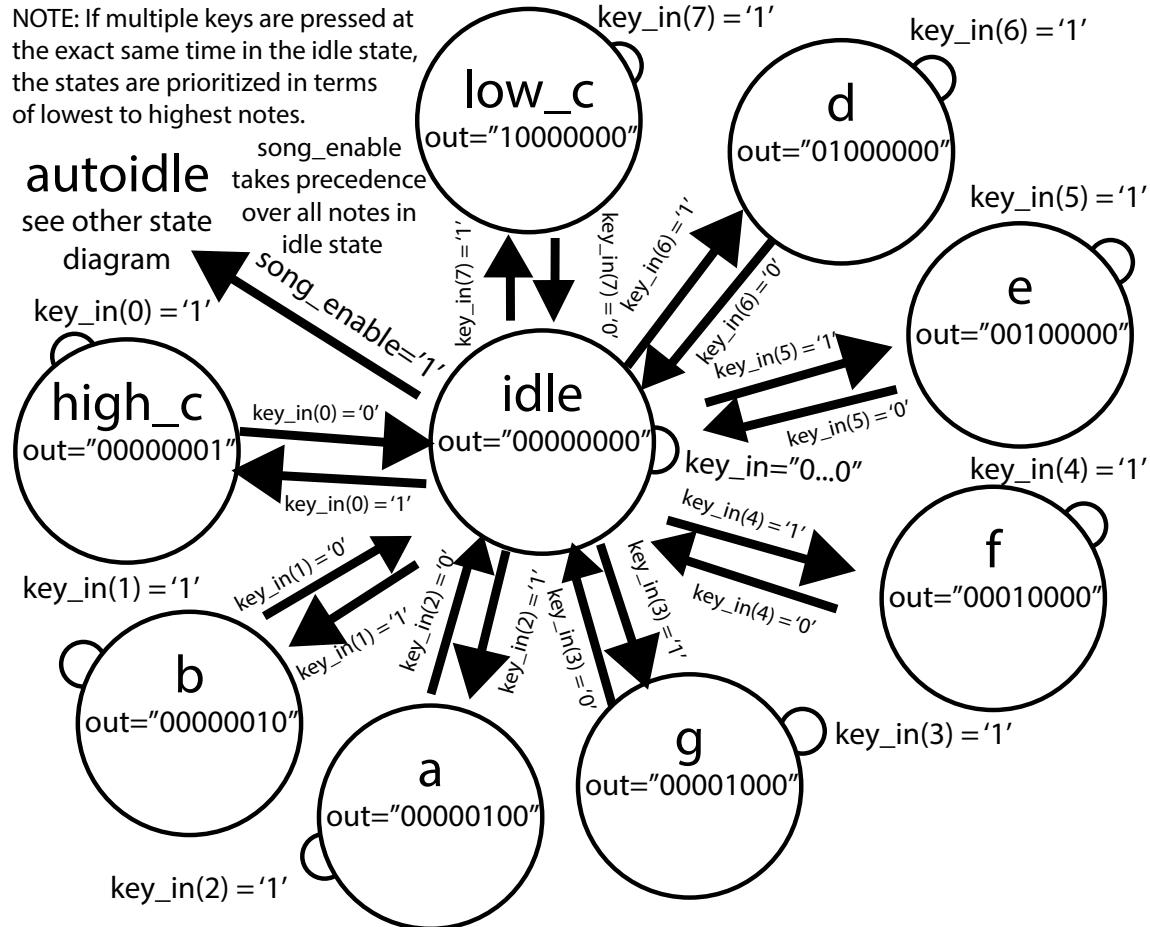


Figure 7: User Play State Diagram

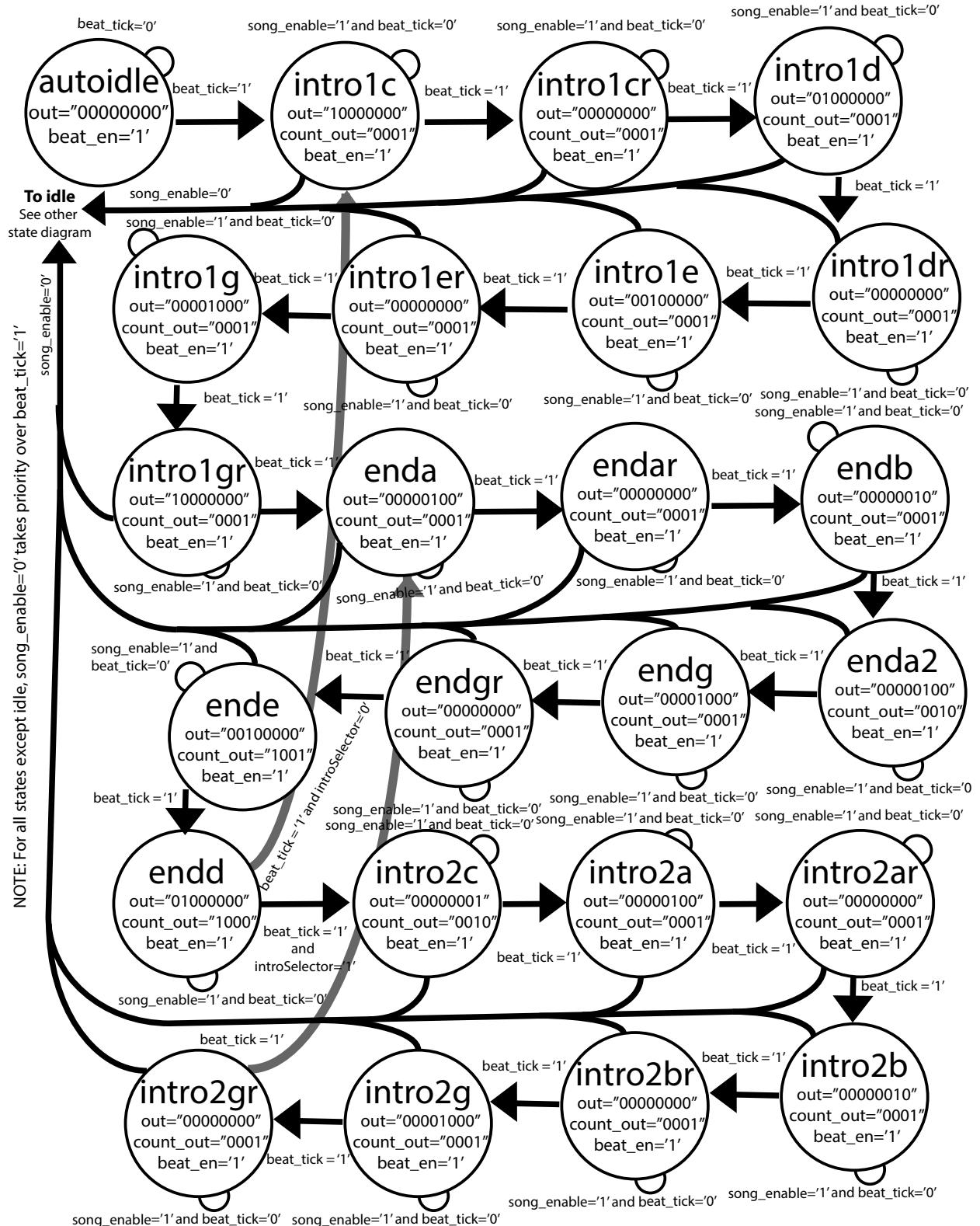


Figure 8: Autoplay State Diagram

### 7.2.2 VHDL Code

Figure 9: OctaveKeyboardTop.vhd

---

```

1  -- Company: ENGS 31
2  -- Engineer: Vivian Hu, Daniel Chen
3  --
4  -- Create Date: 19:58:26 08/12/2014
5  -- Design Name: Top level for Octave Keyboard
6  -- Module Name: OctaveKeyboardTop - Behavioral
7  -- Project Name: OctaveKeyboard
8  -- Target Devices: Nexys3
9  -- Tool versions:
10 -- Description: Top level VHDL module for keyboard
11 --
12
13 library IEEE;
14 use IEEE.STD_LOGIC_1164.ALL;
15 use IEEE.NUMERIC_STD.ALL;
16
17 library UNISIM;
18 use UNISIM.VComponents.all;
19
20 entity OctaveKeyboardTop is
21     Generic (    ACCUMSIZE      : integer := 13;      -- phase accumulator bitsize
22               INDEXSIZE      : integer := 8;       -- SinLUT index bitsize
23               LUTOUT        : integer := 10);     -- SinLUT out bitsize
24
25     Port (    clk          : in  STD_LOGIC;
26             keys         : in  STD_LOGIC_VECTOR (7 downto 0);
27             led_disable  : in  STD_LOGIC;
28             song_enable  : in  STD_LOGIC;
29             tone         : out STD_LOGIC;
30             shutdown     : out STD_LOGIC;
31             led_out      : out STD_LOGIC_VECTOR (7 downto 0));
32 end OctaveKeyboardTop;
33
34 architecture Behavioral of OctaveKeyboardTop is
35
36     -- signals for 100MHz to 50Mhz clk divider
37     signal clk_en      : std_logic := '0';
38     signal slowclk     : std_logic;
39
40     signal led_disable_sync : std_logic := '0';
41     signal song_enable_sync : std_logic := '0';
42
43     -- mapping signals
44     signal step : std_logic_vector(ACCUMSIZE-1 downto 0) := (others => '0');
45     signal controllerKeys : std_logic_vector(7 downto 0) := (others => '0');
46     signal phase : std_logic_vector(INDEXSIZE-1 downto 0) := (others => '0');

```

---

```

47 signal lutfreq : std_logic_vector(15 downto 0) := (others => '0');
48 signal reg_en : std_logic := '0';
49 signal tempo_en : std_logic := '0';
50 signal keyDB : std_logic_vector(7 downto 0) := (others => '0');
51 signal countDone : std_logic := '0';
52 signal count : std_logic_vector(3 downto 0) := (others => '0');

53
54 -- BEGIN component declarations
55 COMPONENT Controller
56 PORT ( clk : in STD_LOGIC;
57         key_in : in STD_LOGIC_VECTOR (7 downto 0);
58         led_disable : in STD_LOGIC;
59         song_enable : in STD_LOGIC;
60         beat_tick : in STD_LOGIC;
61         beat_en : out STD_LOGIC;
62         count_out : out STD_LOGIC_VECTOR(3 downto 0);
63         key_out : out STD_LOGIC_VECTOR (7 downto 0);
64         led_out : out STD_LOGIC_VECTOR (7 downto 0));
65 END COMPONENT;
66
67 COMPONENT FreqLUT
68 PORT ( clk : in STD_LOGIC;
69         key_in : in STD_LOGIC_VECTOR (7 downto 0);
70         increment : out STD_LOGIC_VECTOR (ACCUMSIZE-1 downto 0));
71 END COMPONENT;
72
73 COMPONENT DDS
74 PORT ( clk : in STD_LOGIC;
75         clk10 : in STD_LOGIC;
76         step : in STD_LOGIC_VECTOR(ACCUMSIZE-1 downto 0);
77         phase : out STD_LOGIC_VECTOR(INDEXSIZE-1 downto 0));
78 END COMPONENT;
79
80 COMPONENT PWM
81 PORT ( clk : in STD_LOGIC;
82         sample : in STD_LOGIC_VECTOR(LUTOOUT-1 downto 0);
83         slowclk : out STD_LOGIC;
84         pulse : out STD_LOGIC);
85 END COMPONENT;
86
87 COMPONENT SinLUT
88 PORT ( aclk : in STD_LOGIC;
89         s_axis_phase_tvalid : in STD_LOGIC;
90         s_axis_phase_tdata : in STD_LOGIC_VECTOR(7 DOWNTO 0);
91         m_axis_data_tvalid : out STD_LOGIC;
92         m_axis_data_tdata : out STD_LOGIC_VECTOR(15 DOWNTO 0));
93 END COMPONENT;
94
95 COMPONENT debounce
96 PORT ( clk : in STD_LOGIC;
97         switch : in STD_LOGIC;
98         dbswitch : out STD_LOGIC);

```

```

99      END COMPONENT;
100
101     COMPONENT PlayCount is
102        PORT ( clk : in STD_LOGIC;
103                count_en : in STD_LOGIC;
104                count_to : in STD_LOGIC_VECTOR (3 downto 0);
