Master Bus Processor

by

Clay Kaiser

Philip Macias

Richard Mannion

Final Report for ECE 445, Senior Design, Spring 2019

TA: Zhen Qin

1 May 2019

Project No. 14

Abstract

This report describes in detail our senior design project, the Master Bus Processor (MBP). This device is an audio processor that is capable of compression, equalization, and saturation. Our design is unique in that it combines analog signal processing with a digital controller. This allows for the user to change the order of the processing blocks for any intended effect. We carefully measured and verified all of our results and are happy to report that all of the requirements were met. We measured specific metrics for each of the three blocks so that we were sure our performance met our expectations. This product was developed for the University of Illinois ECE 445 senior design course with the intention of eventually being sold as a product to the public.

Contents

1. Introduction 1
1.1 Objective 1
1.2 Background 1
2. Design 3
2.1 Power 4
2.1.1 AC/DC Conversion 4
2.1.2 Regulation 4
2.2 Analog Processing 4
2.2.1 Compression 4
2.2.2 Equalization 4
2.2.3 Saturation 5
2.2.4 Input/Output Balancing 5
2.2.5 Switch Control 5
2.3 Digital Control 5
2.3.1 Microcontroller 6
2.4 User Interface 6
2.4.1 Display 6
2.4.2 User Input 6
3. Design Verification 7
3.1 Power 7
3.1.1 AC/DC Conversion 7
3.1.2 Regulation 7
3.2 Analog Processing 8
3.2.1 Compression 8
3.2.2 Equalization 10
3.2.3 Saturation 11
3.2.4 Input/Output Balancing 12
3.2.5 Switch Control 12
3.3 Digital Control 13
3.3.1 Microcontroller 13

3.4 User Interface 13
3.4.1 Display 13
4. Costs 14
4.1 Parts 14
4.2 Labor 14
5. Conclusion 15
5.1 Accomplishments 15
5.2 Uncertainties 15
5.3 Ethical considerations 15
5.4 Future work 16
References 17
Appendix A Requirement and Verification Table 18
Appendix B Detailed Part Costs 21
Appendix C Supporting Materials 24

1. Introduction
A common issue facing aspiring musicians is the very high cost barrier to entry. Integrated and digital circuits have contributed to the increased popularity of home studios; however, these digital processors force the user to miss out on the more traditional acoustic properties of formal analog processing equipment, which historically have been very costly and essentially made to order by manufacturers. This is not ideal for most musicians as they prefer to use analog processing over digital processing due to differences in how the sound is perceived by a listener. Currently, there is no affordable option designed for the home user, and certainly nothing that combines the performance of analog processing with the ease of digital control.

1.1 Objective
The objective of our Master Bus Processor is to create a solution tailored for a home user by offering an affordable product that is simple to use and understand. By combining analog audio processing with digital control, we have created a very flexible design which keeps costs down and maintains high-quality audio performance.

1.2 Background
The current offerings for Master Bus Processors are fairly limited, especially for a home studio user. There are two fundamental varieties, digital and analog. Our device will offer is a hybrid of the two. All audio processing circuits are strictly analog; however, all controls are digital. The analog circuitry is so important because many musicians and audiophiles claim that analog audio sounds “much deeper and fuller”, and as a result is much more desirable [1]. Our Master Bus Processor makes use of digital control in order to provide ease of use to the user. Many of the products on the market have many different knobs and controls that are confusing and cumbersome to use during a live mix. By offering a Liquid Crystal screen as well as minimal knobs and buttons to control the device, we have made it much easier to use for a more casual user.

Specifically, what makes our product unique from others that are currently available is the use of digital controls on an analog circuit and the ability to rearrange the order of processing blocks. We also focused on simplifying circuits by use of SMD/SMT components, and lack of discrete channel control. When comparing to the Rupert Neve Portico II Master Buss Processor (MBP), there are many fundamental differences [2]. The Portico II MBP is entirely analog and consequently does not allow the user to change the order of processing blocks. Our design uses digital control to allow the user to select any order of compression, equalization, and saturation through a very simple button and screen interface. The Portico II MBP also has more complex audio processing blocks, allowing for features like discrete control of each channel on the bus. This leads to a cost of $4,000 which is cost prohibitive for most home studio users.

Our solution consists of both digital and analog circuits to allow for the flexibility of digital control with the audio quality of analog processing. We use a microcontroller to control relays in the analog circuit that can change the orientation and exposure of different analog component blocks. This allows the user to use a series of buttons and an LCD display to control circuit parameters such as the order of each analog block and the particular mode that each block performs its desired function. All audio processing is performed using analog circuits and the user is able to use knobs to adjust specific analog block parameters. An overview can be found in Figure 1.

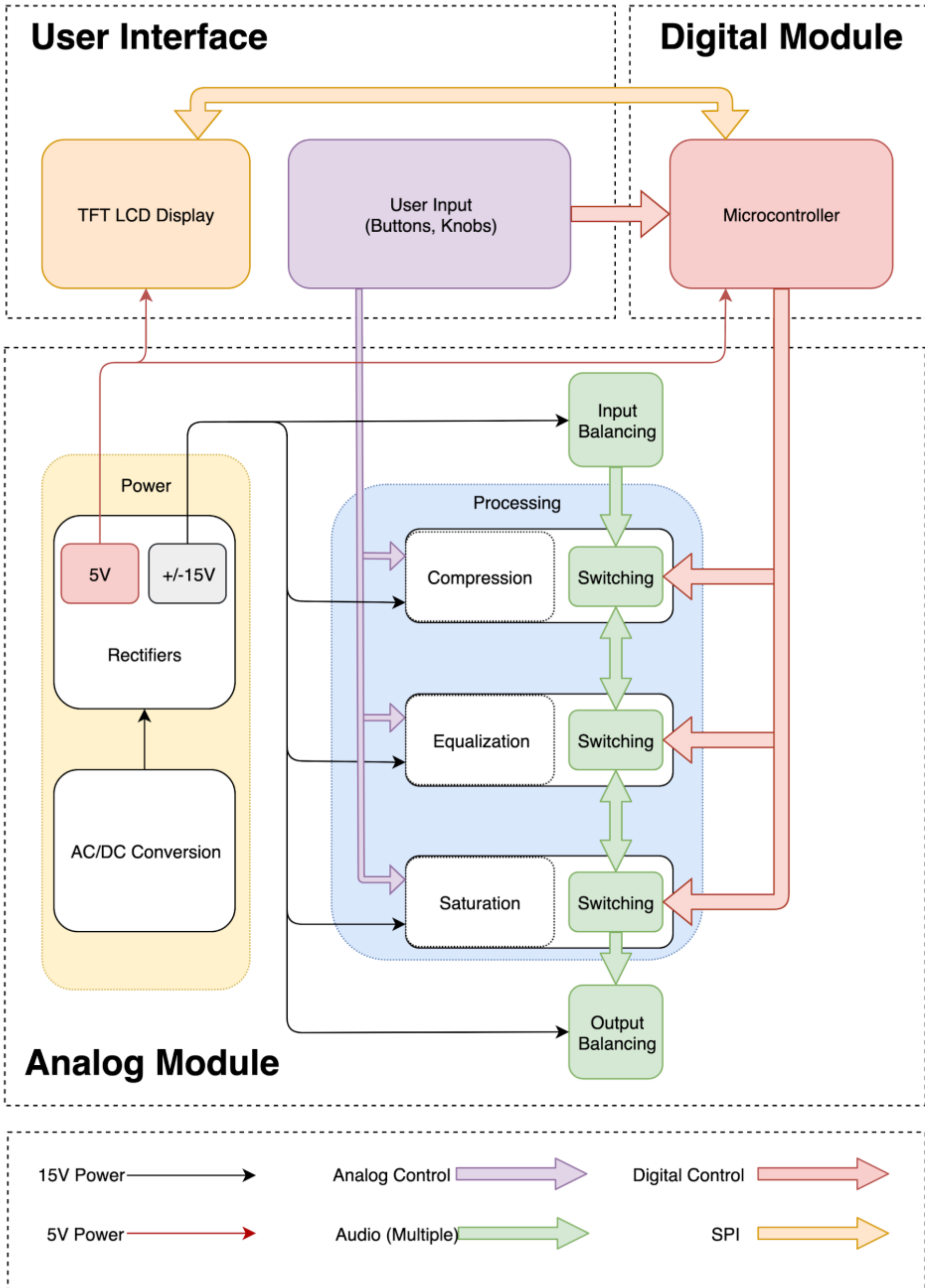

Figure 1 Block Diagram

2. Design

The Master Bus Processor (MBP) is designed to fit inside an industry-standard 19” rackmount enclosure as found in Figure 2. The front control panel occupies two rack-units (2U).

