

Vacuum Tube Stereo Amplifier with Digital Control

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Abstract — Vacuum tube audio amplifier for which the entire signal path is analog but the audio parameters are digitally controlled via a touch screen graphical user interface which also displays visualizations of the amplitude, frequency and phase characteristics of the audio signals. This paper explains the process used to build a 2 channel 20 watt amplifier controlled by a 72MHz microcontroller. The system is split into three main pieces the analog signal path, the digital spectrum analysis, and the graphical user interface.

Index Terms — Analog, Embedded, Touch Screen, STM32F303RC, Vacuum Tube.

I. INTRODUCTION

The audio industry today is dominated by high power solid state devices. These devices have high efficiency ratings and small foot prints making them ideal for 90% of today's consumer base. Even though these devices seem to be perfect they still have some negative aspects. Solid state amplifiers typically have a low total distortion, but they tend to generate odd harmonics that tend not to be musical notes. This is where vacuum tubes come into the picture. During amplification with a vacuum tube only even harmonics are generated, each of which is simply the same musical note of a higher octave. This may seem unimportant but to the other 10% of the market that are musicians, or serious musical enthusiast this is a big deal so much so that they are willing to sacrifice the high power and small footprint to obtain this audio perfection.

This is the niche that digitally controlled vacuum tube audio amplifier fills. This project integrates key features of a typical commercial grade vacuum tube amplifier such as multiple analog inputs, pre equalization controllable gain stages, left and right channel balance, and 6 bands of equalization. What makes this project so unique is the fact that a 7" color touch screen along with an ARM microcontroller is used in conjunction to control the entire system. The digital features of the project include a custom designed user interface that has controls for each of the variable resistors in order to manipulate the boost and cut of each equalization channel, real time

visualizations of the output audio spectrum, and internal case temperatures.

II. DESIGN GOALS

The goal is to design, document, and fabricate an all-analog vacuum-tube pre-amplifier and power amplifier, yet be all digitally controlled. The finished product must incorporate a modern touch screen-based Graphical User Interface (GUI) control for all functions except power. The touch screen should produce an entertaining display that reacts to the audio signal in a similar manner to Microsoft Windows Media Center when not being used for control.

The envisioned end use of the finished product is a residential setting, such as a living or family room of a typical-sized suburban home. It is anticipated that the product will be placed on an entertainment center shelf, a bookcase, or perhaps a piece of furniture such as an end table. The product is intended for serious and critical music listening, an activity that the end user would be doing as a primary activity. The volume produced should be "room filling" but not so loud as to hinder conversation. Based on experience with previous commercially-made stereo receivers, the team agreed that 10 watts per channel minimum, with a goal of 15 watts per channel would suffice.

While a vacuum-tube-based amplifier is desired for its clipping characteristics, it should not introduce excessive distortion when not clipping. This means that for much of the signal, the distortion should be minimal – comparable if not better than a solid state audio amplifier. The amplifier should contribute as low noise as possible (beyond what is already present in the signal) and introduce absolutely no 60 or 120 Hz components, commonly known as "hum". The audio signal path must be completely analog. Ideally the entire audio path could be processed using vacuum tubes, as will be seen in the commercial designs presented later in this document, but would greatly complicate digital control due to the need to interface the high-voltage tube circuits to the low-voltage microprocessor circuit. Solid state operational amplifiers will be used as the basis for a graphic equalizer.

The finished product will not have any physical controls, except for a toggle-type power switch. Due to the use of AC-power-line derived voltages of as high as 500 volts DC, safety is paramount. Accordingly, the finished product shall be free of electrical hazards. All exposed metal surfaces shall be grounded, and the AC power input shall be fused. The physical power switch shall break the hot and neutral power signals when in the "OFF" position. Due to the exposed delicate vacuum tubes that could expose high voltages if broken, the finished product is not intended to be used by small children.