105                tc_tick : out STD_LOGIC);
106    END COMPONENT;
107    -- END component declarations
108
109 begin
110   -- synchronizer for auto-play-song switch input
111   SynchronizeSwitches: process(clk)
112   begin
113     if rising_edge(clk) then
114       led_disable_sync <= led_disable;
115       song_enable_sync <= song_enable;
116     end if;
117   end process SynchronizeSwitches;
118
119   -- slow main clock down by half (here: 100Mhz to 50Mhz)
120   clkDivider: process(clk)
121   begin
122     if rising_edge(clk) then
123       clk_en <= NOT(clk_en);
124     end if;
125   end process clkDivider;
126
127   -- map signals
128   shutdown <= '1';      -- tie shutdown signal high for speaker pmod
129
130   slowclk_buf: BUFG
131     Port map ( I => clk_en,
132                 0 => slowclk );
133
134   -- debouncers for note buttons
135   debouncer0: debounce
136     Port map ( clk => slowclk,
137                 switch => keys(0),
138                 dbswitch => keyDB(0) );
139
140   debouncer1: debounce
141     Port map ( clk => slowclk,
142                 switch => keys(1),
143                 dbswitch => keyDB(1) );
144
145   debouncer2: debounce
146     Port map ( clk => slowclk,
147                 switch => keys(2),
148                 dbswitch => keyDB(2) );
149
150   debouncer3: debounce

```

```

151      Port map ( clk => slowclk,
152                  switch => keys(3),
153                  dbswitch => keyDB(3) );
154
155  debouncer4: debounce
156      Port map ( clk => slowclk,
157                  switch => keys(4),
158                  dbswitch => keyDB(4) );
159
160  debouncer5: debounce
161      Port map ( clk => slowclk,
162                  switch => keys(5),
163                  dbswitch => keyDB(5) );
164
165  debouncer6: debounce
166      Port map ( clk => slowclk,
167                  switch => keys(6),
168                  dbswitch => keyDB(6) );
169
170  debouncer7: debounce
171      Port map ( clk => slowclk,
172                  switch => keys(7),
173                  dbswitch => keyDB(7) );
174
175  KeyControl: Controller
176      PORT MAP ( clk          => slowclk,
177                  key_in       => keyDB, -- change to keys if simulating
178                  led_disable  => led_disable_sync,
179                  song_enable  => song_enable_sync,
180                  beat_tick    => countdone, -- passed to PlayCount
181                  beat_en     => tempo_en, -- passed to PlayCount
182                  count_out    => count, -- passed to PlayCount
183                  key_out      => controllerKeys, -- passed to FreqLUT
184                  led_out       => led_out); -- straight to LEDs
185
186  KeyFrequencies: FreqLUT
187      PORT MAP ( clk          => slowclk,
188                  key_in       => controllerKeys, -- from controller
189                  increment   => step); -- passed to DDS
190
191  PhaseAccum: DDS
192      PORT MAP ( clk          => slowclk,
193                  clk10        => reg_en,
194                  step         => step, -- from freqLUT
195                  phase        => phase); -- to SinLUT
196
197  PulseWM: PWM
198      PORT MAP ( clk          => slowclk,
199                  sample       => lutfreq(9 downto 0), -- from sinLUT
200                  slowclk     => reg_en,
201                  pulse        => tone); -- to speaker
202

```

```

203 SinFreqs: SinLUT
204     PORT MAP ( aclk          => slowclk,
205                 s_axis_phase_tvalid => '1',
206                 s_axis_phase_tdata   => phase, -- from phase accumulator
207                 m_axis_data_tvalid  => open,
208                 m_axis_data_tdata   => lutfreq); -- to PWM
209
210 kidsCounter: PlayCount
211     PORT MAP  ( clk => slowclk,
212                  count_en => tempo_en, -- from controller
213                  count_to => count,    -- from controller
214                  tc_tick => countDone); -- from controller
215
216 end Behavioral;