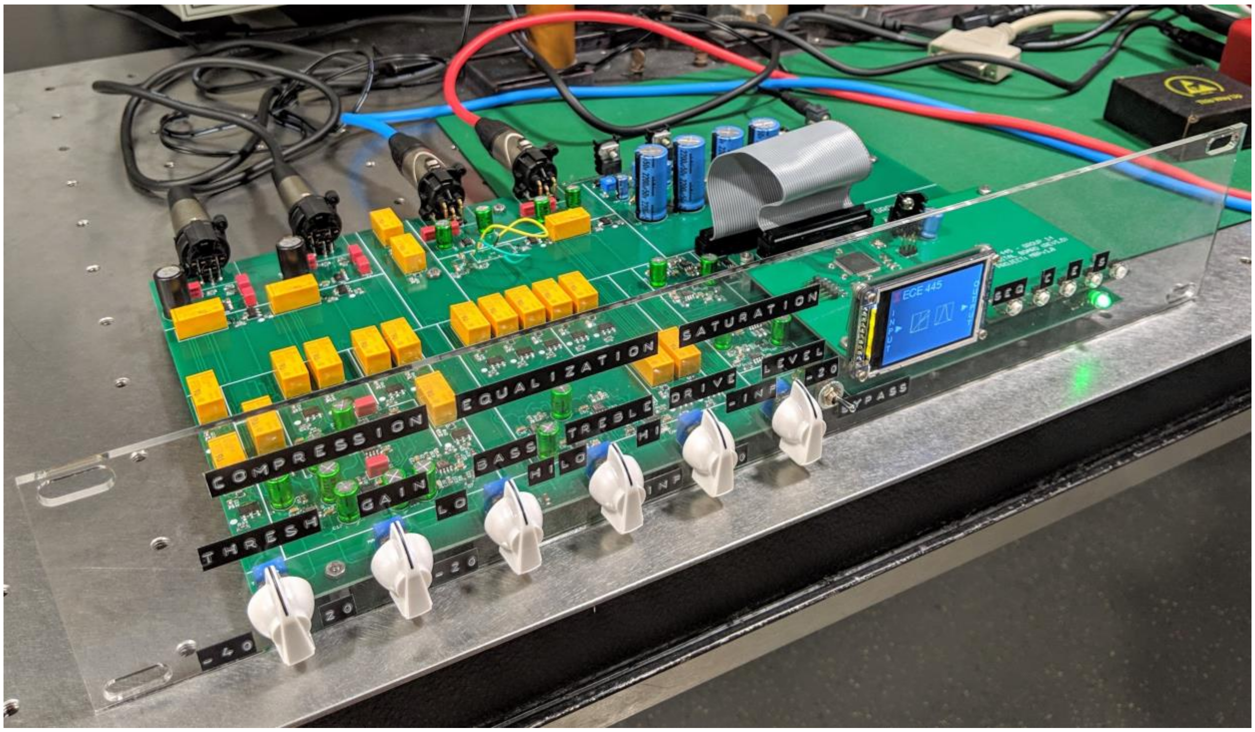

Figure 2   Device During Design Testing

The User Interface, consisting of the LCD screen, selection buttons, and processor control knobs, is mounted on the front panel of the enclosure. Inside the enclosure, the system is divided into two separate printed-circuit-boards (PCBs) in order to reduce noise from interference. The power systems, analog processing blocks, I/O connections, and control knobs are mounted on a large, base PCB. The digital controller is housed on a separated PCB which is mounted above the analog PCB. The two PCBs exchange power and control signals through a central ribbon cable connection (pinout labeled in Figure 11).

2.1 Power

The Power module includes all phases of conversion and rectification from 120 V, 60 Hz AC wall power to the required +15 V, -15 V rails required for analog processing, 5 V rail required for digital control. The sub-modules are located on both the analog PCB (Figure 25) and digital PCB (Figure 23).

2.1.1 AC/DC Conversion

The External "Line-Lump" Transformer converts US AC wall mains power (120 V 60 Hz) to levels which are tolerable by the Voltage Regulators down-line. The AC input voltage provided by the External Transformer is converted to DC by diode Rectifiers and smoothing capacitors in preparation to be received by non-switching Voltage Regulators down-line. Schematics for this block can be found in Figures 9, 26, and 27.

2.1.2 Regulation

The voltage regulators accept the smoothed positive and negative DC buses from the rectifiers and output stable voltage buses to power the analog and digital systems.

2.2 Analog Processing

The analog processing module includes all required audio processing blocks. It also includes the input and output balancing as well as the switch control. The schematics for the entire analog circuit can be found in Figures 8 and 25.

2.2.1 Compression

The Compressor is an automatic-gain-controller that is specialized for use with audio signals. When the audio signal at the input of the compressor exceeds a fixed threshold level, the Compressor reduces its gain by a proportional amount until the signal has fallen below the threshold again. The output of the Compressor is then normalized so that the average amplitude of the audio signal has been increased. By this process, the Compressor is able to improve the perceived loudness of the audio signal. In order to reduce distortion and act as linearly as possible, the Compressor operates on a timescale that spans at least multiple low-frequency wave cycles. The Compressor can be connected in various places in the analog signal chain, where it will interact differently with the other analog processing blocks. The Compressor circuit is based on the THAT Corp 4305 Analog Engine standard application circuit [3] with adjustments to accommodate 2-channel operation. Schematics for this block can be found in Figures 15, 16, and 29.

2.2.2 Equalization

The Equalizer is a series of high- and low-frequency focused filters that can be applied to the audio signal. The filters in the Equalizer block allow the user to boost or cut certain bands of the audio spectrum in order to shape the overall tonal response of the Equalizer block. The Equalizer utilizes an operational amplifier (op-amp) gain stage with filters connected to the inverting and non-inverting inputs in order to achieve active equalization. The Equalizer can be connected in various places in the analog signal chain, where it will interact differently with the other analog processing blocks. The Equalizer circuit is similar to a standard "graphic equalizer" layout, as described by Rod Elliott [4]. Each band of the Equalizer contains a resonant RLC circuit which allows the frequency bands to be boosted or attenuated by connecting the resonant circuits to the feedback network of an op-amp. Since it is impractical to include large, expensive inductors in this design, the resonant circuits contain sub-circuits called 'gyrators' which create simulated inductance values. Circuit level analysis of the simulated inductance from gyrators is described by Berndt D. F. Berndt and S. C. Dutta Roy [5]. Schematics for this block can be found in Figures 17, 18, and 30.