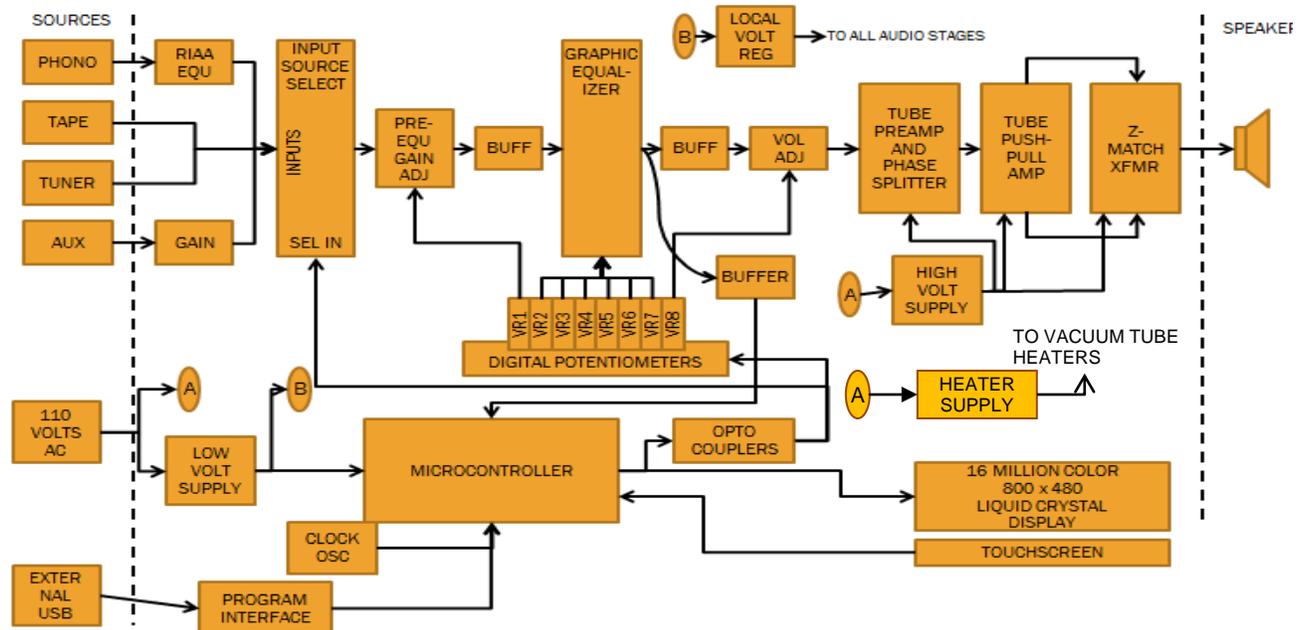


Figure 1: System Block Diagram

III. DESIGN OVERVIEW

See figure 1 for the following discussion. For the project to work correctly and meet the design requirements many subsystems have to work together in harmony. This implies correct interfacing with hardware and software, software and software, a hardware to hardware. Large amounts of attention have been put toward making sure all these systems work together. The entire project can be divided up into 4 major groups. The analog signal path is the main focus of the project. The digital control system is the heart of the project and does all the behind-the-scenes work to get the entire project to work correctly. There are multiple power supplies, each with very different requirements. And finally the user interface which is super critical as it functions as the control panel for the project.

A. Analog signal path

The analog signal path can be subdivided into 4 components: the analog source select, digitally controlled graphical equalizer, per amp stage, power amp stage.

See figure 2 for the following discussion. The finished product is designed to accept up to four audio sources, which enter via commonly available “RCA” jacks. The “Phono” input accepts a signal directly from a magnetic type phonograph cartridge. The signal passes through an operational amplifier filter, derived from a reference design in the LM4562 data sheet, with the complementary filter characteristic to compensate for the Recording Industry Association of America (RIAA) specification applied to vinyl when they are recorded.

