Analog Instrumental Synthesizer

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***Abstract* — The following document will discuss the design and implementation of our Analog Instrumental Synthesizer. The synthesizer is both an effects pedal and synthesizer in one unit. This design is meant to bring a more lively and unique playing experience for both the instrumentalist and the audience. Using our synthesizer the user will be able to switch between 648 different combinations of wave shapes and distortions at will. All this was achieved while using a design meant for ease of use and practicality.**

***Index Terms* — Analog Instrumental Synthesizer, Analog Circuits, Voltage-Controlled Oscillators, Audio System, True Bypass.**

I. Introduction

The Analog Instrumental Synthesizer is mainly modeled for an electric guitar. Throughout the document we will refer to the Analog Instrumental Synthesizer as either the "synthesizer" or the "pedal." The overall design and approach for the pedal was that it was to be a versatile effects device while maintaining a practical and easy to use interface.

The main motivation for this project is to bridge the gap between the effects produced in electronic music and bring them to realization while using an instrument.

It might seem redundant for a device that can implement what a computer can already do. However the current method of producing these sounds does have a common downfall. The live shows are lackluster in comparison to the thrill of seeing a live band. In a club atmosphere or on an IPod it's alright to just hit play on a laptop to enjoy the music. But if this musician is playing a concert in front of a crowd that had paid money to see an artist it would be unacceptable if they just walked up to their computer and just pushed play on windows media. This is where this gap needs to be bridged which will end up adding elements to both electronic music and the traditional bands playing instruments.

This device must also be adaptive to the current methods of playing instruments in a live show setting. This is also a main downfall of using a laptop and the production software, it isn't meant to be used in live settings. They are for carefully configuring the signal after it is recorded. So this device needs to just be able to plug-and-play the instrument to it without changing the instrumentalist current set up. This is for price, convenience, and practicality of the device. If it is too expensive then the device will have some of the same problems as the higher end devices that are out there right now and no progress would have been made by this device.

There also needs to be the convenience of a portable device and it needs to be practical in a way that it can be implemented while not interfering with the users hands. The hands need to be free so this device will not be a hindrance of the ability to play the instrument, another area the laptop software falls short of. The most logical conclusion is to have the feet implement be the catalyst for which distortions are chosen.

For this device to be practical it must work with the current methods of implementing distortions for instruments. If people couldn't just plug and play then this device would be a failure. It would be extremely expensive for someone to already buy a new amplification and sound system just for this device, especially since musicians look at their playing of music not only as a hobby but almost as a lifestyle. Professionals and amateurs alike have spent years to perfect their equipment choices from guitars, to amplifiers, to speakers, even down to the brand of strings they use.

Therefore, for a device like this to be implemented its functionality with the preexisting technology and implementation methods is a must. Also the device needed to be designed in a way to be implemented while using your feet, which may sound obvious to some and abstract to others. However, this is one of the most important functionalities of this device because then the device can be implemented while the hands are busy playing the instrument.

Not only did we want to functionality of typical pedals but we wanted to design such a device that was easy to carry and had a durable housing that would withstand not only internal issues such as heat, but also be able to withstand any external conditions that could potentially damage the circuitry inside.

The main concern was that the guitarist using the synthesizer would be able to choose from an array of effects and waveforms while receive no negative overlapping between the two. The pedal has been designed in such a manner that the user can play a variety of effects and waveforms to give a unique playing experience while receiving no negative overlapping of effects. This has been quite a feat considering the Analog Instrumental Synthesizer actually has 648 different combination options. This was able to give us the capabilities of multiple pedals and combine them in one convenient unit. The output of this pedal is that it will offer the musician that decides to use it a very wide range of tones through layering effects. Some of the tones are more classic tones that any musician would be comfortable and they would feel at ease with. These tones are more common on some high end products. These types of effects will modulate the sound, pitch, frequency, and other timbres of the guitar, but when they are used it will still keep enough of the guitar sound that it would be apparent to audiences that this sound was produced with a guitar. The next type of distortions and modulations that is available for this effect box is the class of distortions and modulations that will do nothing to preserve the timbres of the original instrumental input signal. These will add an interesting dynamic and essentially turn the instrument into a synthesizer. There is a balance so that the user will be able to choose whichever path they want their input instrument signal to go, relinquishing the power of choice to the hands, or feet of the instrumentalist.