2.2.3 Saturation

The Saturator block allows the user to enhance the harmonic content of the audio signal by mixing in small amounts of harmonic distortion. The Saturator uses an op-amp gain stage with a diode-incorporated feedback network in order to provide non-linear gain. The output from this gain stage is then added back to the original audio signal in small amounts by the user through a "blend" control circuit and summing amplifier stage. The Saturator can be connected in various places in the analog signal chain, where it will interact differently with the other analog processing blocks. The Saturator circuit is based on a standard soft-clipping "fuzz" circuit, as described by Rikupetteri Salminen [6]. The Saturator incorporates a diode into the feedback network of an op-amp in order to produce highly non-linear gain. The output from this stage is then summed back with the original, unaffected signal at a very low level in order to give a subtle effect. Schematics for this block can be found in Figures 19, 20, and 31.

2.2.4 Input/Output Balancing

The I/O section consists of the hardware connectors and electronic signal balancing circuits which allow the Master Bus Processor to be connected to other professional audio equipment. The I/O connections use differential amplifiers to receive and drive signals to and from other equipment and a user-selectable hardware bypass was incorporated to directly connect the inputs and outputs of the MBP when necessary. The Inputs and Outputs utilize the THAT Corp 1200- and 1646-Line Receiver/Drivers and the recommended implementation circuits [7] [8], respectively. Schematics for this block can be found in Figures 13, 14, 21, 22, and 28.

2.2.5 Switch Control

The switch control as seen in Figure 14, takes Boolean inputs from the microcontroller to orient and expose the different analog blocks. It consists of a series of power transistors and double contact relays. This allows the microcontroller to change the layout of the analog circuits based on what is inputted by the user. A fail-safe route is provided in the case of a digital circuit failure (Figure 10). A test circuit like that of Figure 6 was constructed to verify proper operation before the circuit was constructed on the PCB.

2.3 Digital Control

The digital control module includes all modules required to instantiate a digital control system for the switching control module. This includes all supporting components for proper functionality of the microcontroller sub-module. The schematic for the entire digital circuit can be found in Figures 7, 23, and 24.

2.3.1 Microcontroller

The microcontroller sends Boolean output signals to the switch control to alter the layout of the analog signal blocks. It also takes input from the user using a series of hardware buttons on the front of the 2U case that allow the user to intuitively interface with the microcontroller. Feedback of these inputs is displayed on the LCD display. A flowchart for the microcontroller is included in Figure 33.

2.4 User Interface

The user interface module includes all required pieces to interface with the user. This includes the LCD display and user inputs, such as the buttons and knobs.

2.4.1 Display

A display allows the user to see the current settings of the digital controls including the order of the analog blocks, and their current mode. The display communicates with the microcontroller using a SPI connection.

2.4.2 User Input

A series of buttons allow the user to interface with the microcontroller. There are buttons labeled: Sequence, Compression, Equalization, Saturation, and Enter. These buttons allow the user to interact with the microcontroller to set circuit parameters.

A series of knobs (potentiometers) are separated based on their corresponding analog processor block. They allow the user to make circuit alterations in real time (Figure 12).

3. Design Verification

The requirement and verification table can be found in Table 4.

3.1 Power

3.1.1 AC/DC Conversion

Requirement: We required that our transformer should step down AC wall mains voltage 120 V to 18-30 V in order to provide enough voltage to keep our voltage regulators turned on but not so much that they would overheat and fail.

Verification: To verify this requirement, we loaded our power supply with the maximum realistic load it would see--14 simultaneous relays--and measured the DC voltage at the smoothing capacitors with a digital multimeter.

Result: We measured the DC voltage at this point to be 26 V. This value is within our specifications and indicates that this block was successful.

3.1.2 Regulation

Requirement: We required that our three voltage regulators should provide 1.8 V to 5.5 V for digital control, -15.8 V to -14.0 V for negative audio supply and 14.0 V to 15.8 V for positive audio supply. These voltages reflect the values outside of which our digital and analog components may turn off or be damaged, respectively.

Verification: To verify this requirement, we loaded our power supply with the maximum realistic load it would see--14 simultaneous relays--and measured the DC voltage at the output of each voltage regulator with a digital multimeter.

Result: We measured the DC voltages at these points to be 5.07 V, -15.01 V, 14.87 V, respectively. These values are within our specifications and indicate that this block was successful. The results are provided in Table 1 below.

Table 1 Regulation Voltages

Desired Voltage	5 V	15 V	-15 V
Measured Voltage	5.07 V	14.87 V	-15.01 V

3.2 Analog Processing

3.2.1 Compression

Requirement 1: We required that our Compressor section be able to provide at least 20 dB of gain reduction so that this block would have the capability to effectively reduce the amplitude of any large signal transients which could be reasonably expected.

Verification 1: To verify this requirement, we connected the audio output of a computer to the balanced input of Channel 1 of the MBP using a digital-to-analog converter. Using the computer as a signal source, we sent a 1 kHz sine wave at maximum volume to Channel 1 of the MBP and removed all blocks except for the Compressor from the MBP signal chain. We found the gain reduction of the signal by measuring the difference in gain at the output of Channel 1 when the Compressor was engaged and not engaged. We used the LeCroy oscilloscope/spectrum analyzer to measure this signal at the positive pin of the balanced output connector of Channel 1. In order to assure that this measurement would be reasonably representative of both the positive and negative pins of the output connectors for Channel 1 and Channel 2, we measured the relative gains of the MBP for each pin on both channels.

Result 1: We measured the signal to be reduced by 20.3 dB with the Compressor engaged. Additionally, we found significant difference in gain between any of the individual pins of the balanced outputs of Channel 1 and Channel 2. These results indicate that the Compressor block was successful and that measurements of the positive pin of the balanced output connector of Channel 1 are reasonably representative of the performance of both channels of the MBP.

Requirement 2: We required that our Compressor be able to engage gain reduction within at least 100 ms and disengage gain reduction in at least 1 sin order to be sufficiently fast to suppress large signal transients and then quickly return to normal gain.

Verification 2: To verify this requirement, we connected the audio output of a computer to the balanced input of Channel 1 of the MBP using a digital-to-analog converter. Using the computer as a signal source, we sent a 1 kHz sine wave at low volume to Channel 1 of the MBP and removed all blocks except for the Compressor from the MBP signal chain. Additionally, we connected a signal generator to the positive input pin of the balanced input connector of Channel 2. We used this signal generator to provide the trigger signal to engage the Compressor block since both channels of the Compressor share the same detector circuit. By turning the trigger signal on and off, we were able to measure the how long the Compressor took to react to the trigger signal and affect the gain of the 1 kHz signal using an oscilloscope.

Result 2: We measured the times taken by the Compressor to engage and disengage gain reduction to be 45.0 ms and 82.8 ms, respectively. Oscilloscope readouts of the input and trigger signals are visible in Figure 3 and Figure 4. These values are within our specifications and indicate that this block was successful.