```

---

Figure 10: Controller.vhd

---

```

1  -----
2  -- Company: ENGS041 14X
3  -- Engineer: Vivian Hu and Daniel Chen
4  --
5  -- Create Date: 14:49:26 08/11/2014
6  -- Design Name: Controller FSM
7  -- Module Name: Controller - Behavioral
8  -- Project Name: Octave Keyboard
9  -- Target Devices: Spartan 6
10 -- Tool versions:
11 -- Description: Basic controller which converts to key input to monotone. Also
12 --                 contains state machine for "Kids" by MGMT.
13 -----
14 library IEEE;
15 use IEEE.STD_LOGIC_1164.ALL;
16 use IEEE.NUMERIC_STD.ALL;
17
18 entity Controller is
19     Port (    clk          : in STD_LOGIC;
20               key_in       : in STD_LOGIC_VECTOR(7 downto 0);
21               led_disable  : in STD_LOGIC;
22               song_enable  : in STD_LOGIC;
23               beat_tick    : in STD_LOGIC;
24               beat_en      : out STD_LOGIC;
25               count_out    : out STD_LOGIC_VECTOR(3 downto 0);
26               key_out      : out STD_LOGIC_VECTOR(7 downto 0);
27               led_out      : out STD_LOGIC_VECTOR(7 downto 0));
28 end Controller;
29
30 architecture Behavioral of Controller is
31     type statetype is (idle, low_c, d, e, f, g, a, b, high_c, autoidle,
32                         intro1c, intro1cr, intro1d, intro1dr, intro1e, intro1er, intro1g, intro1gr,
33                         enda, endar, endb, enda2, endg, endgr, ende, endd,
34                         intro2c, intro2a, intro2ar, intro2b, intro2br, intro2g, intro2gr
35                         );
36     signal curr_state, next_state : statetype := idle;
37     signal output : STD_LOGIC_VECTOR (7 downto 0) := (others => '0');
38     signal reps : STD_LOGIC := '1';
39     signal introSelector : STD_LOGIC := '0';
40     signal repeat_tick : STD_LOGIC := '0';
41 begin
42
43     -- updates state to next state.
44     StateUpdate: process(clk)
45     begin
46         if rising_edge(clk) then
47             curr_state <= next_state;
48         end if;
49     end process StateUpdate;

```

---

```

50
51    -- determines next state
52    CombLogic: process(curr_state, next_state, key_in, led_disable, output,
53                        beat_tick, song_enable, introSelector)
54    begin
55
56        -- defaults
57        next_state <= curr_state;
58        output <= (others => '0');
59        key_out <= output;
60        count_out <= "0001";
61        repeat_tick <= '0';
62        beat_en <= '0';
63
64        -- makes led_out all 0 if led_disable is switched on
65        if (led_disable = '1') then
66            led_out <= (others => '0');
67        else
68            led_out <= output;
69        end if;
70
71        case curr_state is
72
73            -- idle state
74            -- goes to autoplay if song enable
75            -- goes to note states if buttons are pressed, prioritized in order
76            -- of lowest to highest notes.
77            when idle =>
78
79                if song_enable = '1' then
80                    next_state <= autoidle;
81                elsif key_in(7) = '1' then
82                    next_state <= low_c;
83                elsif key_in(6) = '1' then
84                    next_state <= d;
85                elsif key_in(5) = '1' then
86                    next_state <= e;
87                elsif key_in(4) = '1' then
88                    next_state <= f;
89                elsif key_in(3) = '1' then
90                    next_state <= g;
91                elsif key_in(2) = '1' then
92                    next_state <= a;
93                elsif key_in(1) = '1' then
94                    next_state <= b;
95                elsif key_in(0) = '1' then
96                    next_state <= high_c;
97                else
98                    next_state <= idle;
99                end if;
100
101        -- USER INPUT NOTE STATES

```

```

102      -- output is changed to match the note
103      -- goes back to idle when corresponding key is pressed
104
105      when low_c =>
106          output <= "10000000";
107          if key_in(7) = '0' then
108              next_state <= idle;
109          end if;
110
111      when d =>
112          output <= "01000000";
113          if key_in(6) = '0' then
114              next_state <= idle;
115          end if;
116
117      when e =>
118          output <= "00100000";
119          if key_in(5) = '0' then
120              next_state <= idle;
121          end if;
122
123      when f =>
124          output <= "00010000";
125          if key_in(4) = '0' then
126              next_state <= idle;
127          end if;
128
129      when g =>
130          output <= "00001000";
131          if key_in(3) = '0' then
132              next_state <= idle;
133          end if;
134
135      when a =>
136          output <= "00000100";
137          if key_in(2) = '0' then
138              next_state <= idle;
139          end if;
140
141      when b =>
142          output <= "00000010";
143          if key_in(1) = '0' then
144              next_state <= idle;
145          end if;
146
147      when high_c =>
148          output <= "00000001";
149          if key_in(0) = '0' then
150              next_state <= idle;
151          end if;
152
153      -- AUTOPLAY STATES

```

```

154      -- beat_en turns on RepeatCounter
155      -- output corresponds to current note to be pressed
156      -- count_out is the number of quarter seconds a note should be held
157      -- the state moves to the next one once the counter reaches it's
158      -- limit (meaning the note has been held long enough)
159      -- or when the song_enable switch is toggled off (next state becomes
160      -- idle).
161
162      when autoidle =>
163          beat_en <= '1';
164          output <= (others => '0');
165          if (beat_tick = '1') then
166              next_state <= intro1c;
167          end if;
168
169      when intro1c =>
170          beat_en <= '1';
171          output <= "10000000";
172          count_out <= "0001";
173          if (song_enable = '0') then
174              next_state <= idle;
175          elsif(beat_tick = '1') then
176              next_state <= intro1cr;
177          end if;
178
179
180      when intro1cr =>
181          beat_en <= '1';
182          output <= "00000000";
183          count_out <= "0001";
184          if (song_enable = '0') then
185              next_state <= idle;
186          elsif(beat_tick = '1') then
187              next_state <= intro1d;
188          end if;
189
190
191      when intro1d =>
192          beat_en <= '1';
193          output <= "01000000";
194          count_out <= "0001";
195          if (song_enable = '0') then
196              next_state <= idle;
197          elsif(beat_tick = '1') then
198              next_state <= intro1dr;
199          end if;
200
201
202      when intro1dr =>
203          beat_en <= '1';
204          output <= "00000000";
205          count_out <= "0001";

```

```

206         if (song_enable = '0') then
207             next_state <= idle;
208         elsif(beat_tick = '1') then
209             next_state <= intro1e;
210         end if;
211
212
213     when intro1e =>
214         beat_en <= '1';
215         output <= "00100000";
216         count_out <= "0001";
217         if (song_enable = '0') then
218             next_state <= idle;
219         elsif(beat_tick = '1') then
220             next_state <= intro1er;
221         end if;
222
223
224     when intro1er =>
225         beat_en <= '1';
226         output <= "00000000";
227         count_out <= "0001";
228         if (song_enable = '0') then
229             next_state <= idle;
230         elsif(beat_tick = '1') then
231             next_state <= intro1g;
232         end if;
233
234
235     when intro1g =>
236         beat_en <= '1';
237         output <= "00001000";
238         count_out <= "0001";
239         if (song_enable = '0') then
240             next_state <= idle;
241         elsif(beat_tick = '1') then
242             next_state <= intro1gr;
243         end if;
244
245
246     when intro1gr =>
247         beat_en <= '1';
248         output <= "00000000";
249         count_out <= "0001";
250         if (song_enable = '0') then
251             next_state <= idle;
252         elsif(beat_tick = '1') then
253             next_state <= enda;
254         end if;
255
256
257     when enda =>

