Design Review

Lab 2: Optical Theremin

by:

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1. ABSTRACT

The Optical Theremin is a less expensive and more software-intensive version of the traditional Theremin instrument. Both are distinguished among musical instruments in that they are played without physical contact with the instrument itself. A traditional Theremin uses two metal antennas to create two capacitors with the user's hands in order to control pitch and volume. Changing the proximity of the user's hands to the antennas adjusts these two qualities. In contrast, the Optical Theremin instead uses two photodiodes. These photodiodes use light intensity to detect the proximity of the user's hands and adjusts pitch and volume accordingly.

This Optical Theremin is implemented using a National Instruments (NI) myDAQ, NI LabVIEW, photodiodes, and common circuit elements. Using these items, the team developed a photodiode light detector circuit, a transimpedance amplifier, and a buffer. The amplifier and buffer circuits are implemented with a singular Texas Instruments TL074CN low-noise JFET-input op-amp, since it contains four op-amps per chip. The outputs of these circuits are collected using the analog inputs of a myDAQ and used as inputs into the LabVIEW Virtual Instrument (VI). The two light detector signal are input into the LabVIEW VI as well, and used to change the amplitude and frequency of a sine wave. This sine wave is used as an output signal heard through speakers. After this fundamental work was done to ensure the operation of the Theremin, auto-tune and equalizer features were added.

The main Theremin LabVIEW VI is composed of several functions. Going from left to right, the auto-tune feature is implemented first since the key needs to be chosen by the user before any signal processing can be performed. Next is the foundation of the instrument, which is creating the correct amplitude and frequency. Lastly, the code moves on to a block for the equalizer function that adjusts the signal that was created in the previous step.

2. INTRODUCTION

In Lab 2, Part ,1 the team is tasked with designing and implementing an Optical Theremin, a musical instrument played without the use of physical contact and controlled by light intensity. Photodiodes are used because the leakage current produced by them is directly proportional to light intensity. This leakage current is converted to voltages using TI TL074CN op-amps and amplified to a signal that can be realized and collected by a NI myDAQ and processed by a NI LabVIEW VI. The final output is a sine wave played through speakers as a musical tone. A user moves thon's hands in proximity to photodiode, which changes the light intensity received by them, therefore adjusting the volume and pitch.

In Lab 2, Part 2, an auto-tune feature is added and implemented into the main Theremin LabVIEW VI. This feature tapers the output pitch to the nearest half-tone; the specific half-tone is determined by the key the user has chosen to tune the instrument to.

In Lab 2, Part 3, an equalizer feature is also added and implemented into the main Theremin LabVIEW VI. The equalizer is capable of using three filters, low-pass, high-pass, and band-pass for midtones. Additionally, the equalizer can accept other sound files if the user desires to use this function independently of the actual Theremin instrument.

A myDAQ is used for all signal acquisition. It is important because it takes the input analog voltage signal and converts it into a digital signal than can be used by the LabVIEW VI. This digital signal is processed by a USB-STC3, a high-speed USB interface device comprised of internal processor, internal memory, high-speed data transfer, and other miscellaneous chip functions.

The stipulations of the Lab require three main design requirements: High Level Design Requirements, Design Interface Requirements, and LabVIEW Front Panel Requirements. The auto-tune and equalizer features each have their own requirements as well. All these requirements are as follows:

High Level Design Requirements:
- The prototype design shall generate a user-controllable audio tone.
- The design shall allow the user to adjust the frequency of the audio tone based on light intensity.
- The design shall allow the user to adjust the amplitude of the audio tone based on light intensity.
- The design shall allow the user to set the range of audio tones generated
- The design shall allow the user to configure the intensity range that will be seen by each sensor.

Design Interface Requirements:
- The design shall be able to detect two distinct light levels using a photodiode.
- The design shall be able to generate an audio signal output from the myDAQ's 3.5 mm TRS connector.
- The settings of the virtual circuit shall be able to be adjusted by a user through LabVIEW's front panel window.

LabVIEW Front Panel Requirements:
- The maximum and minimum light intensity levels shall be adjustable through the front panel window for each detector for operation in a variety of ambient lighting.
- The range of frequencies that the Theremin produces shall be able to be adjusted through the front panel window.
- The front panel shall display the normalized waveform that controls pitch as a function of time.
- The front panel shall display the normalized waveform that controls volume as a function of time.
- The front panel shall display numeric indicators of the light intensities detected by both photodiodes.

Auto-Tune Design Requirements:
- The design shall tune the pitch to a tone in the equal-tempered scale.
- The auto-tune feature shall be able to be turned on and off by the user.

Equalizer Design Requirements:

- Users shall be able to read in a wav file to be processed by your audio equalization code.
- Users shall be able to adjust volume, bass, midtone, and treble ranges (from the front panel).
- The design shall display graphically, the power spectrum or frequency domain content.
- The design shall have three indicator lights that illuminate on the front panel corresponding to each frequency band.
- The design shall light up three basic 5mm LED (in conjunction with the three indicator lights) (for a particular frequency band) using the digital output lines of the myDAQ.

3.0 RATIONALE

Integral to the functionality of the Optical Theremin is transforming the light intensity of a photodiode into leakage current. Leakage current is then amplified and converted to a voltage signal by an op-amp.