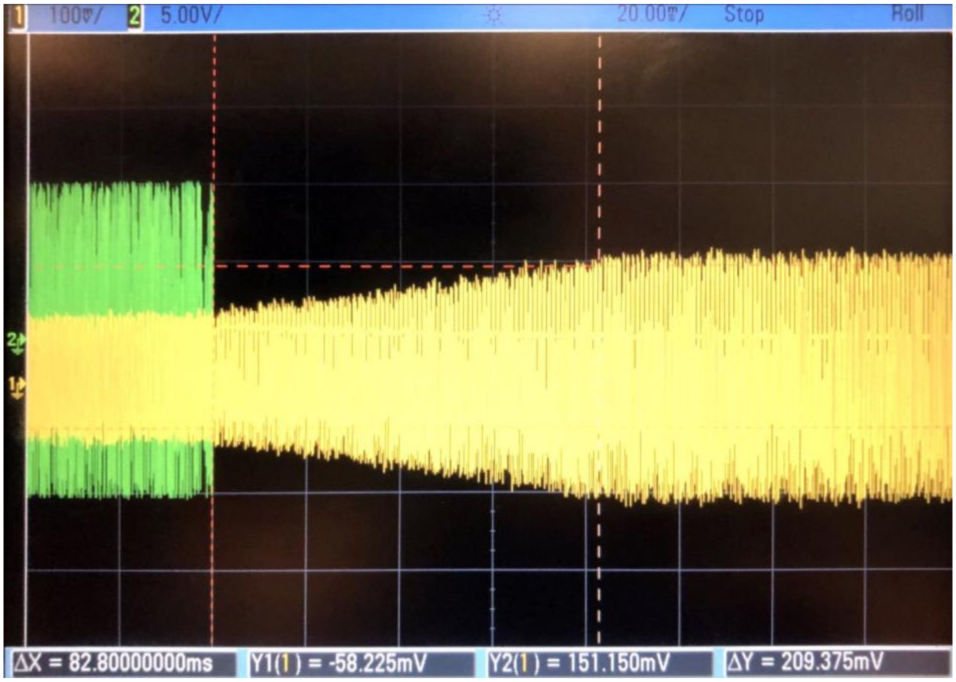

Figure 3 Compression Release

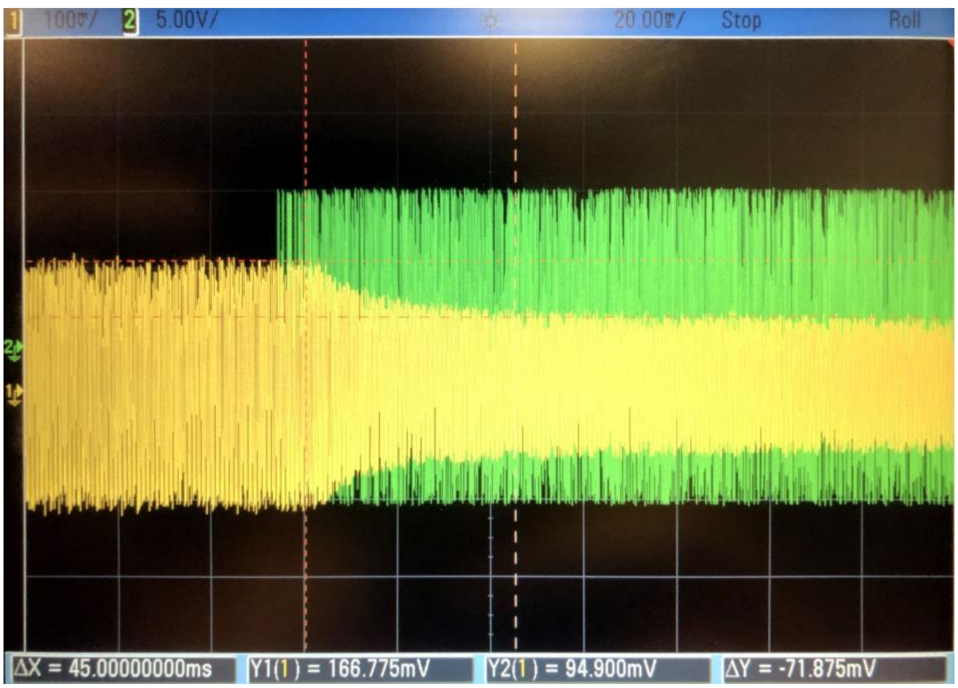

Figure 4 Compression Attack

3.2.2 Equalization

Requirement: We required that the center frequencies of the 80 Hz low and 10.3 kHz high bands of our Equalizer be within 70-90 Hz and 9-11 kHz, respectively, in order for each band to most significantly affect the frequency response of the MBP in these regions.

Verification: To verify this requirement, we connected the audio output of a computer to the balanced input of Channel 1 of the MBP using a digital-to-analog converter. Using the computer as a signal source, we sent sine waves in a range of frequencies from 20 Hz to 20 kHz to Channel 1 of the MBP and removed all blocks except for the Equalizer from the MBP signal chain. We used the LeCroy oscilloscope/spectrum analyzer to measure the gain of each sine wave at the positive pin of the balanced output connector of Channel 1.

Result: We measured the highest gain of the low frequency band at full boost and the lowest gain of the low frequency band at full cut to be at 80 Hz. We measured the highest gain of the high frequency band at full boost and the lowest gain of the high frequency band at full cut to be at 10.3 kHz. Additionally, we compiled all of the gain readings from both bands and the gain readings with Equalizer set completely flat in order to form the frequency response of the MBP, which is visible in Figure 5. These values are within our specifications and indicate that this block was successful.

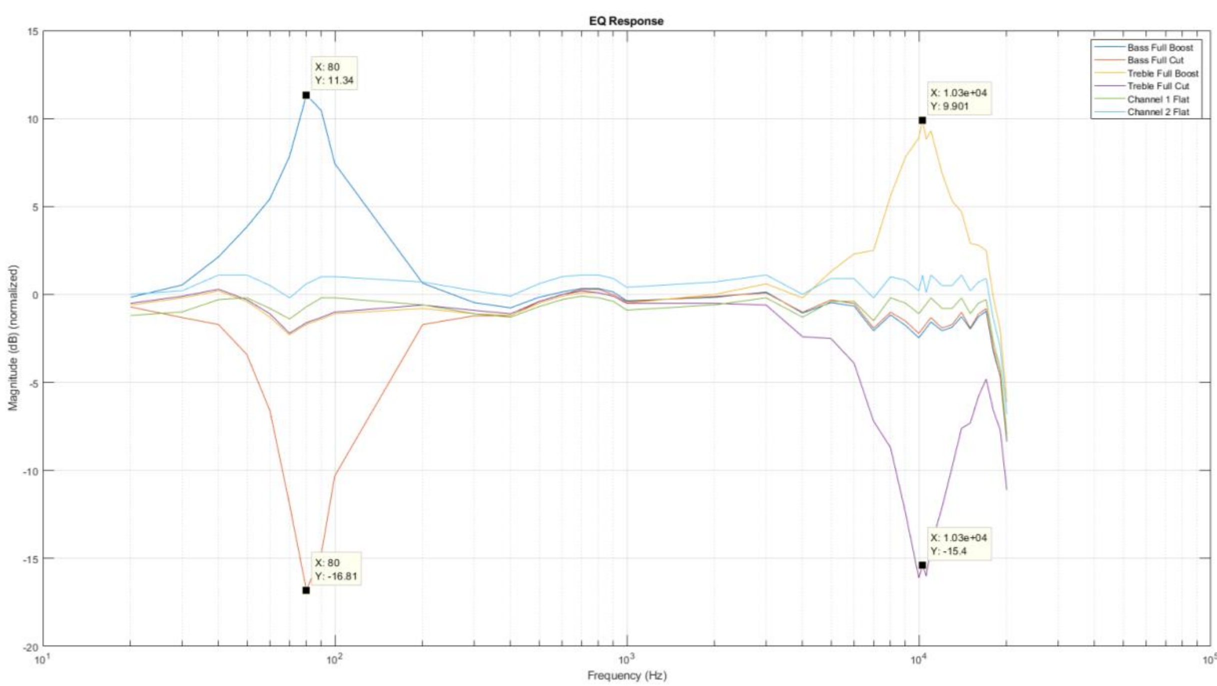

Figure 5 Equalization Response

3.2.3 Saturation

Requirement: We required that harmonic contributions of the Saturator block to the total signal content should be greater than 0 % in order to be effective but less than 10% in order to keep the effect subtle.