```

```

258         beat_en <= '1';
259         output <= "00000100";
260         count_out <= "0001";
261         if (song_enable = '0') then
262             next_state <= idle;
263         elsif(beat_tick = '1') then
264             next_state <= endar;
265         end if;

266
267
268     when endar =>
269         beat_en <= '1';
270         output <= "00000000";
271         count_out <= "0001";
272         if (song_enable = '0') then
273             next_state <= idle;
274         elsif(beat_tick = '1') then
275             next_state <= endb;
276         end if;

277
278
279     when endb =>
280         beat_en <= '1';
281         output <= "00000010";
282         count_out <= "0001";
283         if (song_enable = '0') then
284             next_state <= idle;
285         elsif(beat_tick = '1') then
286             next_state <= enda2;
287         end if;

288
289
290     when enda2 =>
291         beat_en <= '1';
292         output <= "00000100";
293         count_out <= "0010";
294         if (song_enable = '0') then
295             next_state <= idle;
296         elsif(beat_tick = '1') then
297             next_state <= endg;
298         end if;

299
300
301     when endg =>
302         beat_en <= '1';
303         output <= "00001000";
304         count_out <= "0001";
305         if (song_enable = '0') then
306             next_state <= idle;
307         elsif(beat_tick = '1') then
308             next_state <= endgr;
309         end if;

```

```

310
311
312     when endgr =>
313         beat_en <= '1';
314         output <= "00000000";
315         count_out <= "0001";
316         if (song_enable = '0') then
317             next_state <= idle;
318         elsif(beat_tick = '1') then
319             next_state <= ende;
320         end if;
321
322
323     when ende =>
324         beat_en <= '1';
325         output <= "00100000";
326         count_out <= "1001";
327         if (song_enable = '0') then
328             next_state <= idle;
329         elsif(beat_tick = '1') then
330             next_state <= endd;
331         end if;
332
333
334     when endd =>
335         beat_en <= '1';
336         output <= "01000000";
337         count_out <= "1000";
338
339         if (beat_tick = '1') then
340             repeat_tick <= '1'; -- increase reps
341
342             -- choose intro depending on what has previously been played
343             -- The song goes:
344             --      intro1c to endd
345             --      intro1c to endd
346             --      intro2c to endd
347             --      intro2c to endd
348             -- and repeat until song_enable is switched off.
349             if (introSelector = '0') then
350                 next_state <= intro1c;
351             else
352                 next_state <= intro2c;
353             end if;
354
355             elsif (song_enable = '0') then
356                 next_state <= idle;
357
358             end if;
359
360     when intro2c =>
361         beat_en <= '1';

```

```

362         output <= "00000001";
363         count_out <= "0010";
364         if (song_enable = '0') then
365             next_state <= idle;
366         elsif(beat_tick = '1') then
367             next_state <= intro2a;
368         end if;
369
370
371     when intro2a =>
372         beat_en <= '1';
373         output <= "00000100";
374         count_out <= "0001";
375         if (song_enable = '0') then
376             next_state <= idle;
377         elsif(beat_tick = '1') then
378             next_state <= intro2ar;
379         end if;
380
381
382     when intro2ar =>
383         beat_en <= '1';
384         output <= "00000000";
385         count_out <= "0001";
386         if (song_enable = '0') then
387             next_state <= idle;
388         elsif(beat_tick = '1') then
389             next_state <= intro2b;
390         end if;
391
392
393     when intro2b =>
394         beat_en <= '1';
395         output <= "00000010";
396         count_out <= "0001";
397         if (song_enable = '0') then
398             next_state <= idle;
399         elsif(beat_tick = '1') then
400             next_state <= intro2br;
401         end if;
402
403
404     when intro2br =>
405         beat_en <= '1';
406         output <= "00000000";
407         count_out <= "0001";
408         if (song_enable = '0') then
409             next_state <= idle;
410         elsif(beat_tick = '1') then
411             next_state <= intro2g;
412         end if;
413

```

```

414
415     when intro2g =>
416         beat_en <= '1';
417         output <= "00001000";
418         count_out <= "0001";
419         if (song_enable = '0') then
420             next_state <= idle;
421         elsif(beat_tick = '1') then
422             next_state <= intro2gr;
423         end if;
424
425
426     when intro2gr =>
427         beat_en <= '1';
428         output <= "00000000";
429         count_out <= "0001";
430         if (song_enable = '0') then
431             next_state <= idle;
432         elsif(beat_tick = '1') then
433             next_state <= enda;
434         end if;
435
436     when others =>
437         next_state <= idle;
438
439     end case;
440
441 end process CombLogic;
442
443 -- counter which is keeps track of the autoplay song state
444 -- modifies introSelector based on reps
445 -- introSelector is then used to determine whether to go to intro1 or
446 -- intro2 at the end of the end states.
447 RepeatCounter: process(clk, repeat_tick, reps, introselector)
448 begin
449     if (rising_edge(clk)) then
450         if (repeat_tick = '1') then
451             if (reps = '1') then
452                 introSelector <= not introSelector;
453                 reps <= '0';
454             else
455                 reps <= not reps;
456             end if;
457         end if;
458     end if;
459 end process RepeatCounter;
460
461 end Behavioral;

```

---

Figure 11: DDS.vhd

```
1  -----
2  -- Company: ENGS031 14X
3  -- Engineer: Vivian Hu and Daniel Chen
4  --
5  -- Create Date: 14:29:30 08/11/2014
6  -- Design Name: Octave Keyboard
7  -- Module Name: DDS - Behavioral
8  -- Project Name: Octave Keyboard
9  -- Target Devices: Spartan 6
10 -- Tool versions:
11 -- Description: Phase accumulator and register
12 -----
13 library IEEE;
14 use IEEE.STD_LOGIC_1164.ALL;
15 use IEEE.NUMERIC_STD.ALL;
16
17 entity DDS is
18     Generic ( ACCUMSIZE      : integer := 13;      -- phase accumulator bitsize
19               INDEXSIZE      : integer := 8);      -- SineLUT index bitsize
20
21     Port ( clk      : in  STD_LOGIC;
22            step    : in  STD_LOGIC_VECTOR(ACCUMSIZE-1 downto 0);
23            clk10   : in  STD_LOGIC;
24            phase   : out STD_LOGIC_VECTOR(INDEXSIZE-1 downto 0));
25 end DDS;
26
27 architecture Behavioral of DDS is
28     signal curr_phase : unsigned(ACCUMSIZE-1 downto 0) := (others => '0');
29 begin
30
31     AccumPhase: process(clk, clk10)
32     begin
33         if (rising_edge(clk)) then
34             -- increment at enable from PWM (10kHz)
35             if (clk10 = '1') then
36                 curr_phase <= curr_phase + unsigned(step);
37             end if;
38         end if;
39     end process AccumPhase;
40
41     -- take only the 8 most significant bits of the phase as index
42     phase <= std_logic_vector(curr_phase(ACCUMSIZE-1 downto ACCUMSIZE-INDEXSIZE));
43
44 end Behavioral;
```

Figure 12: PWM.vhd

```
1  -----
2  -- Company: ENGS031 14X
3  -- Engineer: Vivian Hu, Daniel Chen
4  --
5  -- Create Date: 10:13:11 08/13/2014
6  -- Design Name: Pulse Width Modulator
7  -- Module Name: PWM - Behavioral
8  -- Project Name: Octave Keyboard
9  -- Target Devices: Nexys3
10 -- Tool versions:
11 -- Description: Pulse width modulator (counter and comparator)
12 -----
13 library IEEE;
14 use IEEE.STD_LOGIC_1164.ALL;
15 use IEEE.NUMERIC_STD.ALL;
16
17 entity PWM is
18     Generic ( LUTOUT : integer := 10;
19
20         Port ( clk      : in STD_LOGIC;
21                 sample   : in STD_LOGIC_VECTOR(LUTOUT-1 downto 0);
22                 slowclk : out STD_LOGIC;
23                 pulse    : out STD_LOGIC);
24 end PWM;
25
26 architecture Behavioral of PWM is
27     signal count : unsigned(13 downto 0) := (others => '0');
28     signal offset : unsigned(LUTOUT-1 downto 0) := (others => '0');
29     constant max : unsigned(13 downto 0) := "01001110001000";    -- max count value
30 begin
31
32     PWM: process(clk, sample)
33     begin
34         -- convert SinLUT output from two's complement to unsigned offset binary
35         offset <= unsigned(not sample(LUTOUT-1) & sample(LUTOUT-2 downto 0));
36
37         if (rising_edge(clk)) then
38
39             -- increment counter
40             count <= count + 1;
41
42             -- compare first 10 bits to SinLUT output
43             if (count(9 downto 0) < offset) then
44                 pulse <= '1';
45             else
46                 pulse <= '0';
47             end if;
48
49             -- if max count hit
```

```
50      if (count = max) then
51          -- send 10kHz enable pulse to phase accumulator
52          slowclk <= '1';
53          count <= (others => '0');    -- restart count
54      else
55          slowclk <= '0';
56      end if;
57  end if;
58 end process PWM;
59
60 end Behavioral;
```