Output current *i* can be calculated using equation 1,

$$i = RL \quad (1)$$

where **R** is the responsivity and L is the photodiode optical power. Output current V_{out} can be calculated using equation 2,

$$V_{out} = -iR_f \quad (2)$$

where R_f is the value of the feedback resistor. Combining equations 1 and 2 results in a unified equation 3 for data transfer,

$$V_{out} = -RLR_f \quad (3)$$

This output voltage signal is then converted to a digital signal by a myDAQ and entered into the LabVIEW VI. Amplitude and frequency values are normalized by scaling sub-VI's, then multiplied by the amplitude and frequency limits respectively, which are determined by the user based on ambient lighting. These scaled signals are combined by a sine wave generation bloc in order to create a real-time running sine wave and output audio tone.

The origin of the light intensity used in the device is the degree to which the user is covering the photodiodes. There are two photodiodes, one each for amplitude and frequency. Amplitude controls the volume of the musical tone and frequency controls its pitch.

Source:

"Tinker, Learn, and Do Engineering with NI MyDAQ - Lab 10: Optical Theremin." National Instruments, 2018. Web. 7 Feb 2018. <ftp://ftp.ni.com/pub/devzone/tut/lab10_theremin.pdf >.

4.0 IMPLEMENTATION

4.1 Initial Block Diagram

The initial block diagram can be viewed in the Appendix as Figure 1. This version of the block diagram shows the Theremin instrument before any additional features are added. The N = 0 level of the block diagram shows the basic functionality of the Optical Theremin. The input is light and selections for the ranges of light intensity, frequency and amplitude; the Theremin transforms that light into the output, an audio signal, restricted by the chosen settings. The N = 1 level of the block diagram shows the two major components of the Theremin. The analog realm of the photodiode circuit, which only uses light as its input, leads into the digital realm of the LabVIEW code, which receives the range settings. The N = 2 level further breaks these two realms down The photodiode circuit is composed of photodiodes, op-amps, and their respective supporting circuit elements. These physical elements all feed into the analog input of the myDAQ, which acts as the bridge in-between the physical and digital realm; the myDAQ produces digital data that the LabVIEW code can use. The LabVIEW code then processes this data and generates the proper sine wave. The myDAQ then once again acts as a bridge between the digital and physical realm by transforming the LabVIEW code's digital result into a analog sound wave that can be heard through speakers.

4.2 Gantt Chart

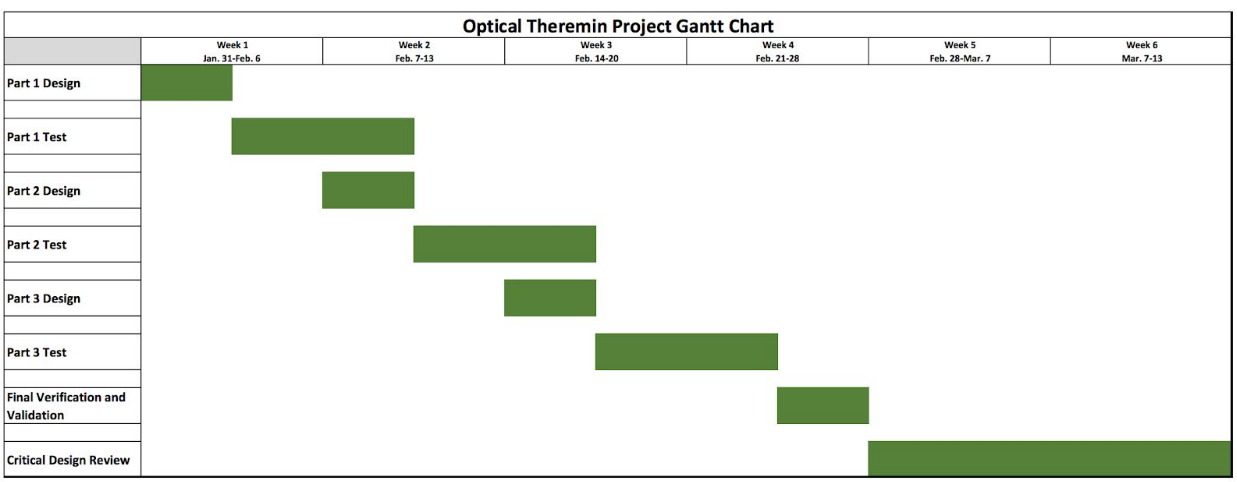


Figure 2: Project Gantt Chart

When planning the project process with a Gantt chart, it was immediately noticed that the balance of project parts and number of weeks followed a remarkable pattern that allowed for an easy routine to be developed. For each part of the assignment, half of a week was allotted for the design and coding of that part and a whole week was allotted for the testing and debugging of that part. Time was also set aside for the final verification and validation tests of the full project. These durations were chosen because it was anticipated that testing and debugging the circuit would take an unknown amount of time, whereas initial design and coding is relatively straightforward. The Critical Design Review was planned to start after the final lab demonstration because most likely the team would be making edits to the device constantly, so starting the Critical Design Review prematurely would have resulted in extensive editing and rewriting later. Additionally, it is important to take writing slowly such that a portion can be drafted, set aside, then looked upon with fresh eyes a few days later in order to produce an optimal quality report.