The “Tape” and “Tuner” inputs are designed to accept “line level” audio of nominally 1V peak value go directly into the multiplexer, each with 10K ohm resistors to ground to provide some Electro-Static Discharge (ESD) protection to the otherwise direct to CMOS input. The “Aux” input has an operational amplifier configured to provide a gain of 10 to enable the use of lower level audio inputs. An analog multiplexer is used, driven by two GPIO from the microcontroller to select one of four input sources. The multiplexer is an 8:1 CMOS analog multiplexer with only the lower four inputs used (the unused upper four inputs are grounded). The digital inputs

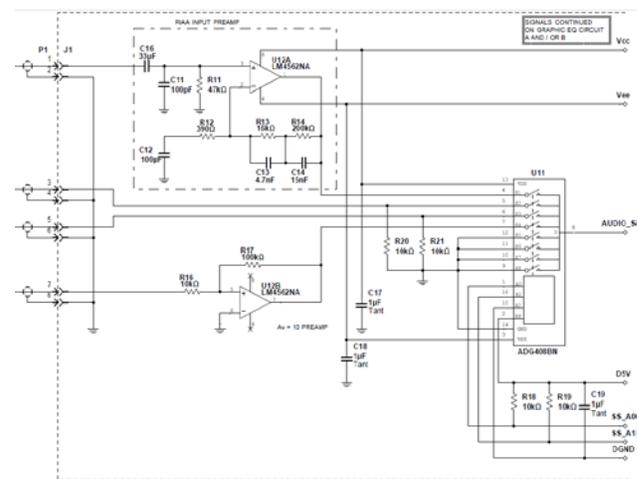


Figure 2: Input Source Select schematic

were designed and simulated, however none worked as well or even provided substantially better performance. Given that scenario the reference circuit was slowly refined. The first improvement was to provide a separate cathode resistor and bypass capacitor for each 6L6. This cut the distortion to around 1.6% THD. Next, attention was paid to the power dissipation of U1 and U2; Separate measurements not shown revealed a dissipation of 100 watts per tube, greatly exceeding the 6L6 tubes power rating of 30 watts. Many hours of study, calculation, and simulation experiments were used to arrive at the final circuit design, as there were several tradeoffs that had to be made:

- 1) Maximum output power occurs with the highest plate voltage. High plate voltages unfortunately run the risk of exceeding the 6L6 maximum plate voltage rating of 450 volts.
- 2) Lowest distortion was achieved with the highest plate voltages.
- 3) Lowest distortion was achieved with lower values of cathode resistor; however this resulted in higher plate voltages.

The next step was to find the ideal impedance presented to the plate by the transformer / speaker combination. The chosen part number of impedance matching transformer provides six taps on the secondary; various combinations of taps can produce impedances ranging from 3000 to 22.5K Ω . Impedances on the low end result in high distortion, while those at the high end cause premature clipping and low power output. A value of 5600 ohms was ultimately chosen, resulting in the best combination of maximum output power and THD.

During further attempts to optimize this design, a load line graph was created (see figure 5); On this graph the blue curves represent the $V_g=0$ and $V_g=12$ grid bias voltage curves taken from the JJ Electronic vendor data

sheet for the 6L6. The red curve represents the maximum allowable plate power dissipation of 30 watts. The five plotted load lines were measured during several optimization attempts (the diamond symbol on some lines represents the amplifier's quiescent point).