---

Figure 13: PlayCount.vhd

---

```

1  -----
2  -- Company: ENGS031 14X
3  -- Engineer: Daniel Chen, Vivian Hu
4  --
5  -- Create Date: 11:40:24 08/16/2014
6  -- Design Name: Play Counter
7  -- Module Name: PlayCount - Behavioral
8  -- Project Name: Octave-Keyboard
9  -- Target Devices: Nexys3
10 -- Tool versions:
11 -- Description: Play Counter used to keep track of beats for the controller FSM.
12 -----
13 library IEEE;
14 use IEEE.STD_LOGIC_1164.ALL;
15 use IEEE.NUMERIC_STD.ALL;
16
17 entity PlayCount is
18     Port ( clk : in STD_LOGIC;
19             count_en : in STD_LOGIC;
20             count_to : in STD_LOGIC_VECTOR (3 downto 0);
21             tc_tick : out STD_LOGIC);
22 end PlayCount;
23
24 architecture Behavioral of PlayCount is
25     constant QRTR_CLK_DIV : integer := 12500000;
26     signal clkcount : integer := 0;
27     signal count : unsigned(3 downto 0) := "0001";
28 begin
29
30     -- counts for a quarter second
31     Qrtr_Sec_Count: process(clk)
32     begin
33         if (rising_edge(clk)) then
34             -- if the clock is rising and counting is enabled
35             if (count_en = '1') then
36                 tc_tick <= '0';
37
38                 -- if a quarter second has passed
39                 if (clkcount = QRTR_CLK_DIV - 1) then
40
41                     -- if enough quarter seconds have passed
42                     if (count = unsigned(count_to)) then
43                         tc_tick <= '1'; -- tell the controller
44                         count <= "0001"; -- reset the count
45
46                     -- otherwise, just wait for enough quarter seconds to pass.
47                     else
48                         count <= count + 1;
49                     end if;

```

---

```
50          clkcount <= 0;
51
52          -- wait for a quarter second otherwise
53      else
54          clkcount <= clkcount + 1;
55      end if;
56  else
57      tc_tick <= '0';
58  end if;
59 end if;
60 end process Qrtr_Sec_Count;
61 end Behavioral;
```

---

Figure 14: FreqLUT.vhd

---

```

1  -----
2  -- Company: ENGS031 14X
3  -- Engineer: Daniel Chen and Vivian Hu
4  --
5  -- Create Date: 15:30:42 08/11/2014
6  -- Design Name: Frequency LUT
7  -- Module Name: FreqLUT - Behavioral
8  -- Project Name: Octave Keyboard
9  -- Target Devices: Nexys3
10 -- Tool versions:
11 -- Description: Frequency LUT that takes the keys and outputs the increment
12 -- corresponding to the notes.
13 -----
14 library IEEE;
15 use IEEE.STD_LOGIC_1164.ALL;
16 use IEEE.NUMERIC_STD.ALL;
17
18 entity FreqLUT is
19     Generic ( ACCUMSIZE : integer := 13;
20               CLKFREQ    : integer := 10000);
21
22     Port ( clk : in STD_LOGIC;
23            key_in : in STD_LOGIC_VECTOR (7 downto 0);
24            increment : out STD_LOGIC_VECTOR (ACCUMSIZE-1 downto 0));
25 end FreqLUT;
26
27 architecture Behavioral of FreqLUT is
28     constant PHASECONSTANT : integer := 2**ACCUMSIZE;
29
30     -- key frequencies (Hz)
31     constant LOWC : integer := 262;
32     constant D : integer := 294;
33     constant E : integer := 330;
34     constant F : integer := 349;
35     constant G : integer := 392;
36     constant A : integer := 440;
37     constant B : integer := 494;
38     constant HIGHC : integer := 523;
39 begin
40
41     getIncrement: process(clk, key_in)
42     begin
43         if rising_edge(clk) then
44             if (key_in(7) = '1') then
45                 increment <=std_logic_vector(to_unsigned(LOWC*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
46             elsif (key_in(6) = '1') then
47                 increment <=std_logic_vector(to_unsigned(D*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
48             elsif (key_in(5) = '1') then
49                 increment <=std_logic_vector(to_unsigned(E*PHASECONSTANT/CLKFREQ,ACCUMSIZE));

```

---

```

50      elsif (key_in(4) = '1') then
51          increment <=std_logic_vector(to_unsigned(F*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
52      elsif (key_in(3) = '1') then
53          increment <=std_logic_vector(to_unsigned(G*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
54      elsif (key_in(2) = '1') then
55          increment <=std_logic_vector(to_unsigned(A*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
56      elsif (key_in(1) = '1') then
57          increment <=std_logic_vector(to_unsigned(B*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
58      elsif (key_in(0) = '1') then
59          increment <=std_logic_vector(to_unsigned(HIGHC*PHASECONSTANT/CLKFREQ,ACCUMSIZE));
60      else
61          increment <= (others => '0');
62      end if;
63  end if;
64 end process getIncrement;
65
66 end Behavioral;

```

---

Figure 15: keyboardTB.vhd

```
1 -----  
2 -- Company: ENGS031 14X  
3 -- Engineer: Daniel Chen and Vivian Hu  
4 --  
5 -- Create Date: 14:17:41 08/25/2014  
6 -- Design Name: Octave-Keyboard Testbench  
7 -- Module Name: C:/Users/F000JW7/Desktop/octave-keyboard/OctaveKeyboard/keyboardTB.vhd  
8 -- Project Name: OctaveKeyboard  
9 -- Target Device: Nexys3  
10 -- Tool versions:  
11 -- Description: Testbench for Nexys3  
12 --  
13 -- VHDL Test Bench Created by ISE for module: OctaveKeyboardTop  
14 -----  
15 LIBRARY ieee;  
16 USE ieee.std_logic_1164.ALL;  
17  
18 ENTITY keyboardTB IS  
19 END keyboardTB;  
20  
21 ARCHITECTURE behavior OF keyboardTB IS  
22  
23     -- Component Declaration for the Unit Under Test (UUT)  
24     COMPONENT OctaveKeyboardTop  
25     PORT(  
26         clk : IN std_logic;  
27         keys : IN std_logic_vector(7 downto 0);  
28         led_disable : IN std_logic;  
29         song_enable : IN std_logic;  
30         tone : OUT std_logic;  
31         shutdown : OUT std_logic;  
32         led_out : OUT std_logic_vector(7 downto 0)  
33     );  
34 END COMPONENT;  
35  
36     --Inputs  
37     signal clk : std_logic := '0';  
38     signal keys : std_logic_vector(7 downto 0) := (others => '0');  
39     signal led_disable : std_logic := '0';  
40     signal song_enable : std_logic := '0';  
41  
42     --Outputs  
43     signal tone : std_logic;  
44     signal shutdown : std_logic;  
45     signal led_out : std_logic_vector(7 downto 0);  
46  
47     -- Clock period definitions  
48     constant clk_period : time := 10 ns;  
49
```

```

50 BEGIN
51     -- Instantiate the Unit Under Test (UUT)
52     uut: OctaveKeyboardTop PORT MAP (
53         clk => clk,
54         keys => keys,
55         led_disable => led_disable,
56         song_enable => song_enable,
57         tone => tone,
58         shutdown => shutdown,
59         led_out => led_out
60     );
61
62     -- Clock process definitions
63     clk_process :process
64 begin
65     clk <= '0';
66     wait for clk_period/2;
67     clk <= '1';
68     wait for clk_period/2;
69 end process;
70
71
72     -- Stimulus process
73 stim_proc: process
74 begin
75     -- hold reset state for 100 ns.
76     wait for 100 ns;
77
78     wait for clk_period*5;
79
80     -- start with both switches off
81     led_disable <= '0';
82     song_enable <= '0';
83
84     -- try some keys
85     keys <= "10000000";
86     wait for 250us;
87     keys <= "10001000";
88     wait for 50us;
89     keys <= "00010000";
90     wait for 200us;
91     keys <= "00100010";
92     wait for 300us;
93     led_disable <= '1'; -- check that disabling leds work
94     wait for 200us;
95     keys <= "00000010";
96     wait for 200us;
97     keys <= "00000100";
98     wait for 200us;
99     keys <= "00001000";
100    wait for 200us;
101    keys <= "00011111";