4.3 Bill of Materials:

- (4) 1 kΩ resistors
- (2) 15 MΩ resistors
- (2) OP906 photodiodes
- (1) TL074 low-noise JFET-input op-amp, quad package
- (3) LEDs, miscellaneous color
- (3) 330 Ω resistors
- Breadboard
- Circuit wire
- Speakers
- NI myDAQ
- NI LabVIEW

4.4 Physical Circuit Design

The fundamental component of the circuit is the TL074CN op-amp. It is needed to transform the leakage current into a measurable voltage level the myDAQ could use. This particular op-amp was used because it is specifically capable of amplifying extremely small current values, in this scenario the leakage current. The pin connections of this op-amp can be seen in Figure 4. The op-amp was powered with the myDAQ's power supply of ±15 V. It was found that a buffer was necessary to remove any interference from the photodiode. This was created using two 1 kΩ resistors for each buffer. Additionally, it was found through trial and error that a resistor value of 15 MΩ produced an appropriate output voltage for the myDAQ of approximately 5 V. A schematic of the photodiode and buffer circuits can be seen in Figure 3. The implemented circuit can be seen in Figure 5. Later, after the equalizer feature was added, three colored LEDs were implemented into the circuit to show its operation. Each LED is paired with a 330 resistor in order to limit the current going to the LED per its current rating.

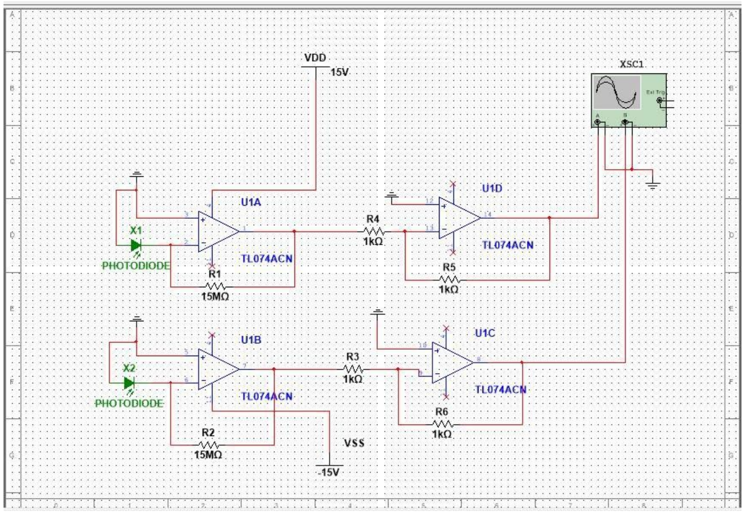


Figure 3: Multisim schematic of the photodiode circuit

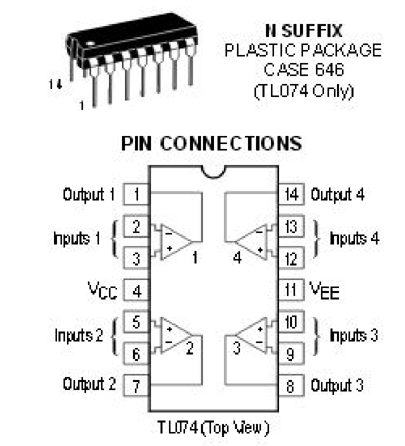


Figure 4: TL074 pin connections

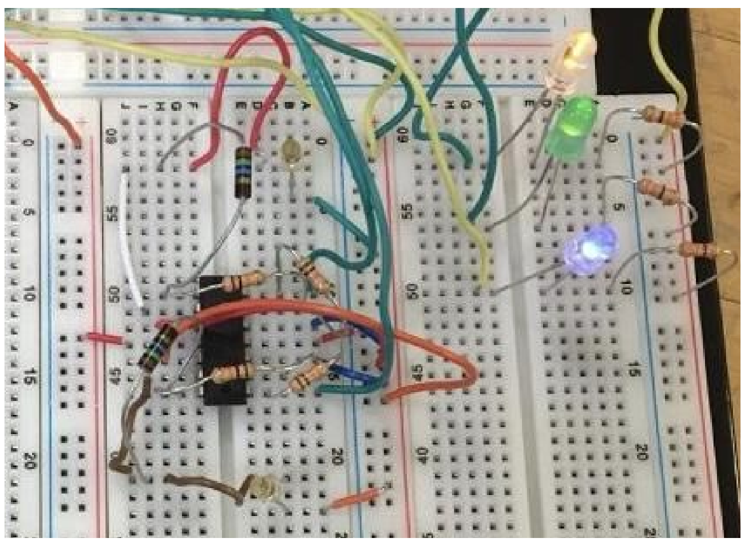


Figure 5: Photograph of implemented circuit

4.5 DAQ Assistant Settings

The following settings were used for the input DAQ Assistant:

- Analog inputs a0 and a1
- ±10 V Signal Input Range
- ‘N Samples’ Acquisition Mode
- 100 Samples to Read
- 44 kHz Rate

Analog inputs were chosen since the op-amps output an analog voltage signal. The input voltage range of ±10 V was chosen because the op-amps produced a voltage of around 5 V, and a range of ±10 V provides ample leeway for actual values being slightly above or below 5 V. N Samples was chosen because continuous samples would have resulted in data overflow in the LabVIEW code. Setting 100 samples to 44 kHz resulted in the DAQ assistant outputting the desired two arrays.