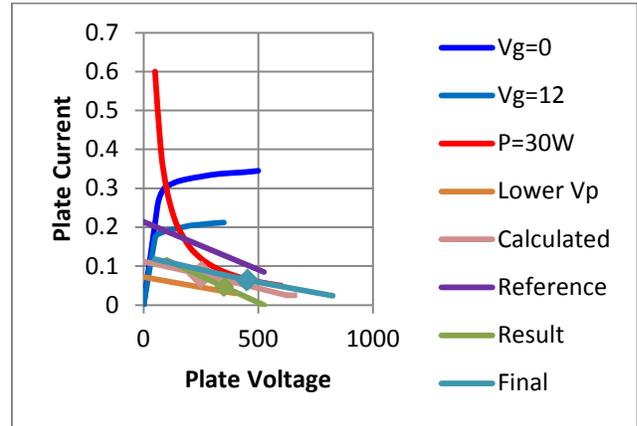


Figure 5: Bias Voltage Curves

The resulting load line, which was measured from a simulation of the final configuration of the amplifier, is close to ideal. The line is nearly tangent to the 30W power curve, with a nearly-centered Q point, and gives the lowest distortion / highest power characteristic possible in this design, while still meeting the output power requirement. Simulation results of the final design configuration with a 1 KHz input yields 11.7 Watts rms into an 8-ohm load with 2.1% THD when the output is just under the onset of clipping.

B. Digital Control System

The STM32F3 series is a 32-bit ARM Cortex M3 core.

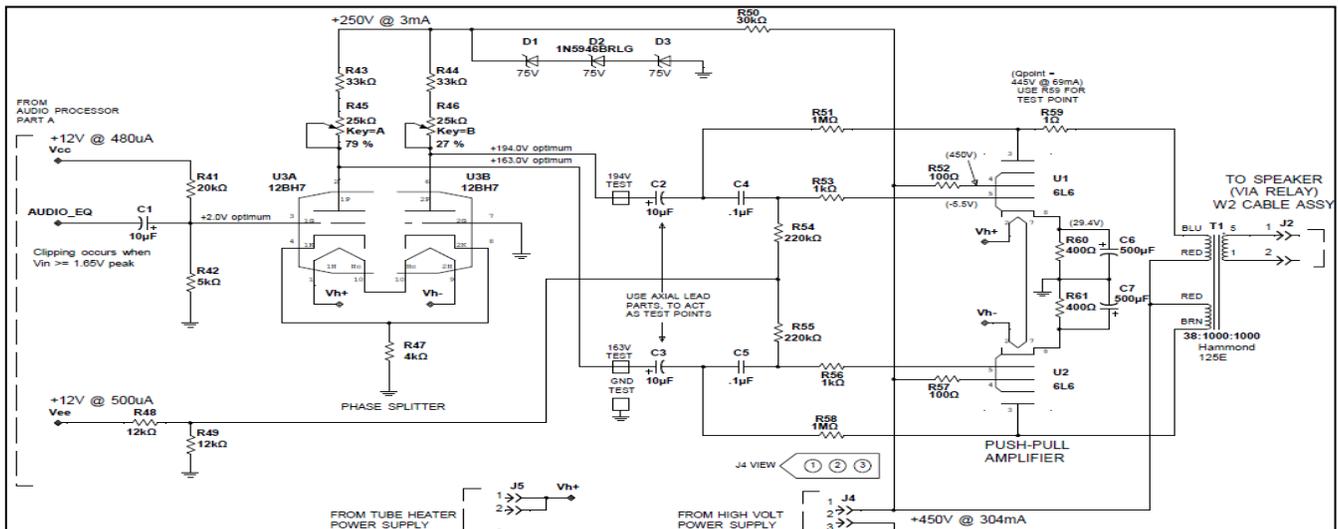


Figure 4: Vacuum tube phase splitter and power amp

The M4 provides high quality digital signal processing, floating point calculations, and many advance peripheral functions while operation at 72 MHz. The STM32F3 are full-system-on-chip solutions that provides all required functionality in a single chip.

The ADC is one of the critical peripherals that will be used. The STM32F3 has 2 internal ADCs each with 16 channels ADC 1 channel 1 will be configured to take 12 bit samples at a 40 KHz rate. To guarantee that the samples will be taken at precisely the same time every time a timer will be configured to trigger the start of every conversion. The timer peripheral will be used to aid the sample capture and insure that a correct time base is keep. A timer will also be configured to through an interrupt every time the screen needs to be updated. By using hardware timers the timing sequence of the entire project can be easy controlled and stay very accurate without the need for a real time operating system.