```

```
102     led_disable <= '0'; -- see that enabling them again works
103     wait for 50us;
104     keys <= "00000000";
105     wait for 200us;
106     keys <= "10111000";
107
108     -- just see that state changes correctly
109     -- (autoplay takes too long to simulate, as each beat is 1/4 second)
110     song_enable <= '1';
111     wait;
112   end process;
113 END;
```

---

### 7.2.3 Resource utilization

Figure 16: Advanced HDL Synthesis Report

```

Macro Statistics
# Counters : 3
  14-bit up counter : 1
  32-bit up counter : 1
  4-bit up counter : 1
# Accumulators : 1
  13-bit up accumulator : 1
# Registers : 8
  Flip-Flops : 8
# Comparators : 2
  10-bit comparator greater : 1
  4-bit comparator equal : 1
# Multiplexers : 10
  1-bit 2-to-1 multiplexer : 2
  13-bit 2-to-1 multiplexer : 7
  8-bit 2-to-1 multiplexer : 1
# FSMs : 1

```

Figure 17: Device Utilization Summary

#### Slice Logic Utilization:

Number of Slice Registers:	189	out of	18224	1%
Number of Slice LUTs:	335	out of	9112	3%
Number used as Logic:	335	out of	9112	3%

#### Slice Logic Distribution:

Number of LUT Flip Flop pairs used:	346			
Number with an unused Flip Flop:	157	out of	346	45%
Number with an unused LUT:	11	out of	346	3%
Number of fully used LUT-FF pairs:	178	out of	346	51%
Number of unique control sets:	20			

#### IO Utilization:

Number of IOs:	29			
Number of bonded IOBs:	29	out of	232	12%
IOB Flip Flops/Latches:	2			

#### Specific Feature Utilization:

Number of BUFG/BUFGCTRLs:	2	out of	16	12%
---------------------------	---	--------	----	-----

## 7.2.4 UCF

Figure 18: UCF file

```
## Clock signal
NET "clk" LOC = "V10" | IOSTANDARD = "LVCMOS33";
Net "clk" TNM.NET = sys_clk_pin;
TIMESPEC TS_sys_clk_pin = PERIOD sys_clk_pin 100000 kHz;

## Leds
NET "led_out<0>" LOC = "U16" | IOSTANDARD = "LVCMOS33";
NET "led_out<1>" LOC = "V16" | IOSTANDARD = "LVCMOS33";
NET "led_out<2>" LOC = "U15" | IOSTANDARD = "LVCMOS33";
NET "led_out<3>" LOC = "V15" | IOSTANDARD = "LVCMOS33";
NET "led_out<4>" LOC = "M11" | IOSTANDARD = "LVCMOS33";
NET "led_out<5>" LOC = "N11" | IOSTANDARD = "LVCMOS33";
NET "led_out<6>" LOC = "R11" | IOSTANDARD = "LVCMOS33";
NET "led_out<7>" LOC = "T11" | IOSTANDARD = "LVCMOS33";

## Switches
NET "led_disable" LOC = "T10" | IOSTANDARD = "LVCMOS33";
NET "song_enable" LOC = "T9" | IOSTANDARD = "LVCMOS33";

##JA
NET "keys<4>" LOC = "T12" | IOSTANDARD = "LVCMOS33";
NET "keys<0>" LOC = "V12" | IOSTANDARD = "LVCMOS33";
NET "keys<5>" LOC = "N10" | IOSTANDARD = "LVCMOS33";
NET "keys<1>" LOC = "P11" | IOSTANDARD = "LVCMOS33";

##JB
NET "keys<6>" LOC = "K2" | IOSTANDARD = "LVCMOS33";
NET "keys<2>" LOC = "K1" | IOSTANDARD = "LVCMOS33";
NET "keys<7>" LOC = "L4" | IOSTANDARD = "LVCMOS33";
NET "keys<3>" LOC = "L3" | IOSTANDARD = "LVCMOS33";

##JD, LX16 Die only
NET "tone" LOC = "G11" | IOSTANDARD = "LVCMOS33";
NET "shutdown" LOC = "E11" | IOSTANDARD = "LVCMOS33";
```