The pedal is capable of implementing these 15 guitar effects:

A. Triangle Wave
B. Square Wave
C. Saw-tooth Wave
D. Inverted Saw-tooth Wave
E. Sharp-tooth Wave
F. Shark-fin Wave
G. Koviak Wave
H. Pease Wave
I. Sweet Distortion
J. Savory Distortion
K. Tremolo Effect
L. Phasor Effect
M. Delay Effect
N. Reverb Effect
O. Chorus Effect

In addition to being capable of producing all of these effects and the 648 combinations of them, the user will be capable of selecting a bypass line for each of the 5 effect groups, which will be outlined later.

The input is going to match with the industry standard of using a quarter inch mono jack to transmit the signal. This is to allow the pedal to have just a simple "plug-n-play" feel to it. Since almost every instrument uses this sort of cable to carry its signal over short distances this would be the ideal input.

The output of the device will be identical to the input. Again, this size cable is an industry standard for most if not all guitar amplifiers so it would be in the device's best interests to comply with these standards. The output signal itself will need to be at unity gain in relation to the input. This is to minimize the amount of adjust ing needed on the user's end. Some guitar effect pedals that we have used in the past have outputs that are very clearly not at unity gain, and this can cause severe clipping in some low-end amplifiers.

II. Distortions

As mentioned before the device will be able to take in the output of a standard guitar as a sine wave and then depending on user choice the input will be changed into a different shape using a voltage-controlled oscillator thus giving the input a new waveform.

A. Bypass

Each of our effect groups will have the option to bypass the signal giving the user the ability to play a clean undistorted signal. In addition to being able to play through with a purely clean signal, this will enable user to be able to select individual effect types to use or not use.

B. Triangle Wave

Created by our voltage-controlled oscillator, this particular wave form will be used to simulate a more soft tone than those produced by other waveforms such as the square and saw-tooth waves. This is due to the abrupt signal changes and built-in harmonics. These types of waveforms can be used in wide range of frequencies.

The voltage-controlled oscillator is driven by the output of an LM2907 Frequency to Voltage Converter IC, which will output a DC voltage that is dependent on the frequency of the instrument input. One of the natural outputs of the voltage-controlled oscillator is a triangle wave, so gain control is all that is necessary before sending the signal to the next phase.

Fig. 1. LM2907 Frequency to Voltage Converter

C. Square Wave

This distortion is to void any sound variation that would add different timbres to the output. This wave is to give a clean and bright sound. The voltage-controlled oscillator will also be used in order to produce the square wave. As mentioned before, this waveform will be a more harsh sound. The square wave was a very common waveform used in early electronic devices, such as video game consoles, as it was simple to create the wave.

Another natural output of the voltage-controlled oscillator is the square wave and, as before, all that is necessary prior to the output of the effect is gain control in order to ensure that the signal is not too loud.

D. Saw-tooth wave

Due to its similarities between the triangle wave and the square wave the saw-tooth will have combined output characteristics of each wave. It will have the smooth qualities of a triangle wave while also giving the hints of harshness heard in the square wave. This gives the overall tone a somewhat aggressive nature to it. This wave will be an indirect product of the voltage-controlled oscillator.

Unlike the triangle and square waves, the saw-tooth wave was manually shaped by circuitry external to the oscillator. The square wave is treated as a digital signal that is used as a control line for a pair of switches, in such a manner so that only one switch is open at a time. The switches will allow the triangle wave to pass through it once opened by the signal from the square wave. In the case of one of the switches, the triangle wave is inverted. The resulting waveform from all of this is a rising slope saw-tooth wave.