Verification: To verify this requirement, we connected the audio output of a computer to the balanced input of Channel 1 of the MBP using a digital-to-analog converter. Using the computer as a signal source, we sent a 3 kHz sine wave to Channel 1 of the MBP and removed all blocks except for the Saturator from the MBP signal chain. With the Saturator's non-linear amplifier set to maximum gain and the harmonics level set to full volume, we used the LeCroy oscilloscope/spectrum analyzer to measure the gain of the fundamental 3 kHz signal and each harmonic present at the positive pin of the balanced output connector of Channel 1.

Result: With full drive/level: THD = 0.1186 % We measured the relative gains of the fundamental, 2nd harmonic, 3rd harmonic, 4th harmonic, and 5th harmonic to be 0 dBm. -39.3 dBm, -30.6 dBm, -44.3 dBm, and -37.9 dbm, respectively. The gain of the 6th harmonic and greater were not discernable above the noise floor of the MBP. Based on the harmonic contributions which are visible in Table 2, we calculated the total harmonic distortion provided by the Saturator to be 0.1186 % by using the following equation:

$$THD(\%) = \frac{total\ power\ of\ all\ harmonics\ above\ fundamental}{total\ output\ power\ of\ signal} * 100 \qquad \text{Eqn 1.}$$

This value is within our specifications and indicates that this block was successful.

Table 2 Measured Frequency and Gain for Harmonics

Harmonic	1st	2nd	3rd	4th	5th	6th
Frequency	3 kHz	6 kHz	9 kHz	12 kHz	15 kHz	18 kHz
Gain	0 dBm	-39.3 dBm	-30.6 dBm	-44.3 dBm	-37.9 dBm	N/A

3.2.4 Input/Output Balancing

Requirement: We required that the differential amplifiers responsible for conversion to and from differential signal format and single ended signal format at the Inputs and Outputs of the MBP contribute at most 0.01 % total harmonic distortion in order to ensure that they would accurately perform their conversion responsibilities.

Verification: To verify this requirement, we connected the audio output of a computer to the balanced input of Channel 1 of the MBP using a digital-to-analog converter. Using the computer as a signal source, we sent a 3 kHz sine wave to Channel 1 of the MBP and removed all blocks except for the Saturator from the MBP signal chain. We disabled all harmonic contributions from the Saturator in order to ensure the signal measured would be reasonably representative of the Input and Output circuits only. We used the LeCroy oscilloscope/spectrum analyzer to measure the gain of any harmonics present at the positive pin of the balanced output connector of Channel 1.

Result: We could not measure any harmonics discernable above the noise floor of the MBP, indicating that the total harmonic distortion contributions from the Input and Output circuits is less than 0.01 %. This value is within our specifications and indicates that this block was successful.

3.2.5 Switch Control

Requirement 1: We required that for the switch control, the current on each line needs to be less than 40 mA, and less than 200 mA across all 14 relays.

Verification 1: In order to verify this requirement, we built a test circuit of a single relay as it would appear on our final product. This circuit, which consisted of a relay, a darlington transistor, 2 resistors, and a diode, can be seen in Figure 6. This was a simple circuit that we used to test the relay in both the on and off states. In order to verify the current across the relay, we biased it in the active state so that it had current going through it.

Result 1: We measured this current with a Digital Multimeter and found that it was 0.371 mA, which is well below our max requirement of 40 mA. Across 14 relays, the max number of relays that could be on at one time, this would give a current of 5.194 mA which is again much lower than our maximum requirement of 200 mA.

Requirement 2: We required that when switching, the relays must not produce any significant audio artifacts or dangerous discharge voltages. This is necessary ensure the user will not experience any excessive signal volumes while using the MBP in normal operation.

Verification 2: To verify this requirement, we switched throughout the various signal chain combinations offered by the MBP and used the LeCroy oscilloscope/spectrum analyzer to measure the gain of any artifacts present at the positive pin of the balanced output connector of Channel 1.

Result 2: No consistent or significant discharge artifacts were measured, indicating that this block was successful.

3.3 Digital Control

3.3.1 Microcontroller

Requirement: For the microcontroller we had several requirements that we had to meet for a successful digital controller. These requirements are that the microcontroller has 20 output pins, 5 input pins, SPI communication, and non-volatile memory.

Verification: All of these requirements were easily verified by simply looking at the datasheet for our microcontroller and confirming that each requirement was met.

Result: We chose to use the ATmega-1280 as our microcontroller because it met all of these requirements and was simple to use with the Arduino software. The SPI communication let us easily control the LCD display.

3.4 User Interface

3.4.1 Display

Requirement: For the display, our main requirement was that it fits into a standard 1U space, which is at most 1.75 inches tall.

Verification: We were able to verify this by measuring the height of our display with a ruler and we determined that it was 1.6 inches tall, which fit our requirement.

Result: We decided on using an Adafruit display because they provide a robust graphics library that made it very simple for us to draw what we needed on the screen.

4. Costs

4.1 Parts

A detailed breakdown of all parts and their respective quantities and costs can be found in Table 5 and a summarized part cost breakdown can be found below in Table 3.

Table 3 Summarized Part Costs

Item	Price
Digital Components	\$66.20
Analog Components	\$317.71
PCBs	\$207
Total	\$590.91

Grand Total = \$28,800 + \$590.91 = \$29390.91 Eqn 2.

4.2 Labor

We chose 40\$/hour as an average hourly salary for an ECE graduate from UIUC. We estimated that we will work 15 hours/week over the course of the semester which is 16 weeks.

(40\$/hour) x (15 hours/week * 16 weeks) * 3 people = \$28,800 Eqn 3.

5. Conclusion

5.1 Accomplishments

Overall, our project was a great success. We met or exceeded every requirement that was set in our initial design document as described in previous sections of this report. Our final product has three analog audio processing circuits that are capable of compression, equalization, and saturation on two separate channels. The digital control allows the user to change the order of the blocks as well as take out certain blocks from the chain. The LCD screen has a very simple and clean user interface that displays to the user the currently signal chain that they have chosen. When the device boots up it is able to recall from memory what the last signal chain was and set the processor to that setting. We are very happy with the results and are proud of what we have accomplished over this semester.

5.2 Uncertainties

During the development of our MBP we ended up running into one issue that caused a failure on channel two. After our mock demo, when our processor was completely finished, we noticed that there was a popping sound coming from the audio output of the processor. We knew that something was wrong, and we were quickly able to deduce that the issue was only coming from channel two of the processor. Once we figured this out, we started to probe the pins on our active components which were the THAT IC chips that were the output drivers as well as the op-amp chips. We found that one of the op-amps had broken down and was not operating as intended. This broken chip was then allowing a very high voltage, almost 15 V, over the next op-amp in the circuit which would then cause that one to break down. We found that four different op-amps had failed and quickly replaced those chips on the board. Once this was done, we verified that all the chips were working as intended by probing them and reading the voltages on a Digital Multimeter. Finally, we played audio through channel two and were able to verify that it was once again operating as intended and no other damage had been caused.

5.3 Ethical considerations

Because our device will use wall power, it is important that all safety guidelines are adhered to in respect to the design of the power block of our device. Improper circuit design can damage other circuits in our device as well as other devices connected to the input and output connections. Most importantly, improper design can lead to injury of the user, due to electrocution. In the scope of this class, we plan to mitigate these concerns by following the direction of course supervisors for power supply design. In the case of an ultimate go-to-market strategy, UL certification will be obtained to inform potential clients that our product is safe to purchase and use.