### 7.3 Memory Map

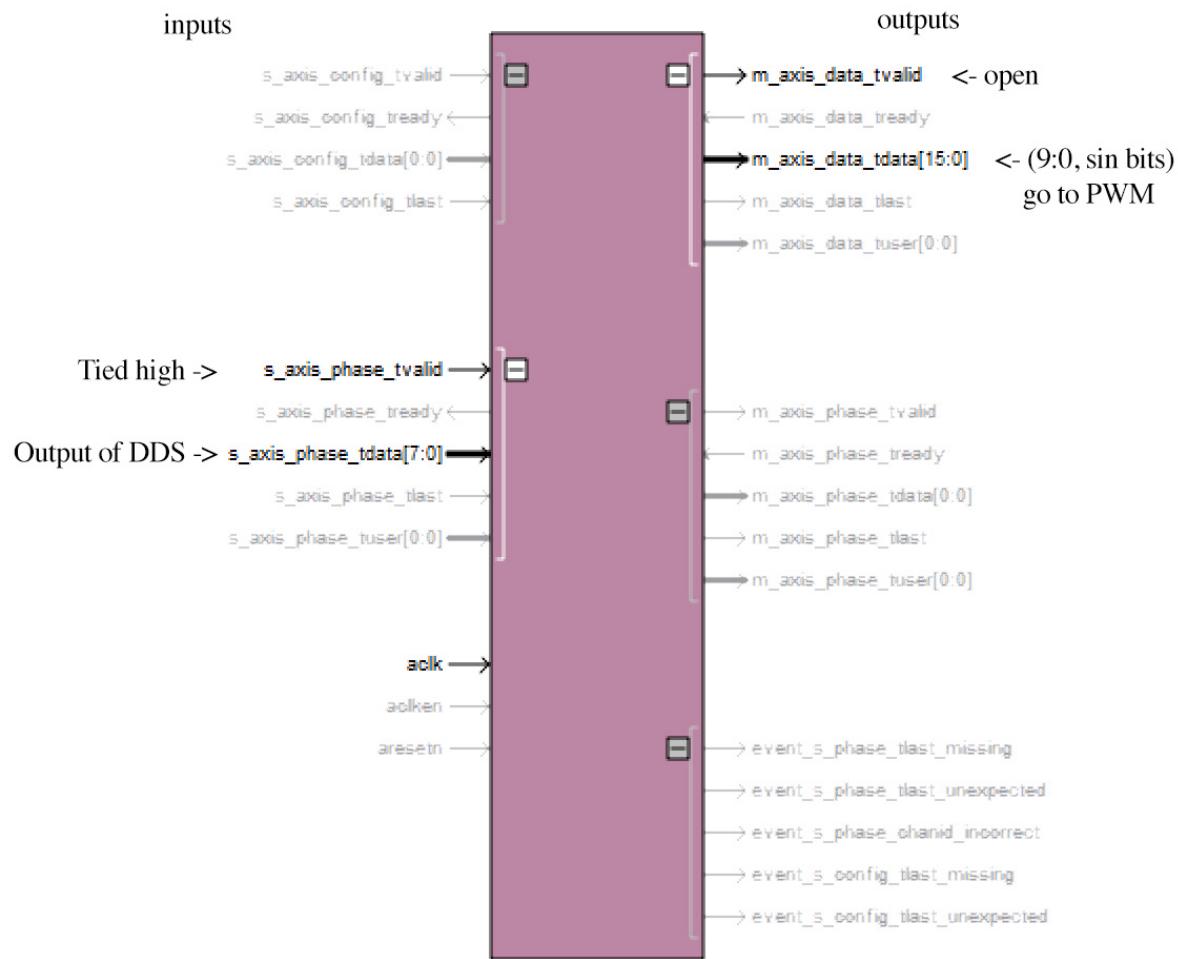


Figure 19: Memory Map for Sine LUT

## 7.4 Timing Diagram

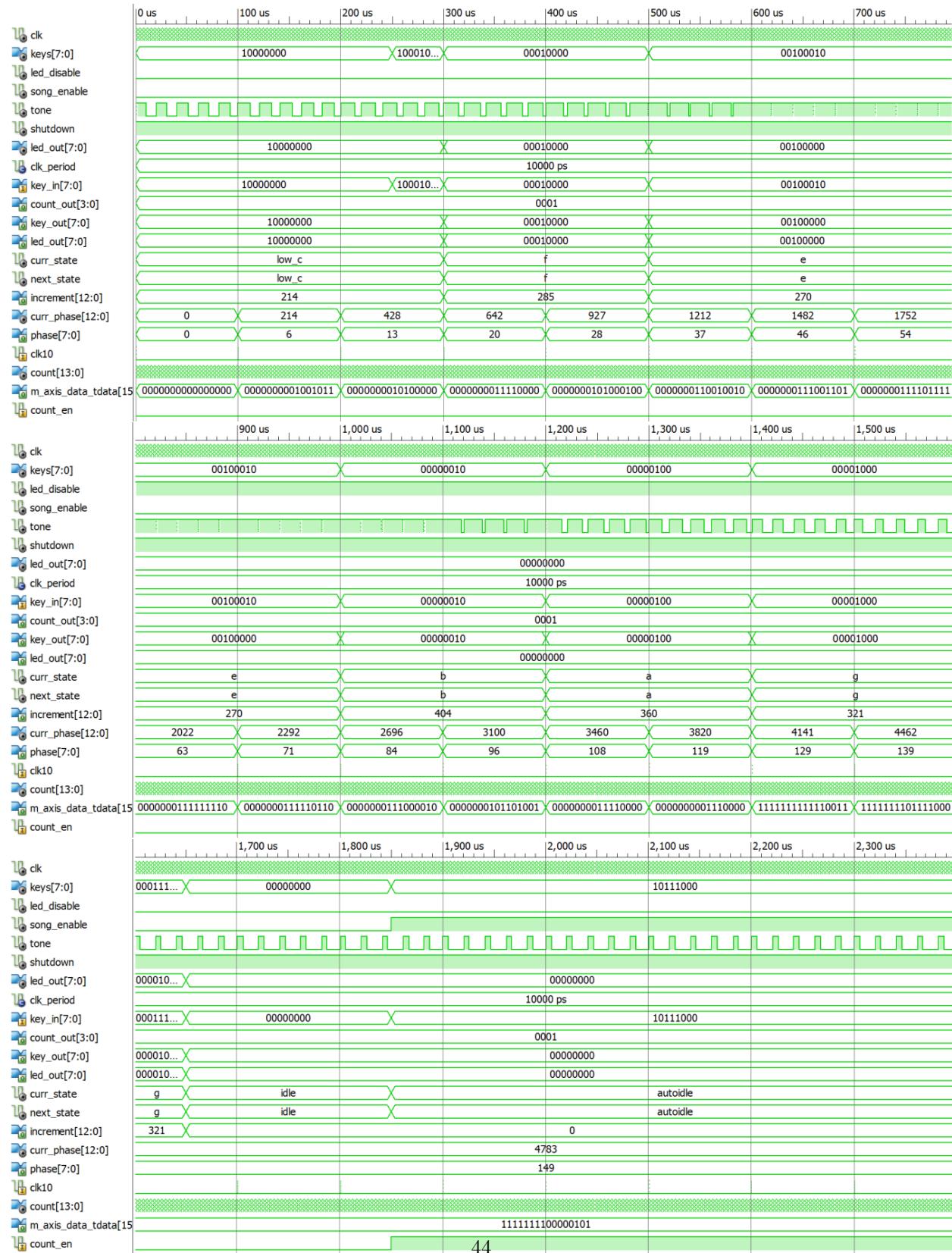


Figure 20: Timing Diagram of Test Bench

The critical path is between clkcount\_8 and clkcount\_23 in kidsCounter. The delay is 4.866ns. Here is the excerpt from the synthesis report:

Figure 21: Critical Path information (excerpt from Synthesis Report)

```
Timing constraint: Default period analysis for Clock 'clk_en'
Clock period: 4.866ns (frequency: 205.508MHz)
Total number of paths / destination ports: 3669 / 262
```

---

Delay:	4.866 ns (Levels of Logic = 3)			
Source:	kidsCounter/clkcount_8 (FF)			
Destination:	kidsCounter/clkcount_23 (FF)			
Source Clock:	clk_en rising			
Destination Clock:	clk_en rising			
Data Path: kidsCounter/clkcount_8 to kidsCounter/clkcount_23	Gate	Net		
Cell:in->out	fanout	Delay	Delay	Logical Name (Net Name)
FD:C->Q	3	0.525	1.221	kidsCounter/clkcount_8 (kidsCounter/clkcount_8)
LUT6:I0->O	7	0.254	1.186	
				kidsCounter/GND_11_o_clkcount[31]_equal_1_o<31>4
				(kidsCounter/GND_11_o_clkcount[31]_equal_1_o<31>3)
LUT5:I1->O	13	0.254	1.098	kidsCounter/_n00281 (kidsCounter/_n0028)
LUT4:I3->O	1	0.254	0.000	
				kidsCounter/clkcount_23_rstpot
				(kidsCounter/clkcount_23_rstpot)
FD:D		0.074		kidsCounter/clkcount_23
Total		4.866 ns	(1.361 ns logic, 3.505 ns route)	
			(28.0% logic, 72.0% route)	

---

Based on this information, the maximum clock speed for this circuit is 205.508MHz, meaning the clock period must be at least 4.866ns.

## 7.5 Synthesis Warnings

Figure 22: Synthesis Warnings

```
WARNING: HDLCompiler:89 -
    " \\ psf \\ home \\ Documents \\ ENGS031 \\ finalproject \\ OctaveKeyboard \\ OctaveKeyboardTop.vhd"
    Line 95: <debounce> remains a black-box since it has no binding entity.
WARNING: Xst:1710 -
    FF/Latch <increment_9> (without init value) has a constant value of 0 in block
    <FreqLUT>. This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1895 -
    Due to other FF/Latch trimming, FF/Latch <increment_10> (without init value)
    has a constant value of 0 in block <FreqLUT>.
    This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1895 -
    Due to other FF/Latch trimming, FF/Latch <increment_11> (without init value)
    has a constant value of 0 in block <FreqLUT>.
    This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1895 -
    Due to other FF/Latch trimming, FF/Latch <increment_12> (without init value)
    has a constant value of 0 in block <FreqLUT>.
    This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1293 -
    FF/Latch <PulseWM/count_13> has a constant value of 0 in block
    <OctaveKeyboardTop>.
    This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1293 -
    FF/Latch <kidsCounter/clkcount_31> has a constant value of 0 in block
    <OctaveKeyboardTop>.
    This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1293 -
    FF/Latch <kidsCounter/clkcount_30> has a constant value of 0 in block
    <OctaveKeyboardTop>.
    This FF/Latch will be trimmed during the optimization process.
...
same error for clkcount_29 through clkcount_26
...
WARNING: Xst:1293 -
    FF/Latch <kidsCounter/clkcount_25> has a constant value of 0 in block
    <OctaveKeyboardTop>.
    This FF/Latch will be trimmed during the optimization process.
WARNING: Xst:1293 -
    FF/Latch <kidsCounter/clkcount_24> has a constant value of 0 in block
    <OctaveKeyboardTop>.
    This FF/Latch will be trimmed during the optimization process.
```

None of the warnings from synthesis pose practical issues. The FF/Latch trimming is due to the usage of integers and simply warns us that bits 31 to 24 of clkcount and 13 of count will not be represented in the final program, as they are not used. The first warning, regarding the debouncer core, is resolved in a later step before generating the programming file.