E. Inverted Saw-tooth wave

This output is achieved by using an inverting operational amplifier to basically flip or invert the input of the saw-tooth wave given from the voltage-controlled oscillator. The same method is used to generate the inverted saw-tooth, but the polarity of the square wave is flipped so that the inputted triangle wave is also flipped. The resulting wave is a falling slope saw-tooth which is very similar in sound to the non-inverting saw-tooth, but with a subtle, distinct difference.

F. Sharp-tooth wave

This waveform is simply a series of voltage impulses, giving the signal a very harsh and dry sound. It is implemented by sending it through a comparator to turn it into a simple square wave, then is sent through a derivative amplifier circuit in order to draw out those periodic and harsh teeth.

G. Shark-fin wave

This effect is named after the shape of its wave form when observed in an oscilloscope. The secret to this effects tone is in its fin-like shape, this distortion is meant to give a balance to the input giving it both a true guitar effect and a modulated synthesized sound. A pure square wave that is formed not from clipping, with zero noise, has a very digital 80's video game sound to it. The other half of this wave is the actual input guitar signal. This gives a perfect balance of the raw guitar signal and a modulated "synthy" output.

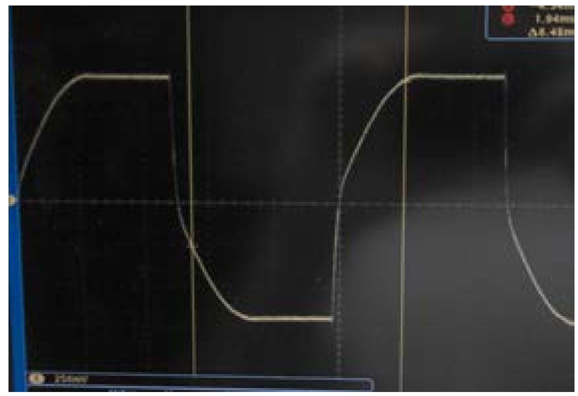

Fig. 2. Shark-fin Waveform

H. Koviak distortion

The koviak is a modified version of a custom made distortion pedal made by a Danish electrical engineer. However this tone was made using tubes and our project is all solid state for durability and reliability reasons. This distortion gives the fuzziness of a standard distortion found in most pedals yet when a chord is played the user will be able to hear each note very clearly. Most other distortions would get a harmonic interference that muddles the sound. This tone solves that problem for people that want to add body to their sound without destroying the beauty of their chord progressions. The koviak is able to keep the overdriven sound and this effect will definitely give a signature tone that any "pedalhead" would gawk over.

I. Pease distortion

This type of distortion is used in order to allow the user to create a frequency shift using the pedal. Depending on how much the pedal is pushed the shift is increased and decreased.

This circuit is implemented very similarly to the voltage-controlled oscillator circuit used in the previous waveforms. It also uses the LM2907, but in addition to the LM331 Voltage to Frequency Converter IC. The voltage from the LM2907 is offset by a value specified by the user using the foot pedal, and is then fed into the input of the LM331. The offset will allow the user to change the pitch of whatever note is being played while playing it.

J. Sweet Distortion

This effect is what any guitarist and almost any music aficionado would refer to as "distortion." From an electrical engineering perspective distortion is just any alterations to the signal's waveform. However to a guitarist distortion is just when the signal is amplified then clipped so that the signal is close to a square wave. The guitarist is unaware of what the electronics are doing however they do recognize a warmer and fuzzier tone than the guitar can create on its own. We implemented two separate types of this distortion in this pedal because there are so many different tones that different types of guitarist are used to having for different types of music we decided we would have to implement at least two of the most popular styles of distortion. We named this one sweet so that it is easy to tell which style was selected. This style of distortion has a warmer, mellow tone, without sacrificing piercing high notes, prolong sustain, and a more clear tone that is ideal for any type of solo.