A potential breach of ethics in our project stems from the use of open source hardware/software. In our project we will be using an ATmega microcontroller as well as the Arduino bootloader. Open source projects allow us greater flexibility, affordability, and reliability by using work that is not our own. Although this work is legal to use in the scope of our project, it is important that we follow proper ethics guidelines of the open source community. Specifically, it is important to not claim anyone else's work as your own work as this would violate IEEE Code of Ethics #7: "...to credit properly the contributions of others" [9]. To avoid this breach of ethics we will explicitly credit any contributions to our project from

ATmega hardware and Arduino software and make sure that protected intellectual property is not copied without consent.

5.4 Future work

One thing that we want to implement in a future iteration of our project is the ability to monitor certain parameters in each processing block. We would implement this feature in our digital control by taking signals from the processing blocks and performing digital signal processing (DSP) in order to provide feedback to the user. Such metrics could include the amount of gain/cut in dB from the Compression block, amount of bass/treble boost and cut from the Equalization block, and the total harmonic distortion from the Saturation block. These metrics would be displayed to the user via the LCD screen and could be brought up using the buttons.

Another potential feature that we would like to implement in the future would be the ability to recall the knobs to their last setting when the device was powered down. Our current design has the ability to recall the order of the processing blocks that the user had set before by storing this information in the memory. We could similarly have the positions of the knobs be stored into memory by using an encoder and then recalled when the device is turned on again. The knobs could return to their positions with the use of motors that the knobs would be attached to.

For our final product, we would like to have the entire processor in a standard 2U rackmount chassis. Our current design features an acrylic front plate that was made as a proof of concept as well as to make the prototype more presentable. We want to expand on this and make the entire chassis and change from acrylic to a solid black material so that the inside is not visible. The 2U rackmount size is standard for the industry and will fit into a typical home studio setup.

One final area that we could potentially improve on is to upgrade our current processing blocks. We want to improve matching between the two channels so that they both give identical performance metrics. We also want to add more tunability to each processing block so as to ultimately increase the performance metrics of the blocks. This gives the user more control and allows the metrics to have a much stricter tolerance in order to improve performance.

References

[1] scientificamerican.com, “Which Sounds Better, Analog or Digital Music?”, 2017. [Online]. Available: https://blogs.scientificamerican.com/observations/which-sounds-better-analog-or-digital-music/ [Accessed 18-Feb-2019].

[2] ruperneve.com, “Master Buss Processor”, 2019. [Online]. Available: https://rupertneve.com/products/master-buss-processor/#overview [Accessed 18-Feb-2019].

[3] THAT Corp, “THAT 4305 Datasheet”, 2015 [Online]. Available: http://www.thatcorp.com/datashts/THAT_4305_Datasheet.pdf [Accessed 16-Feb-2018]

[4] Rod Elliott, “Equalisers, The Various Types And How They Work”, 2015 [Online]. Available: http://sound.whsites.net/articles/eq.htm

[5] Berndt, D. F.; Dutta Roy, S. C. (1969), "Inductor simulation with a single unity gain amplifier", IEEE Journal of Solid State Circuits, SC-4: 161–162

[6] Rikupetteri Salminen “Design Your Own Distortion”, 2000 [Online]. Available: http://www.generalguitargadgets.com/how-to-build-it/technical-help/articles/design-distortion/

[7] THAT Corp, “THAT 1200 Datasheet”, 2017 [Online]. Available: http://www.thatcorp.com/datashts/THAT_1200-Series_Datasheet.pdf

[8] THAT Corp, “THAT 1606/1646 Datasheet”, 2015 [Online]. Available: http://www.thatcorp.com/datashts/THAT_1606-1646_Datasheet.pdf

[9] ieee.org, "IEEE Code of Ethics", 2019. [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 7- Feb- 2019].

Appendix A Requirement and Verification Table

Table 4 System Requirements and Verifications

Requirement	Verification	Result
POWER		
Must convert 120 V AC to **18-30** V DC	Input 120 V AC and measure open-circuit voltage confirming above 18 V DC.	26 V (satisfied)
Must provide **1.8 - 5.5** V for the digital control system and safely provide 500 mA to 2 A current	Measure open-circuit voltage and ensure that it is below 5.5 V. Connect a resistive load until voltage reaches 4.9 V and ensure that at least 500 mA current available using an ammeter.	5.07 V (satisfied)
Must provide 14.0 - 15.8 V for the analog control system and safely provide 500 mA to 2 A current	Measure open-circuit voltage and ensure that it is below 15.8 V. Connect a resistive load until voltage reaches 14.0 V and ensure that at least 500 mA using an ammeter.	14.87 V (satisfied)
COMPRESSION		
Must be able to provide at least 20 dB gain reduction without overloading its input	Input a 1 kHz sine wave. Record the input and output waveforms and verify at least 20 dB gain reduction at maximum setting in MATLAB. Verify stability of output using oscilloscope.	20.3 dB (satisfied)
Must be able to engage full gain reduction within at least 100 ms	Input a 1 kHz sine wave. Record the input and output and verify response time in MATLAB.	45.0 ms (satisfied)
Must be able fully disengage gain reduction in 1 s	Input a 1 kHz sine wave. Record the input and output and verify response time in MATLAB.	82.8 ms (satisfied)
EQUALIZATION		
One available band must be in the region of 70-90 Hz	Sweep input signal frequency from 20 Hz - 20 kHz, measure relative gain at 80 Hz	80 Hz (satisfied)
One available band must be in the region of 9-11 kHz	Sweep input signal frequency from 20 Hz - 20 kHz, measure relative gain at 10.3 kHz	10.3 kHz (satisfied)

Requirement	Verification	Result
SATURATION		
Must be able to contribute 0-10% total harmonic distortion to the audio signal	Input a 3 kHz sine wave. Set to maximum setting and measure the input and output. Verify total harmonic distortion is within range using MATLAB, set to minimum setting and verify also within range	0.1186 % (satisfied)
INPUT/OUTPUT BALANCING		
Must not overload at less than +/-14 V swing	Input a 1KHz sine wave with magnitude +14 V. Measure the input and output an oscilloscope and confirm stability using matlab	N/A could not test safely
SWITCH CONTROL		
Must not allow discharges onto the audio path when switching	The test circuit from Figure 6 will be built and connected to oscilloscope. Biased in the off position, output signals will be tested for leakage	YES
Must input less than 40 mA per control line, 200 mA total, from I/O pins on microcontroller	The test circuit from Figure 6 will be built and input control current will be measured at both logic high and low	0.317 mA or 5.194 mA total (satisfied)
MICROCONTROLLER		
Must have at least 20 output pins for connection to switch control	Verify that pin-layout includes at least 20 output pins on chip schematic	YES
Must have at least five input pins for connection from buttons	Verify that pin-layout includes at least five input pins on chip schematic	YES
Must support SPI and have required pins for this standard	Verify that SPI is a supported protocol in peripheral features table	YES

Requirement	Verification	Result
Must have non-volatile memory for program data (>10 kB)	Verify that non-volatile memory is included in product features table and that it includes more than 10kB	YES
Must have at least 5 analog input pins for reading voltage ranges	Verify that pin-layout includes at least five analog input pins on chip schematic	YES
LCD DISPLAY		
Must fit in a 1U space (1.75” tall)	Measure height of display using ruler, make sure less than 1.75”	1.6” (satisfied)
USER INTERFACE		
Must travel at least 2 mm to allow for easy feedback to user	Press button and measure travel using a ruler	YES
Must maintain desired position	Turn knob and release. Measure voltage differential on leads using a voltmeter for consistency	YES