In order to increase the data transfer rate and also decrease the amount of CPU load the data that is being captured by the ADC will be moved across the high speed bus by the Direct Memory Access (DMA) controller. This will enable simulations data transfers between the ADC to memory and updates to the LCD screen.

See figure 7 for the following discussion. Digital Potentiometers will be used to control the gain levels of each channel along with pre equalizer gain stage and the volume amplifier which will be directly after the equalizer stage. To interface with the digital potentiometers a serial protocol that resembles SPI will be implemented. Each of the digital potentiometers has 4 independent channels that can be address via the first 2 bits of data that is transferred to them. The next 8 bits of data will be the value for the identified potentiometer. Since there are 8 channels that need to be controlled, two AD8403s will be daisy chained. This will allow 1 serial data line from the STM32F3 to

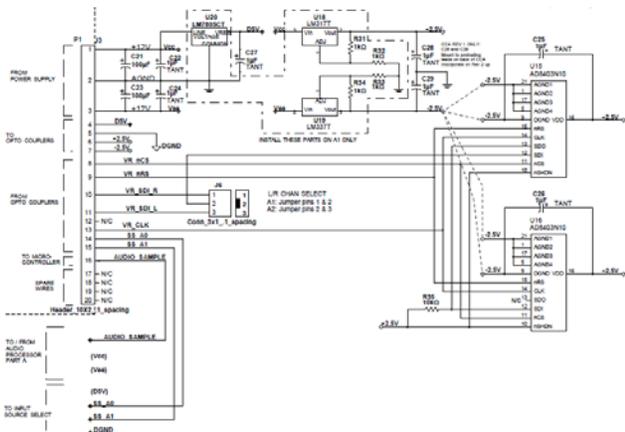


Figure 7: Digital potentiometer schematic

control 8 channels. The only down side to this design is that in order to change just one of the values in any of the resistors all the data for all 8 channels needs to be clocked back in. This can easily be achieved and does not require a specified transfer frequency since the clock and the enable lines are also being supplied by the STM32F3. Since the AD8403 are the place where analog and digital meet there is a high possibility for digital noise to interfere with the analog signal path. In order to minimize this noise SFH6731 optocouplers will be placed on the digital board and provide a galvanic separation of the two different voltages. The SFH6731s also provide another function: Since AD8403 requires control voltages 0 to 5 volts and the analog signals are ± 1.5 volts the AD8403 needs a floating ground at -2.5 volts to enable them to process the analog signal. The SFH6731 enables the TTL digital signal to be converted to a custom voltage range that will be generated on the analog board. Figure 6 is the interconnect diagram showing the cable connection between the various boards.