K. Savory Distortion

This next type of distortion was named "Savory" just to help the user know which style of distortion the user selected. This style is closer to a square wave than the sweet distortion mention above. This style of distortion has a few common names such as "dirty," "growling" or "crunchy." We decided to name this as "savory" to help with recognition. In comparison to the sweet distortion mentioned above this distortion is much more like a square wave than the sweet. This distortion is designed for low pitched rhythmic sections. It will add body to any rhythm that is played and can help fill any room with a full and bright tone.

III. EFFECTS

After the desired distortion is selected and implemented the new distorted sound can either be bypassed directly to the output or the user can then choose to apply one of the multiple effects designed for the pedal. The list of effects is as follows.

A. Tremolo

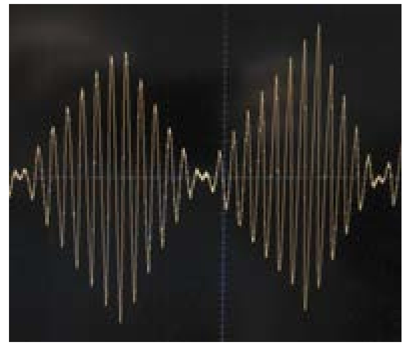

Fig. 3. Tremolo Waveform

This effect is achieved by creating a low frequency sinusoidal waveform which is then multiplied by the original, or modified, guitar signal. The result is a sound that is similar to that of the original but it is pulsed in and out to create a wobble sound. This is comparable to turning the volume control up and down rapidly. The oscillation frequency of this effect will be directly controlled by the foot pedal.

This effect is achieved simply by multiplying the input signal with the output of a low frequency oscillator, which will cause the volume to rise and fall in a linear fashion. The mentioned foot pedal will be attached to the low frequency oscillator in a way that will allow the user to dictate the desired frequency of the oscillations.

B. Phasor

This effect is done by sending the input of the guitar or distortion through a series of all-pass filters. These filters are also known as stages. As the sound passes through each stage the signal becomes more and more out of phase. The more stages the greater the effect. A feedback loop is also added to give the circuit a more prominent output. At the output of the effect the out of phase signal is then combined with the original output. The resulting sound is a whooshing type of noise that some describe as listening to a plane or jet pass by overhead. The oscillations within the phasor will be controlled by a knob located on the housing of the pedal itself.

C. Delay

The delay will create a sustained version of whatever input signal it is given. There are two attributes to this effect are the delay time and the decay. The delay time is how long the sustain will last while the decay is how long it takes from the peak of the last note to reach zero. Both of these attributes will be controlled using knobs located on the pedal box. At the core of all of our Delay, Chorus, and Reverb effects is the PT2399 Echo Processor IC, which is often used in homemade digital delay effect pedals.

D. Chorus

The chorus also mixes a delayed signal with the original input in order to create a large number of harmonically related notches in the frequency response. This delay is almost as long as an echo effect. When implemented, this particular effect will sound as though multiple guitars are playing together. This will be a more subtle sound due to the absence of a feedback loop. This is another effect that is used to clean out some of the harsher tones cause by distorting the sound wave and can give the guitar a mellower and brighter sound.

Fig. 4. PT2399 Echo Processor

E. Reverb

The reverb will sound as though you are in an empty room and the sound of the input is bouncing off of the walls. This is often used in music to create a more full sound. The signal is saturated with extra “musical” noise. This effect actually is sometimes used to clean out some of the dirtier side effects of the distortions. This effect will have a knob on the pedal box in order to increase or decrease the amount of time the reverb will be sustained.

Typical reverb effects are done right on the guitar amplifier, as they depend on the vibrations of the attached speaker to operate. Because our pedal is not attached to any speakers, this had to be done artificially through the use of the aforementioned IC. Though the sustain of the reverb is available to the user, the delay time will not be controllable as the effect would be highly sensitive to any user control.