## 7.6 Data Sheets

The proceeding pages contain data sheets for parts used in this project that are not already on the class website. They include data sheets for these parts:

- PmodAMP2
- PmodBB

# PmodAMP2™ Reference Manual

Revision: August 2, 2012

Note: This document applies to REV B of the board.



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## Overview

The PmodAMP2 amplifies low power audio signals to drive a monophonic output. The module features a digital gain select that allows output at 6 dB and 12 dB with pop-and-click suppression. A Digilent 6-pin connector provides the audio input to the module and a 1/8-inch mono jack supplies the speaker output.

For customer convenience, Digilent has an inexpensive speaker and enclosure available for sale that is suitable for use with the PmodAMP2. Also, unlike most Digilent Pmod modules that accept only digital inputs, the PmodAMP2 accepts analog inputs and pulse width modulated digital inputs.

## Inputs and Outputs (I/O)

The PmodAMP2 accepts either digital or analog inputs at a voltage range of 0-Vcc. Typically a Digilent system board supplies power to the module at 3.3V, though the maximum supply voltage is 5.0V. The connector J1 provides the audio input, gain select, shutdown select, and power. (See figure 1)

There are several suitable inputs for the PmodAMP2. The typical input is a pulse width modulated (PWM) signal produced by a digital output from a Digilent programmable logic system board or microcontroller board. The low pass filter on the input acts as a reconstruction filter to convert the PWM digital signal into an analog voltage on the amplifier input.

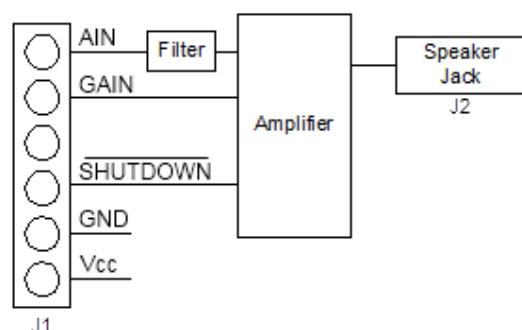
The PmodAMP2 also accepts analog inputs with an input voltage range of 0-Vcc. These inputs will often be from an analog to digital converter module, like the Digilent PmodDA1 or PmodDA2. The output of a digital to analog



### Features Include:

- Analog Devices SSM2377: Filterless, High Efficiency, Mono 2.5 Watt Class-D Audio Amplifier
- Digital gain select
- Pop -and-click suppression
- Micropower shutdown mode
- 1/8-inch mono speaker jack
- A 6-pin header for input
- 2.5V – 5V operating voltage

Figure 1



converter module will normally have a voltage range of 0-3.3V and should have a sample rate of at least 16Khz. The low pass filter on the input removes the high frequency artifacts generated during the sampling process.

Additionally, the PmodAMP2 accepts inputs from a variety of line level audio signals. A line level input, like the output of a portable CD player or MP3 player, will typically be a 1V peak-to-peak analog voltage. The input band-pass filter clarifies and amplifies the input voltage from the signal source and then directs the signal to the output jack to drive a speaker. The connector J2 operates as the speaker output. (See figure 1)

## Functional Description

The gain on the PmodAMP2 may be selected by tying the GAIN input to either logic '1' or logic '0'. (See table 1)

**Table 1**

GAIN Input	Gain
1	6 decibels (dB)
0	12 decibels (dB)

The PmodAMP2 features a micropower shutdown mode with a typical shutdown current of 100 nA. Users can enable the shutdown by applying a logic low to the SHUTDOWN pin. A10K-ohm resistor pulls the pin down to ground. To operate the AMP2 users must ensure the SHUTDOWN pin is in the highest position.

Customers will generally use the PmodAMP2 module with a Digilent programmable logic system board or microcontroller board. These boards produce either a pulse width modulated digital signal or an analog signal via a digital to analog converter. Most Digilent system boards have 6-pin connectors that allow the PmodAMP2 to plug directly into the system board or to connect via a Digilent 6-pin cable.

Some older model Digilent boards may need a Digilent Module Interface Board (MIB) and a 6-pin cable to connect to the PmodAMP2. The MIB plugs into the system board and the cable connects the PmodAMP2 to the MIB.

*Note: For more information about the operation and features of the Analog Devices SSM2377 Audio Amplifier integrated circuit please see the datasheet available at [www.analog.com](http://www.analog.com).*

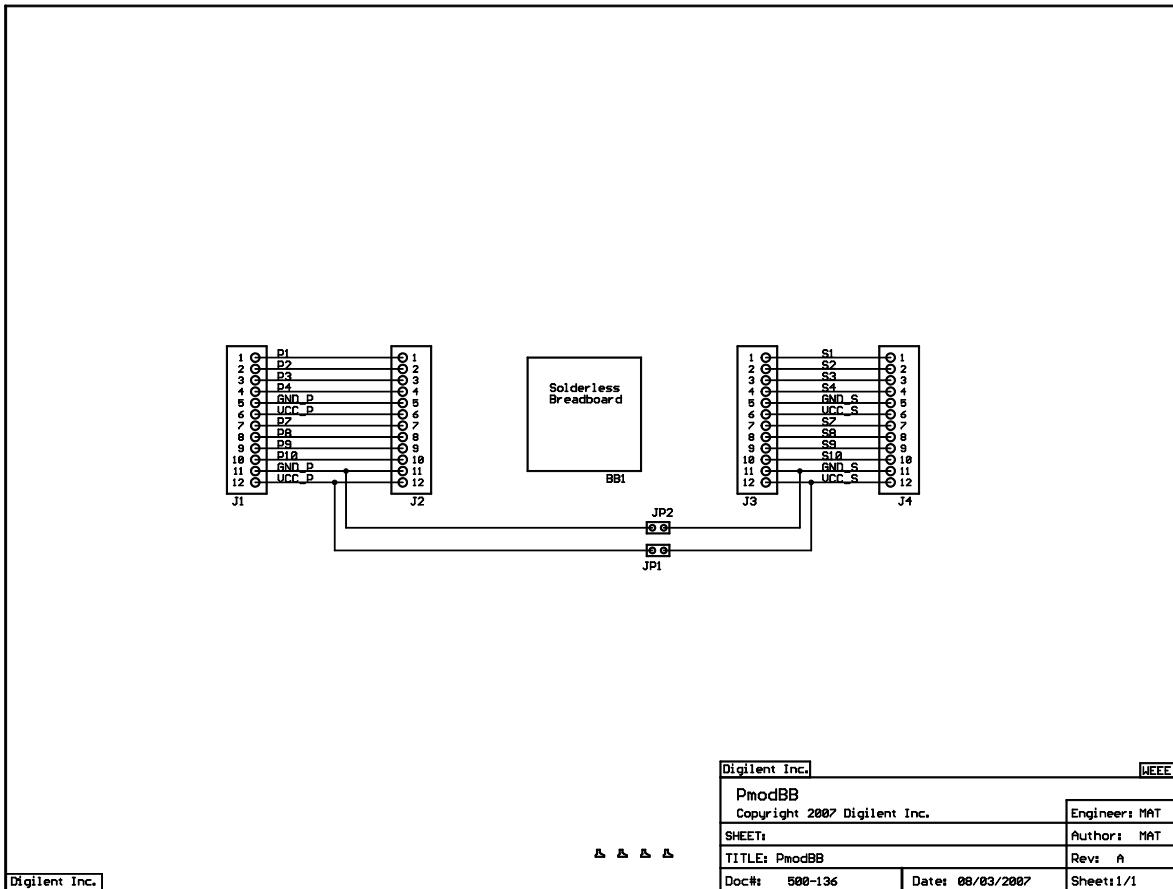


Figure 25: PmodBB Schematic