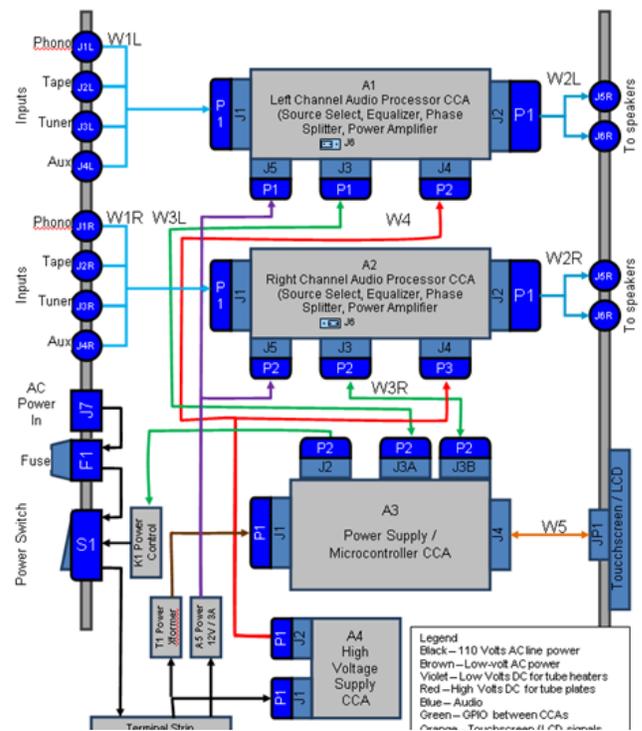


Figure 6: Cable interconnect diagram

C. User Interface

What separates this amplifier from all vacuum tube amplifiers available in the market is its user interface. A Graphical User Interface (GUI) has been put in place as a means to control the system. While the visualizations and equalizer controls are displayed to the user via an LCD

display, the user input is obtained via a touch panel; the LCD controller is the Solomon Systech SSD1963, and the touch panel controller is the Shenzhen XPTEK Technology XPT2046.

The display panel integrated in this system (see figure 9) has both the LCD screen and the touch panel integrated. In addition, the controllers for both the LCD and the touch panel are also integrated in the display panel. This panel provides a forty (40) pin connection via which the microcontroller will be able to communicate with both integrated controllers. The table below shows the important features provided by the display panel.

Table 1: Display Panel Features

Resolution	800 x 480 pixels
Display Size	7-inches diagonal
Colors	The LCD is offers sixteen (16) million colors at 24-bits, but only 16-bits are required to generate the GUI and visualization.
Voltage	3.3V at 330mA
Buffer	1215K bytes frame buffer
MCU communication	Serial

The integrated SSD1963 controller handles the entire LCD screen refresh, and offers the ability to program brightness, contrast and saturation. “The XPT2046 is a 4-wire resistive touch screen controller that incorporates a 12-bit 125 kHz sampling SAR type A/D converter.[In addition, it] operates down to 2.2V supply voltage and supports digital I/O interface voltage from 1.5V to VCC in order to connect low voltage up. [It] can detect the pressed screen location by performing two A/D conversions. In addition to location, the XPT2046 also measures touch screen pressure.”[1]



Figure 9: Display panel

V. BOARD DESIGN

As mentioned above the project will have a total of 3 PC boards, 2 of which will be identical left and right analog processor boards and the third is the microcontroller board. The analog processors (see figure 8) contain the entire audio signal path on them including the push pull tubes and the resistance matching transformer. A 2 x 20 header provides an interface to the microcontroller. The yellow portion at the bottom of the figure 8 is a ground bus providing a very low impedance ground.

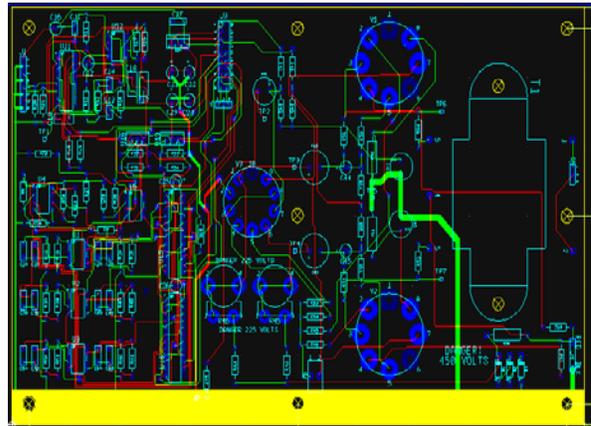


Figure 10: Analog processor board layout

The microcontroller (see figure 10) contains the STM32F303 controller, external crystal oscillator, opto couplers and the low voltage power supplies. There will be a 2 x 20 port connecting the LCD to the digital board, a 2 x 10 JTAG connection to allow for in circuit programming and two 2 x 10 headers to interface with the analog boards.