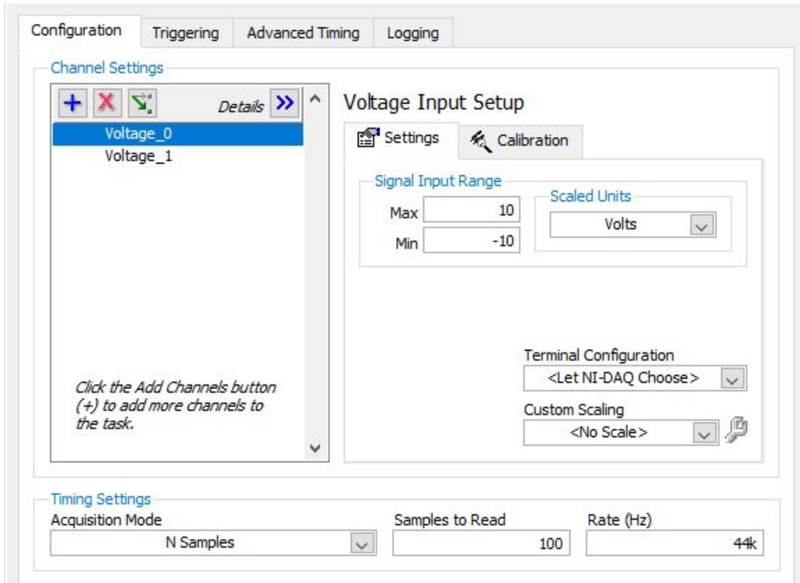


Figure 6: Input DAQ Assistant window

The following settings were used for the output DAQ Assistant for the photodiodes:

- ±2 V Signal Output Range
- Continuous Samples Generation Mode
- 10k Samples to Write
- 1 kHz Rate

The Signal Output Range of ±2 V was chosen since this would provide enough leeway for the amplitude of the generated sine wave. The output DAQ assistant doesn't have to consider any data overflow problems, so a Continuous Samples Generation Mode was chosen so that there would be a smooth transition between different musical pitches. Setting 100k samples at 1 kHz provides enough leeway for the data of the generated signal.

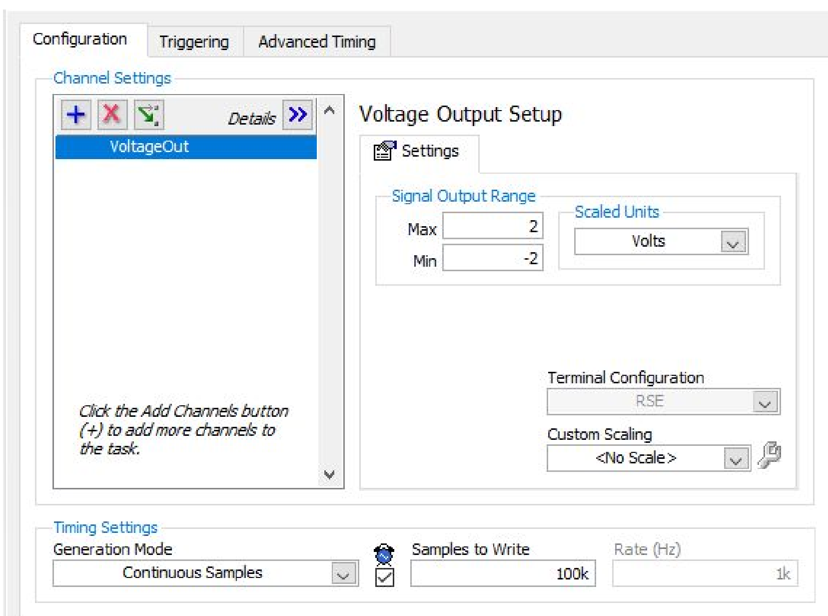


Figure 7: Output DAQ Assistant window for photodiodes

The following settings were used for the output DAQ assistant for the equalizer LEDs:

- Digital outputs d0, d1, and d2
- 1 Sample (On Demand) Generation Mode
- 100k Samples to Write
- 44 kHz Rate

Digital outputs were chosen since the LEDs only need a simple on or off setting, and set to 1 Sample for this same reason. 100k samples at 44 kHz were chosen to match the input DAQ Assistant settings. These can be seen in Figure 8 on the next page.

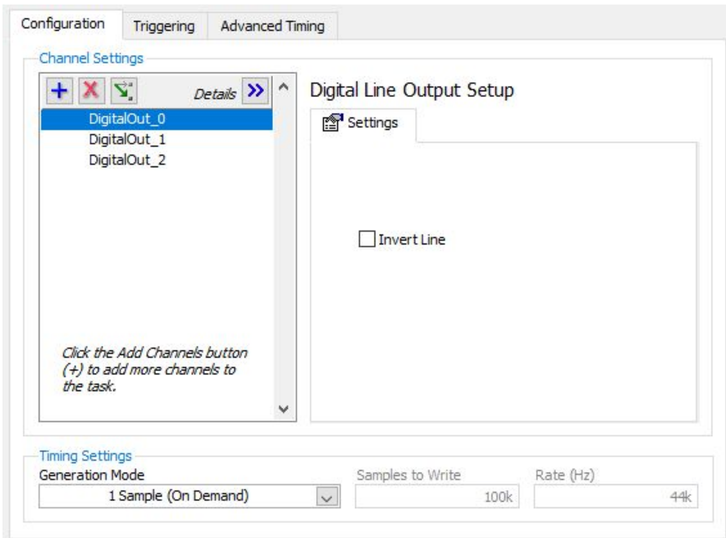


Figure 8: Output DAQ Assistant window for LEDs

4.6 LabVIEW Code

Below are the full LabVIEW Main VI and Front Panel:

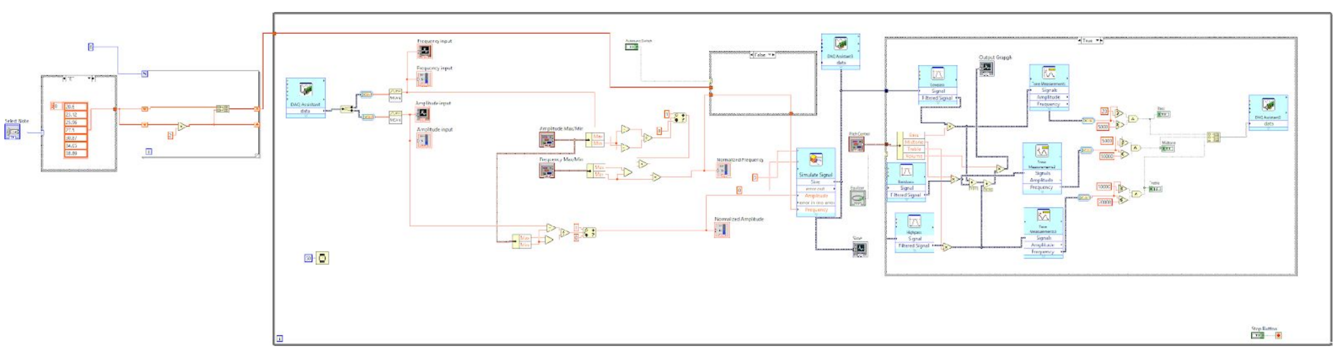


Figure 9: Full Main VI

The Main VI is organized by step by step functions moving from left to right. At the very left is the auto-tune feature, since the user needs to first select the key. This moves on to the main operation of the Theremin, which is collecting and processing data on light intensity and outputting a sine wave as a musical tone. Lastly, the equalizer feature is added to adjust this output sine wave to desired settings.

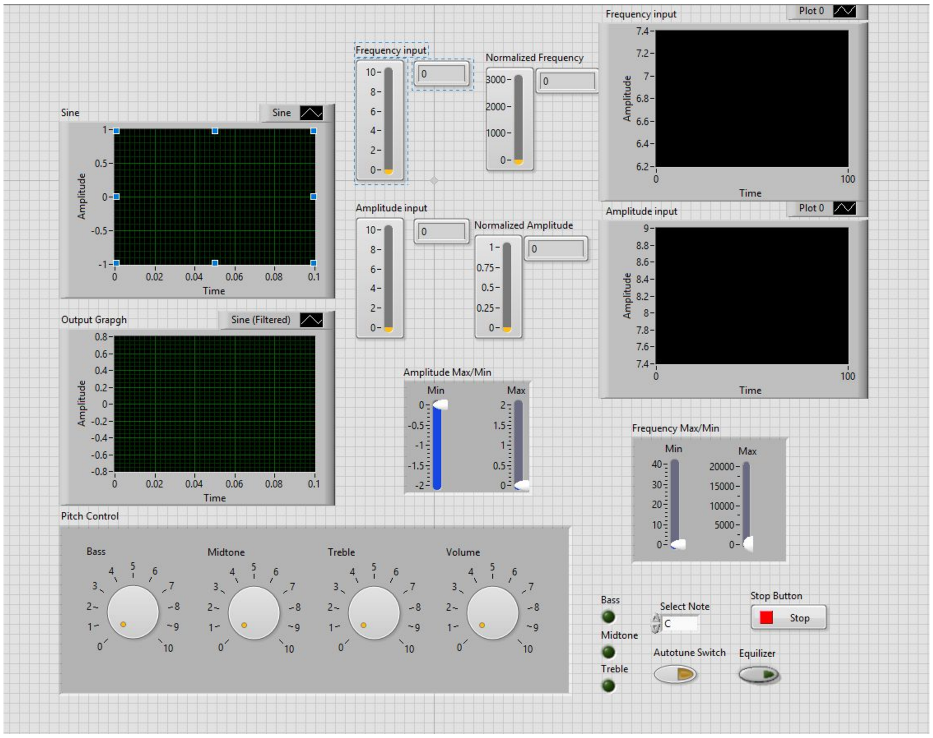


Figure 10: Full Main Front Panel

At the top of the Main Front Panel are the fundamental operations of the Theremin; input and output data with means to adjust the maximum and minimum of input amplitude and frequency. At the bottom are the auto-tune and equalizer features with their respective controls.