IV. Power Supply and Voltage Regulation

Typical guitar effect pedals use external adapters for their power regulation. One of the issues with using adapters is the inability to use adjacent outlets on either walls or power strips/surge protectors. In our design, we chose to have all of our power transformation within the unit, making the external part count close to 0 and removing the outlet clutter.

For our main power supply we chose to use an Astrodyne power supply that outputs ±12V @ .63A.

Using the two 12V outputs, we decided to add a series of 78XX and 79XX linear voltage regulators to provide out IC’s with their required voltage levels. The output voltages from this area of the circuit will be ±12 V, ±5 V, and a reference ground. These are the nominal voltages required to power our ICs and to designate reference voltages within the various parts of the device’s circuitry.

In addition to these 5 voltage values, we also have a separate +5V output that comes from its own voltage regulator. The purpose of this is to isolate the CD4066 IC, which requires the ±5V values, from the other portions of the device that need 5V in order to cut down on noise effecting the outputs of the switches.

This power regulation system was fitted neatly onto a Vectorbord, shown in fig. 5, that was then placed beneath the main PCB board in the enclosure. This Vectorbord is connected to the astrodyne power supply and both are fixed to the bottom of the housing unit.

Due to time constraints, we were unable to fully test the power at all locations of the device to ensure that no component is receiving too much power. However, because the transformer is regulated and is followed by voltage regulators, we are confident that our circuitry will not be subjected to any electrical mishaps.

V. Design Method

When it came to designing our synthesizer we as a group wanted to finish with a professional sounding pedal box that was easy to carry around and worked like any other pedal previously used.

In order to accomplish some of the more common distortions, such as the “sweet” and “savory” distortions, we looked to other pedals to see how other engineers and designers were to accomplish such tasks.

Other distortions and effects required a more rigorous approach when it came to designing. Using a software program called FL studios we were able to determine what types of waveforms we wanted to try to replicate in order to properly achieve a specific distortion or effect. Once the proper research had been made for an effect or distortion we then used LTspice to test the potential circuit to see if we would get favorable results. If this initial test passed, the next step was to then connect this design to other designs to see it’s reaction to additional inputs or outputs. After passing this test we then started to physically put these circuits together and testing them.

Once a design is passed as a working distortion or effect the next step was to physically assemble the desired circuit and test it using an actual guitar input.

Closely monitored via oscilloscope a guitar input was then applied to the distortion or effect to see if the desired output was given. We monitored both the input and output of the circuit and were able to closely monitor the input voltage powering the system using a power supply placed at the lab station.

After a group of these effects and distortions were physically tested and completed the final step of the testing process was to pair or group these effects to ensure that they would have no negative overlapping when applied at the same time.

VI. Project management

Due to the nature of our project our group was able to maintain a very minimal budget. Most of our components were easily accessible through Dr. Douglas, sampled from online vendors such as Texas Instruments, or found within the senior design lab. The biggest purchases made were for the PCB board and the housing for the PCB board and the pedal itself.

Containing only three members our group set no leader. At the beginning of the project each member was assigned a section and was responsible for completing tasks necessary for his own area within the project. Most problems addressed were worked on in a collaborative fashion in order to provide quick and sometimes straight forward solutions.

It was entrusted that each member keep in contact with the group so that everyone was updated and to ensure that proper progress was being made. If it was found that a member was behind others in the group would come forward and help to put the project back on track.

In the initial stages, each member was tasked with a list of components to work on, in the interest of keeping the individual workloads identical. George was tasked with a majority of the waveform circuits, while Chris and Kendall split the remaining ones amongst themselves. In addition to those circuits, Chris was tasked with the power regulation circuitry and Kendall was given the selection and switching circuitry.

VII. implementation

Such thorough testing proved to be well worth the effort when it came to designing the PCB board layout. After testing and tuning each effect, the effect was drawn into CadSoft’s EAGLE software in order to prepare the circuit to be laid out onto the PCB design. Once every part was drawn onto the schematic, including the selection/switching system, we were able to use EAGLE to organize the components onto the PCB. Every effect was placed onto the board so that every component used in any given effect was within close reach to avoid clutter on the actual PCB.