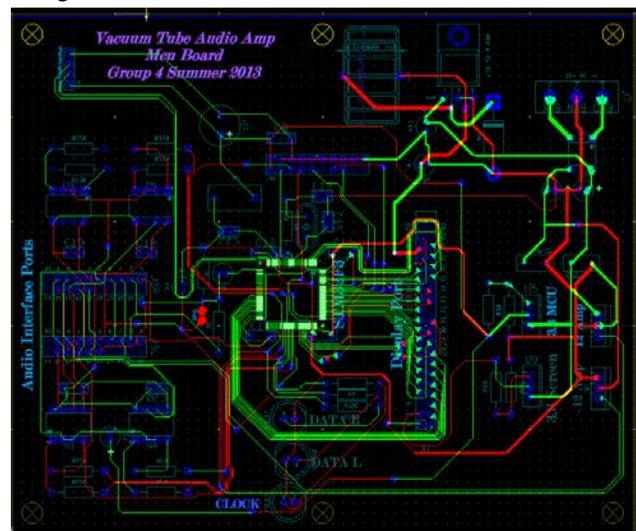


Figure 8: Microcontroller board layout

V. POWER SUPPLY

The finished product is designed to operate using 120V / 60Hz utility power. A three-prong grounded power cord of the type used for desktop computers supplies power to the unit via an IEC320-C14 type chassis-mounted connector J7. The ground lead will terminate at a chassis ground point and have continuity to all exposed metal parts (via a dedicated ground wire if necessary) for user safety. The two 120 volt leads will terminate at a two-position screw terminal barrier strip. The barrier strip will be equipped with a plastic cover plate for safety during test and servicing. Power from J7 shall be fused.

120 volt power is supplied to the following three places:

A. Low Voltage

Transformer T1 supplies 12 VAC to the A3 Power Supply / Microcontroller. The low voltage power supply therein will provide power to all the digital and analog components of the system except the vacuum tubes. While all components have a specific preferred voltage for operation, most have a minimum and maximum which may not be violated. The LCD and touch screen are particularly sensitive to small deviations.

The low voltage power supply consists of a transformer which provides ± 18 volts at 200 mA. The output of the transformer passes through a bridge rectifier. The ± 18 volts rectifier output will be regulated by LM317 and LM337 regulators to generate the various voltages required. The power supply circuit has been divided into several sub-circuits; each of the sub-circuits handles one output voltage.

B. High Voltage

Transformer T2 supplies 360 VAC at 300 mA to the A4 High Voltage Supply CC, which in turn generates the high DC voltage at 300 milliamps required to operate the vacuum tube plate circuits. This supply consists of a series-dropping resistor and PI-type inductor / capacitor filter. The output is not regulated (the zener stack will not be used), and varies from about 480 volts at turn on to about 420 volts once the tubes warm up, but is very low ripple. A parallel resistor provides bleed-down of the capacitor charge after power-off. (See figure 10)

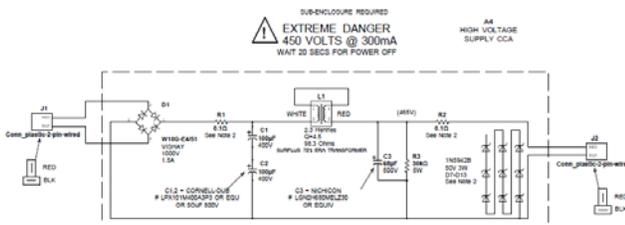


Figure 11: High voltage power supply schematic

C: High Current

Transformer T3 supplies 8VAC at 5 amps to the A5 rectifier / filter CCA and is only used to provide the power to operate the vacuum tube heaters.