To focus on each segment of the assignment, first below is the Part 1 LabVIEW code:

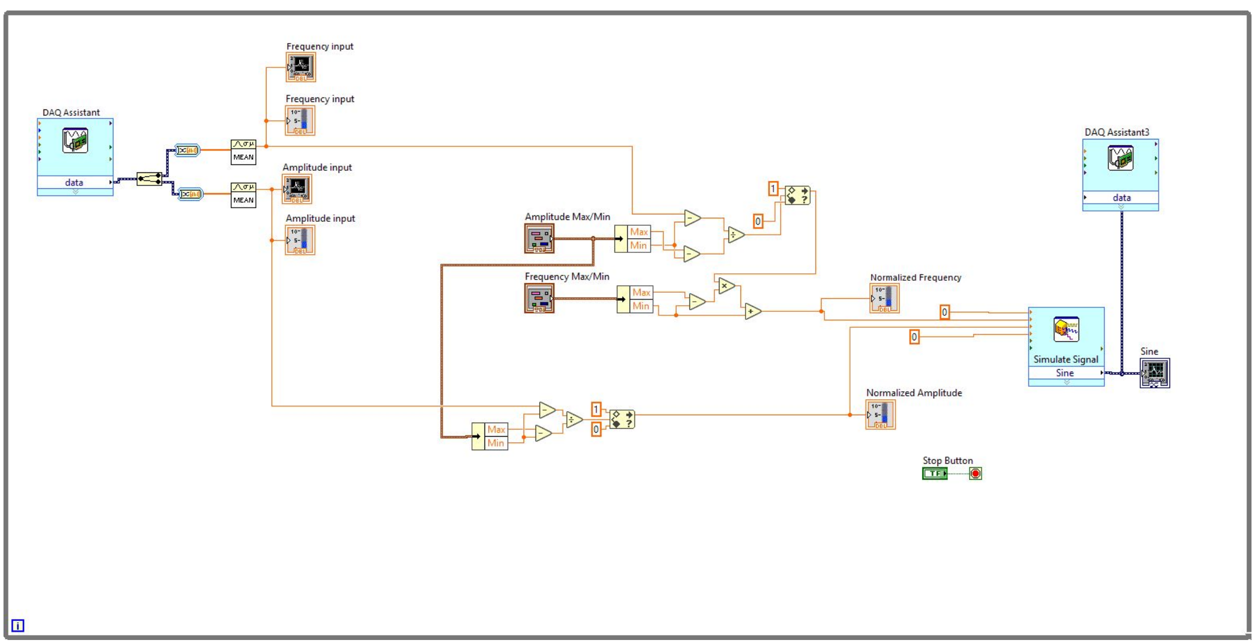


Figure 11: Part 1 LabVIEW code

Part 1 is enclosed in a for-loop with a delay time of 50 ms. The myDAQ receives two analog voltage signals using the input DAQ Assistant, one each for the pitch and volume controls. These are split and diverted into two different arrays, one each to be processed into frequency and amplitude. Both are converted from dynamic data into a 1D double array. These arrays are then average and scaled, which is done by subtracting the lower limit from the upper limit, dividing by the difference between the upper and lower limit, and confining this quotient between 0 and 1. These are then sent to the Simulate Signal which produces a sine wave from the frequency and amplitude data. As seen in Figure 11, the Simulate Signal configuration settings continuously generates the sine wave for a smooth signal, and also matches the DAQ Assistant output settings.

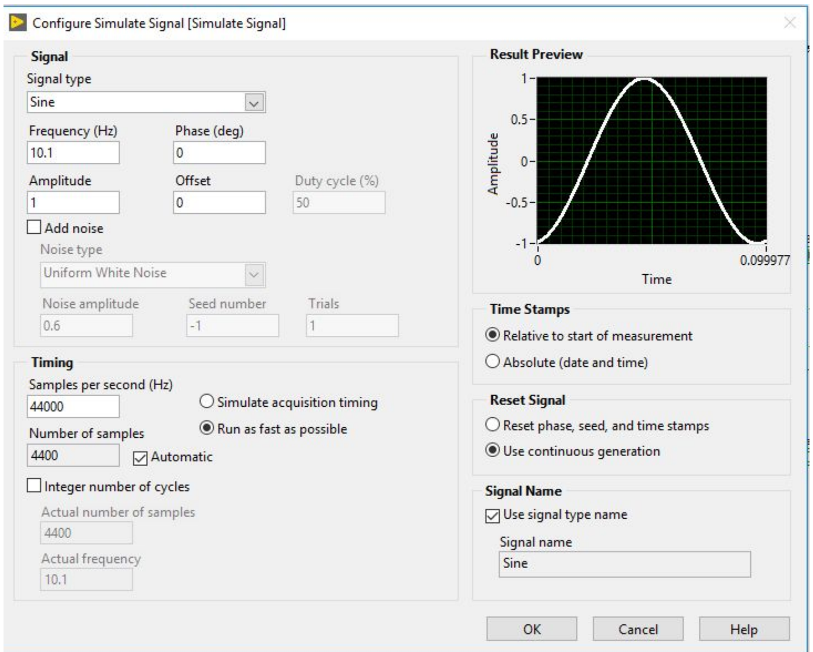


Figure 12: Simulate Signal configuration settings

Moving on, below is the Part 2 LabVIEW Code.