Not every part of our design is located on the PCB. As mentioned previously the power related circuitry was implemented on a Vectorbord, and the microcontroller was kept on its development board.

IIX. Housing

The housing for our pedal is custom made by George Compton to comfortably fit the power supply and the PCB board. The enclosure itself is made up of a steel frame which is then enclosed by cut sheets of plexiglass. These materials were used in order to provide a relatively inexpensive yet durable enclosure for our hardware. Of course the enclosure will also have the standard stereo input and output for the guitar and amplifier to plug in, but it will also have other features to accommodate for the distortions and effects.

As with the power circuitry, due to time constraints we are unable to fully stress test the frame of the housing to see if they meet our desired specifications. We are confident that the steel frame is sturdy enough to withstand enough stress to allow the user to step onto the device without issue. It is likely that the device, however, will not be able to hold a person’s full weight so it would be advised that the user should not use the device in such a fashion.

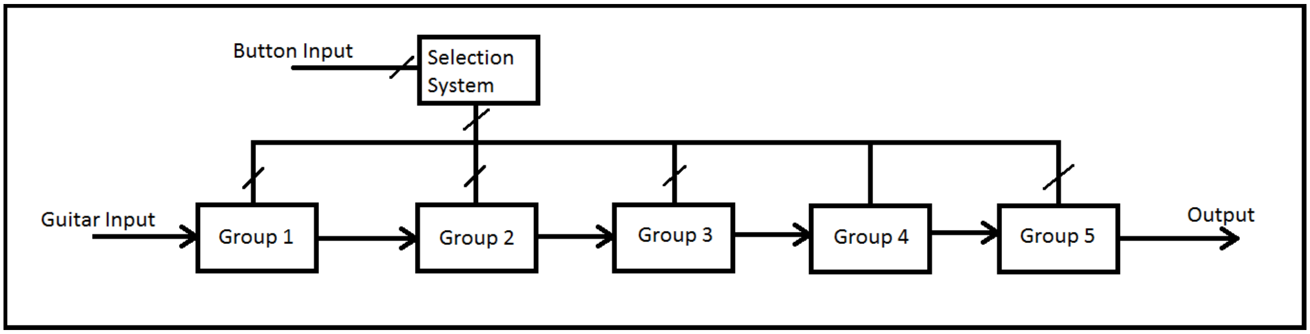

Fig. 5. Selection System Block Diagram

This enclosure will be fitted with a handful of knobs which will allow the user to control certain aspects of the phasor, delay, and the reverb effect. Mostly these knobs will increase or decrease the period in which the input signal will be affected.

Five different buttons will allow the user to cycle through an array of different distortions and effects. As mentioned previously, the layout of these buttons were carefully planned so that no negative feedback or overlapping will occur between effects. While each push button will cycle through a set list of effects or distortions LEDs will be used to indicate to the user which has been activated.

Located on the side of the housing is where the pedal is mounted. The pedal is a potentiometer that will allow the user to further change the abilities of an effect such as the tremolo. When this effect is activated the pedal can be used to increase or decrease the oscillation that will make the signal sound like its being turned up and down rapidly. How rapidly this occurs depends on the user input from the pedal.

IX. SWITCHING

The last but definitely not least important object of functionality for any instrumentation project is how the switching is implemented.

This pedal is selecting through 15 different effects that can be combined into 648 signature tones! Trying to buy a bunch of single effect pedals to complete this many functions would not only be wildly expensive. It would also sound horrible.

You might be asking yourself how we would be able to make the bold assumption that our pedal not only can have more effects, but also outperform any pedal on the market. The answer resides in the switching.