VI. SOFTWARE

See figure 12 which shows the design of the software modules and how they will interact with each other. On the left side of the diagram the action is triggered by the user; the Touch Screen module receives the input through the XPT2046 Controller and passes the details to the Digital Equalizer. The right side of the diagram receives its input from the audio being played; it passes to the Digital Equalizer the values. The digital equalizer indicates to the GUI module whether it shall display visualization or the Equalizer screen and the needed values. Graphic User Interface (GUI) module generates the next state of the LCD screen and gives it to Display module which then updates the LCD Screen through the SSD1963 Controller. Each of these modules will be broken up into several sub-modules in order to achieve better development.

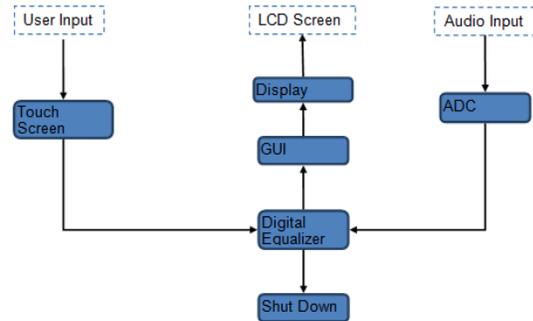


Figure 12: Software Block Diagram

See figure 13 for the state diagram which shows the states of the GUI. Starting by powering ON the display and initializing all the components. It then goes to the equalizer screen; this way the user can immediately select input source and equalizer settings. Whether the equalizer screen times out due to inactivity, or user chooses to go to visualization mode, the software goes into the visualization mode and stays there until a touch event happens, at which point it goes back to the equalizer screen.

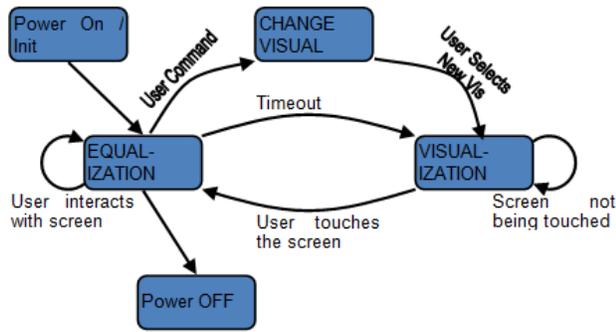


Figure 13: Software State Diagram

The equalizer screen allows the user to select a preset equalizer configuration or custom adjust one of its own. The equalizer adjustments include six (6) frequency bars allowing the user to adjust the amplification of each individual frequency. It also includes balance adjustment allowing the volume ratio between the two channels to be adjusted. In addition, the equalizer screen has the volume bar.

All programming has been written in C and compiled using Atollic Studio. All graphics are generated via algorithms and none are stored in memory in order to save space.

VII. CONCLUSION

This project has been designed to yield a unique, high-quality audio amplifier that will provide years of enjoyment for the serious audiophile who prefers the “tube sound”. The design and development was a very enjoyable and valuable learning experience for the team members, each of whom has learned a lot during its execution.

ACKNOWLEDGEMENT

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BIOGRAPHIES



Jason Lambert

Jason Lambert is graduating UCF with a Bachelor’s of Science in Computer Engineering in August 2013. He will be accepting a position at Texas Instruments as a Digital Application Engineer. His interests are rock climbing and table top board games.



Stephen Nichols

Stephen Nichols is a senior in UCF’s Electrical Engineering program and will graduate with a Bachelor’s of Science in Electrical Engineering degree in August, 2013. He has been working as an engineer at L-3 Communications / Coleman Aerospace since 2000, with 19 years of experience in engineering and 33 years of experience in electronics. His interests include amateur astronomy, antique electronics and home movie making. He is married and has three children.



Rafael Enriquez

Rafael Enriquez received an Associate’s Degree in Arts from Valencia College in 2010 just before entering the University of Central Florida from which he is receiving his Bachelor’s of Science in Computer Engineering in August 2013. He has been acquiring software development experience via self-employment opportunities and a 2-year Co-op at TSC Auto ID Technology. His interests include golf, tennis and motorcycles.