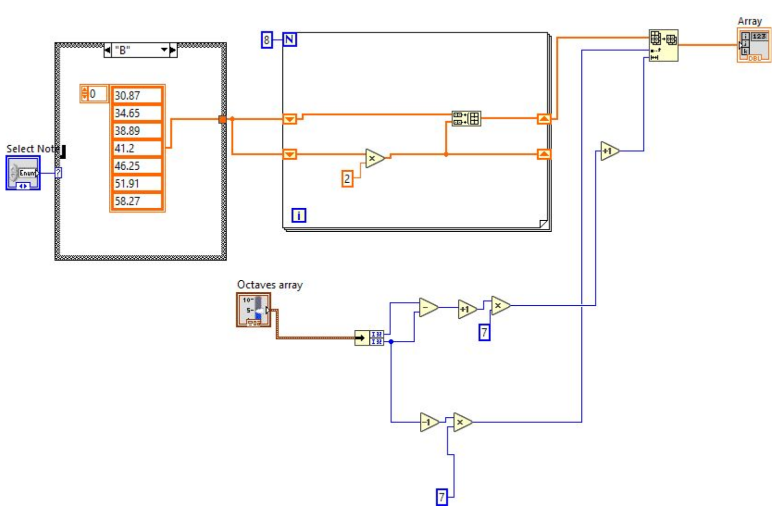


Figure 13: Part 2 LabVIEW code

The key selection portion at the beginning of Figure 13 shows a case structure that contains the twelve major keys, with each case containing the first octave of notes at that key. An enumerated input is utilized for the means of which the user selects the key. The first octave array is then sent to a for-loop with eight iterations to produce eight octaves. Shift registers are used to concatenate the first octave to the new produced eight octaves. Lastly, the user can select an octave range they want to constrain to using the array subset function, so that the final output only contains the octave ranges that the user desires. A Boolean switch for the auto-tune can be seen in Figure 9 and uses a true or false case structure. When set to true, notes from the octave array are wired to the output frequency. When set to false, simply the input array is wired to the output array.

Lastly, below is the LabVIEW code for Part 3, the equalizer:

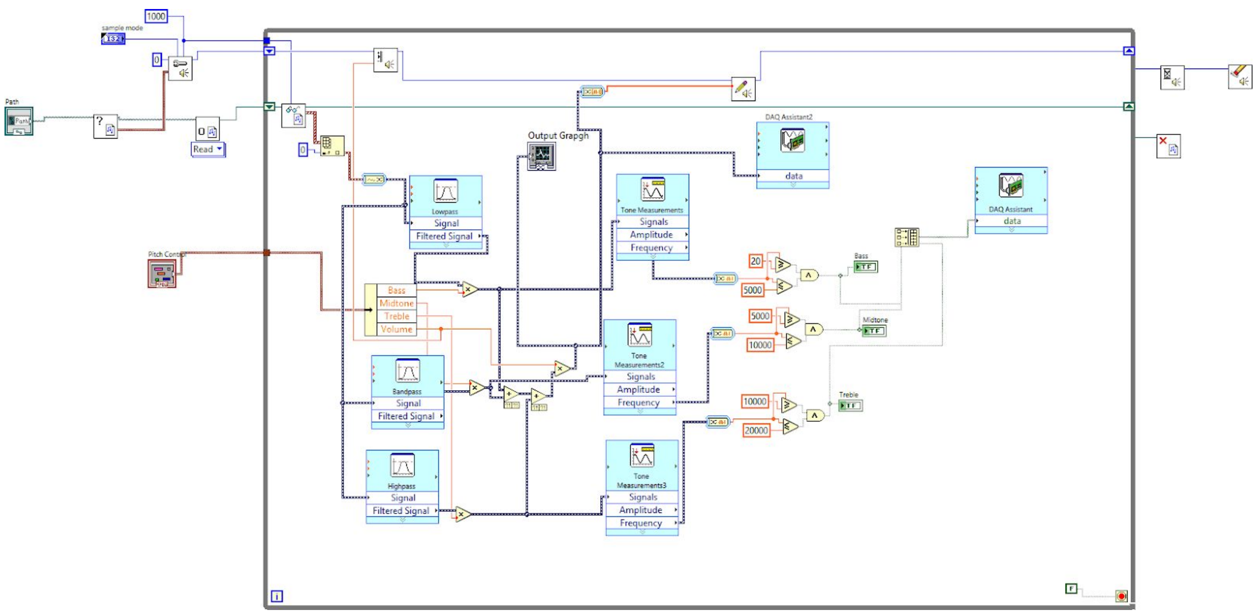


Figure 14: Part 3 LabVIEW code

The equalizer processes the sine wave coming from the main Theremin instrument. The waveform is divided into three branches and each is routed through a third-order Butterworth filter. As seen in Figure 14, at the top is the Lowpass filter, in the middle is the Bandpass filter, and at the bottom is the Highpass filter. The ranges of all are configurable by the user in the Front Panel. The output of all these filters are sent through a multiply function so that the user can adjust the intensity of any of the filters. The signals are then superimposed using an add function, and then sent through a final multiply function that is used to adjust the amplitude of the whole waveform and therefore the master volume. This final waveform is then sent to the same DAQ Assistant as used in Part 1, as seen in Figure 7.

At the top right of Figure 13, a method to read input .wav files can be seen. A file path is set up then read at a rate of 1000 samples per second. This reading of the wave file is then sent through the same equalizer discussed in the paragraph above.

In order for the LEDs to light up in correspondence with the equalizer functions, each of the three components is sent through a Tone Measurements express VI, which outuputs a measurement of the amplitude of each signal. This is then sent to greater/equal to and lesser/equal to functions. If the amplitude meets the requirements of these functions, a Boolean indicator lights up the corresponding LED, therefore showing what frequencies are being played through the equalizer.

4.7 Final Design Demonstration

During the circuit test, it was found that the Theremin instrument and auto-tune feature worked perfectly, however there were a few issues with the equalizer function. The .wav input was not functioning properly at that time, and some of the pitch control knobs could not be adjusted at the same time as other knobs. Since this was a bonus feature, it did not impact the overall assignment and function of the Theremin instrument. In future iterations, this bonus feature can be amended.