Appendix B Detailed Part Costs

Table 5 Complete Part Costs

Part	Manufacturer	Quantity	Price	Subtotal
COM-08720	SparkFun	2	$0.95	$1.90
CSTNE16M0VH3L000R0	Murata	2	$0.43	$0.86
C0402C104K4RAC7411	KEMET	10	$0.06	$0.62
ERJ-2GEJ106X	Panasonic	6	$0.13	$0.78
1480	Adafruit	1	$24.95	$24.95
PRT-13054	SparkFun	3	$0.95	$2.85
CAB-13028	SparkFun	1	$2.50	$2.50
FSMRA6JH	TE	6	$0.27	$1.62
DEV-09716	SparkFun	1	$14.95	$14.95
PRT-09015	SparkFun	1	$0.95	$0.95
PRT-12807	SparkFun	1	$0.50	$0.50
M20-7911042R	Harwin	1	$1.40	$1.40
1-826629-0	TE	1	$1.38	$1.38
1N4148WS	ON Semi	8	$0.17	$1.36
1N914BWS	ON Semi	1	$0.15	$0.15
3362P-1-101LF	Bourns	2	$1.02	$2.04
AC1206FR-101K43L	Yageo	1	$0.11	$0.11
AC1206FR-102K7L	Yageo	2	$0.11	$0.22
AC1206FR-104K7L	Yageo	2	$0.11	$0.22
APC1206B250RN	ARCOL	1	$0.18	$0.18
BSP52T1G	ON Semi	21	$0.31	$6.51
C1206C220F4HACAUTO	KEMET	3	$0.44	$1.32
CPF210R000FHE14	Vishay	2	$0.98	$1.96
CRCW1206100KFKEAC	Vishay	6	$0.10	$0.60
CRCW1206100RFKEAC	Vishay	6	$0.19	$1.14
CRCW120610K0FKEAC	Vishay	46	$0.09	$4.19
CRCW12061K00FKEAC	Vishay	3	$0.19	$0.57
CRCW1206200RFKEAC	Vishay	2	$0.10	$0.20
CRCW120620K0FKEAC	Vishay	4	$0.19	$0.76
CRCW12062K20FKEAC	Vishay	5	$0.10	$0.50
DS2Y-S-DC12V	Panasonic	10	$2.95	$29.50
ERJ-8ENF1800V	Panasonic	21	$0.05	$0.97
ERJ-8ENF3302V	Panasonic	1	$0.10	$0.10
ERJ-8ENF4303V	Panasonic	1	$0.10	$0.10
ERJ-P08F6203V	Panasonic	1	$0.25	$0.25
FKP2D001001D00JI00	WIMA	8	$0.69	$5.52
FKP2D004701D00JSSD	WIMA	4	$0.41	$1.64
FM4004W-W	Rectron	8	$0.10	$0.80
GRM3195C2A363JA01D	Murata	2	$0.67	$1.34

Part	Manufacturer	Quantity	Price	Subtotal
LM317T/NOPB	TI	2	$1.58	$3.16
LM337T/NOPB	TI	1	$1.74	$1.74
M2012SS1G45	NKK	1	$4.33	$4.33
NC3FAH-0	Neutrik	2	$1.02	$2.04
NC3MAH	Neutrik	2	$1.27	$2.54
NE5532DR	TI	14	$0.71	$9.90
PTD902-2015K-B103	Bourns	6	$2.01	$12.06
RAPC722X	Switchcraft	1	$0.92	$0.92
RC1206FR-07220KL	Yageo	4	$0.23	$0.92
RC1206FR-075K1L	Yageo	4	$0.23	$0.92
RC1206FR-076K2L	Yageo	2	$0.23	$0.46
UES1V220MPM	Nichicon	1	$0.56	$0.56
UKA1H101MPD	Nichicon	3	$0.77	$2.31
UKA1H470MED	Nichicon	3	$0.44	$1.32
UKZ1E221MHM	Nichicon	2	$0.78	$1.56
WP154A4SEJ3VBDZGW/CA	Kingbright	1	$2.05	$2.05
COM-00102	SparkFun	20	$1.50	$30.00
4527	Keystone	1	$1.08	$1.08
RT1206FRE07750RL	Yageo	1	$0.19	$0.19
VJ1206A680JXAAC	Vishay	4	$0.40	$1.60
12061A182FAT2A	AVX	2	$0.95	$1.90
12065A271FAT2A	AVX	2	$0.90	$1.80
12062A102F4T4A	AVX	4	$1.32	$5.28
CRCW120647K0FKEA	Vishay	2	$0.13	$0.26
AC1206FR-0716KL	Yageo	2	$0.11	$0.22
CRGP0402F100R	TE	20	$0.02	$0.42
1646S08-U	THAT	2	$4.43	$8.86
4305Q16-U	THAT	2	$4.90	$9.80
NE5532DR	TI	4	$0.85	$3.40
C1206C104J3RACTU	KEMET	10	$0.36	$3.61
CRCW120620K0FKEAC	Vishay	10	$0.09	$0.91
CRCW120610K0FKEAC	Vishay	10	$0.07	$0.70
CRCW080510K0FKEAC	Vishay	10	$0.06	$0.58
C0805C104K3RACTU	KEMET	10	$0.13	$1.27
5VT 2-R	Bel Fuse	5	$0.23	$1.15
5ST 1.6-R	Bel Fuse	5	$0.21	$1.05
ERJ-8ENF3001V	Panasonic	1	$0.10	$0.10
1N914BWS	ON Semi	30	$0.15	$4.35
CRCW12061K00FKEAC	Vishay	10	$0.09	$0.91
RC1206FR-075K1L	Yageo	10	$0.05	$0.54
CRCW120610K0FKEAC	Vishay	10	$0.07	$0.70

Part	Manufacturer	Quantity	Price	Subtotal
1646S08-U	THAT	1	$4.43	$4.43
NE5532DR	TI	20	$0.71	$14.14
1200S08-U	THAT	1	$5.65	$5.65
1N4148WS	ON Semi	10	$0.15	$1.52
GPU572401500WA00	Reliapro	1	$13.95	$13.95
C1206C224F3JAC7800	KEMET	2	$5.48	$10.96
UKA1H222MHD	Nichicon	4	$3.02	$12.08
1200S08-U	THAT	2	$5.65	$11.30
ATMEGA1280-16AU	Atmel	1	$10.94	$10.94
C1206C104J3RACTU	KEMET	44	$0.36	$15.88
DS2Y-S-DC12V	Panasonic	11	$2.95	$32.45
UES1H100MPM	Nichicon	16	$0.35	$5.63
Analog PCB	PCBway	1	$146	$146
Digital PCB	PCBway	1	$51	$51
Display PCB	PCBway	1	$5	$5
Debug PCB	PCBway	1	$5	$5
			TOTAL	**$590.91**