For any of the products on the market the current method of building a pedal that have a lot of functionalities is to construct it around a single DSP chip then a micro controller will switch through up to hundreds of preset tones. The inherent problem with this method is the lack of personality that can be implemented when you have maybe a hundred tones to choose but none of these can be personalized. With our project the ability to layer the options and set the amplitudes and frequencies are all done by the user to fit their needs, not by some programmer in a computer lab. Also, almost any musician can tell the difference between the analog hardware and digitally sampled waveforms. Therefore, our project is superior to the digital multi-effects pedals in both tone quality and in "personality."

It is agreed that our project can top a digital multi-effect pedal but how does it stack up to single effect pedals which are also implemented in an analog fashion. Wouldn't these two options be equivalent? The short answer is no.

One of the main reasons that it wouldn't be ideal to just buy a bunch of single effects pedals and run them in series is some effects the order is important to preserving the tone. For example an experienced instrumentalist would know that a phase oscillating circuit should go after a wave shaping distortion. The opposite would lead to a flat muddled sound. With this pedal only combinations that complement each other are permitted by our intuitive selection system. There is another major problem with having many single effect pedals in series… and that is the tone loss that is experienced. This loss in tone is not a product of the effect implementation itself, which is usually pretty good in the single effect pedals, but in the switching.

These single effect pedals are implemented in a way that the controlling switch is only on the input line. A small amount of background noise is added to the signal on the output line. This is usually not a problem for just one or two of these pedals but any serious musician loves to have many effects in their arsenal. However, the more effects they add the more tone they lose. This double edged sword of tonality is why so much focus was given to a seemingly trivial aspect of this project.

The way our project implements selection through separate effects is through the use of rotary and toggle switches, much like any other standard single effects pedal. The difference is the mechanical switch that the user is interfaced with never comes in contact with the signal. These switches make a "pop" on signal lines due to arching, which is also unpleasant to the listener. Instead these mechanical switches are used to switch the signal lines off and on between solid state MOSFET IC switches to minimize noise added by the switch and eliminate the popping sound created by arching.

X. CONCLUSION

Throughout the course of our project we have learned to better work with deadlines, work as a group, and bettered our problem solving skills as engineers.

We, as a group, were able to meet regularly and discuss upcoming sections we were to work on and any problems or ideas we had. By doing this we were able to discuss and set milestones in the project based on difficulty and amount of work each member was able to put towards completing tasks. This was a big help in ensuring that we were able to complete the Analog Instrumental Synthesizer on time. It is expected that this experience of working as a team has better prepared us for when we join the industry as engineers.

Because of the large amount of exposure to analog circuitry within this project, we as a group have a more broad and robust understanding of these sorts of circuits. Prior to this project, most of our in-class experiments involved using one major component at a time, so our project has taught us the intricacies and subtleties of combining analog circuits together. In addition, we have also become much more familiar with the software used to both simulate and draft circuits. Because of the large size and large component count of our device, we have also got a lot more practice with soldering components.

ACKNOWLEDGEMENT

We would like to thank our review panel for taking the time out of their schedules to be a part of our senior design. Your judgment and analytical participation are much appreciated. We also thank Dr. Richie for his patience with the senior design groups and insight he has provided us over the past two semesters. We thank Mr. Douglas for his patience in helping us obtain our various components as needed throughout this semester.

PROJECT ENGINEERS

George Compton will be graduating from the University of Central Florida in August of 2013 with a Bachelor's of Science in Electrical Engineering. His interests include audio signal processing, digital signal processing, and embedded systems. His plans are to go into the workforce and start a career.

Kendall Murphey will be graduating from the University of Central Florida in August of 2013 with a Bachelor's of Science in Electrical Engineering. His interests include processor architecture and control engineering. He plans to enter the workforce immediately after graduation and pursue self-study in his preferred fields.

Christopher Suarez will graduate from the University of Central Florida in May of 2013 with a Bachelor's of Science in Electrical Engineering. His plans are to join the work force for a couple years before returning to school to pursue a Master's degree in his field.