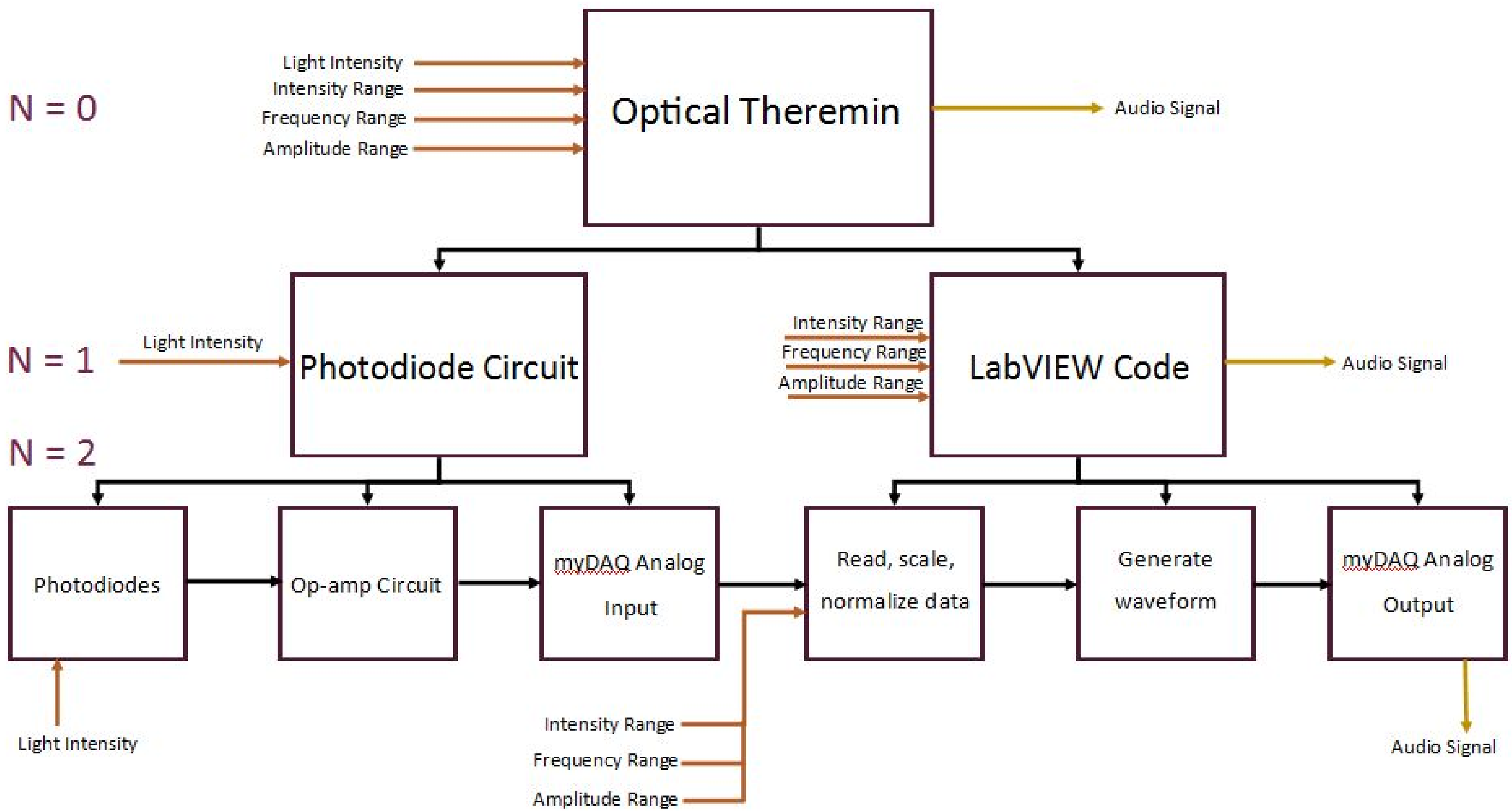
5. CONCLUSION

The designed and implemented Optical Theremin is capable of creating auto-tuned musical tones from the control of light intensity as desired. Exact frequency and amplitude settings can additionally be controlled by the user via the Front Panel of the LabVIEW code. In summary, the Front Panel exhibits: data on detected light intensities, controls to configure ranges of frequency and amplitude, normalized waveform after pitch and volume attenuation, auto-tone switch, auto-tune key and octave range selection, equalizer switch, equalizer indicators, and finally pitch and master volume control.

The photodiodes, op-amp circuit, myDAQ settings, and LabVIEW code all performed as expecting for the main Optical Theremin instrument. The additional auto-tune feature also performed well. The bonus equalizer portion had a few issues that can be identified and amended in the future. Overall, the design met all the requirements and a few of the bonus equalizer requirements.

6. APPENDIX

Figure 1: Initial Block Diagram


N = 0
Light Intensity
Intensity Range
Frequency Range
Amplitude Range
Optical Theremin
Audio Signal
N = 1
Light Intensity
Photodiode Circuit
Intensity Range
Frequency Range
Amplitude Range
LabVIEW Code
Audio Signal
N = 2
Photodiodes
Op-amp Circuit
myDAQ Analog Input
Read, scale, normalize data
Generate waveform
myDAQ Analog Output
Light Intensity
Intensity Range
Frequency Range
Amplitude Range
Audio Signal