Appendix C Supporting Materials

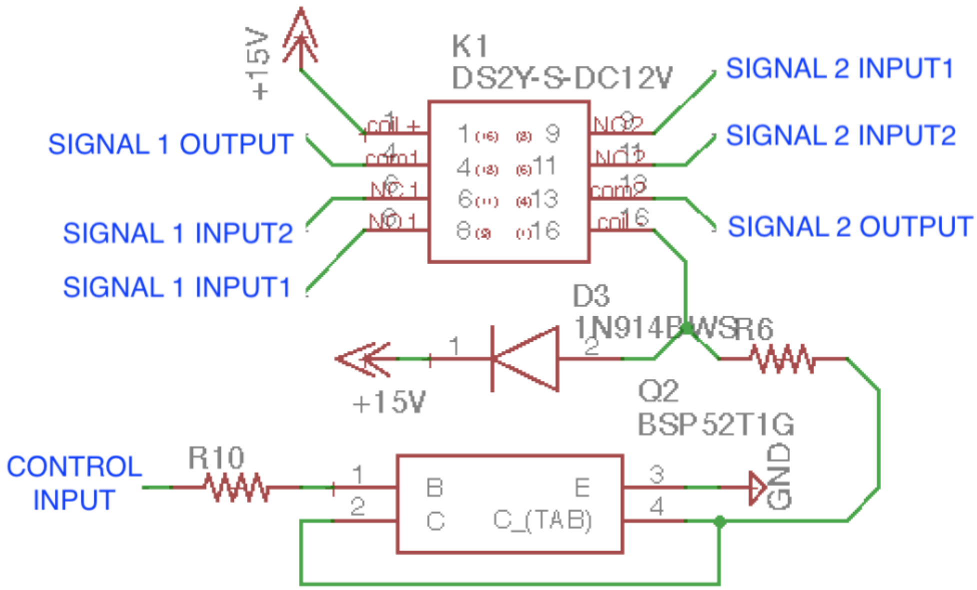

Figure 6. Switch Control Test Circuit

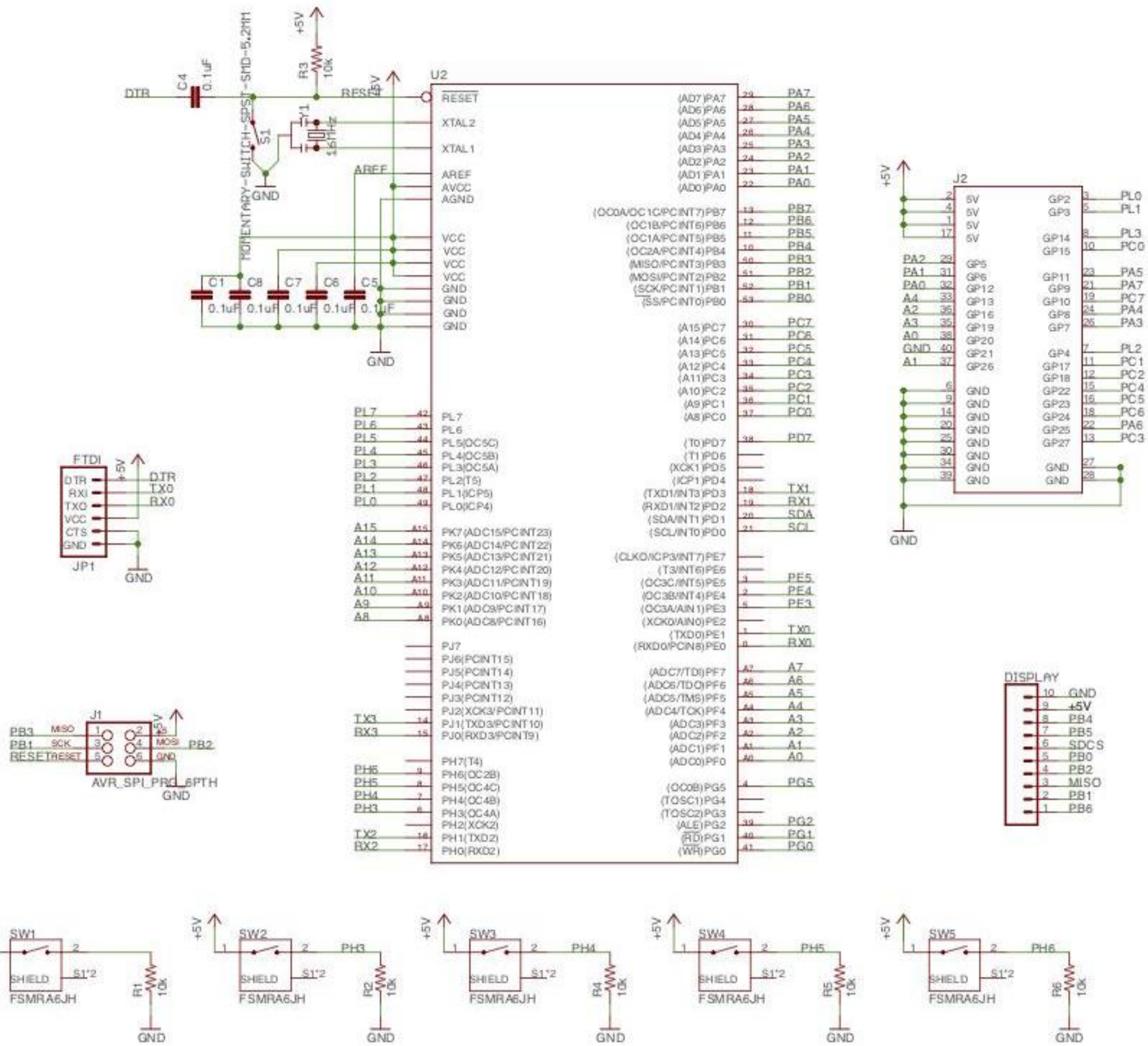

Figure 7. Digital Control Board Schematic

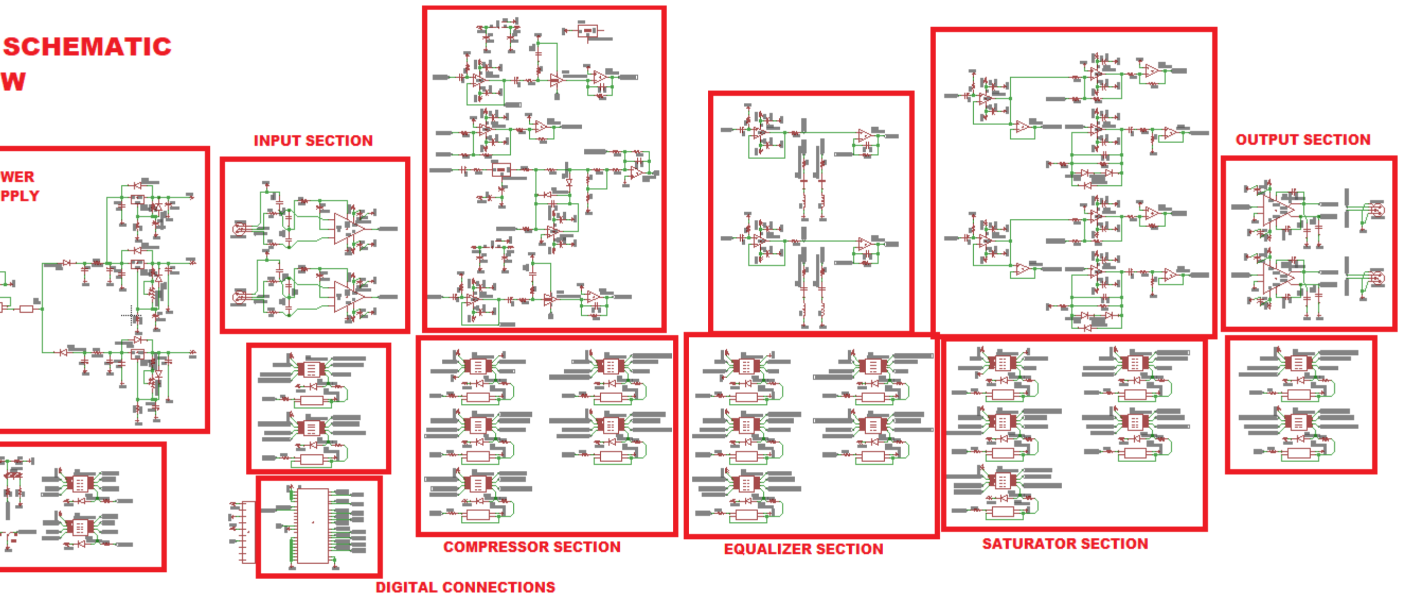
SCHEMATIC
W
WER
PPLY
INPUT SECTION
COMPRESSOR SECTION
DIGITAL CONNECTIONS
EQUALIZER SECTION
SATURATOR SECTION
OUTPUT SECTION

Figure 8. Analog Processing Schematic Overview

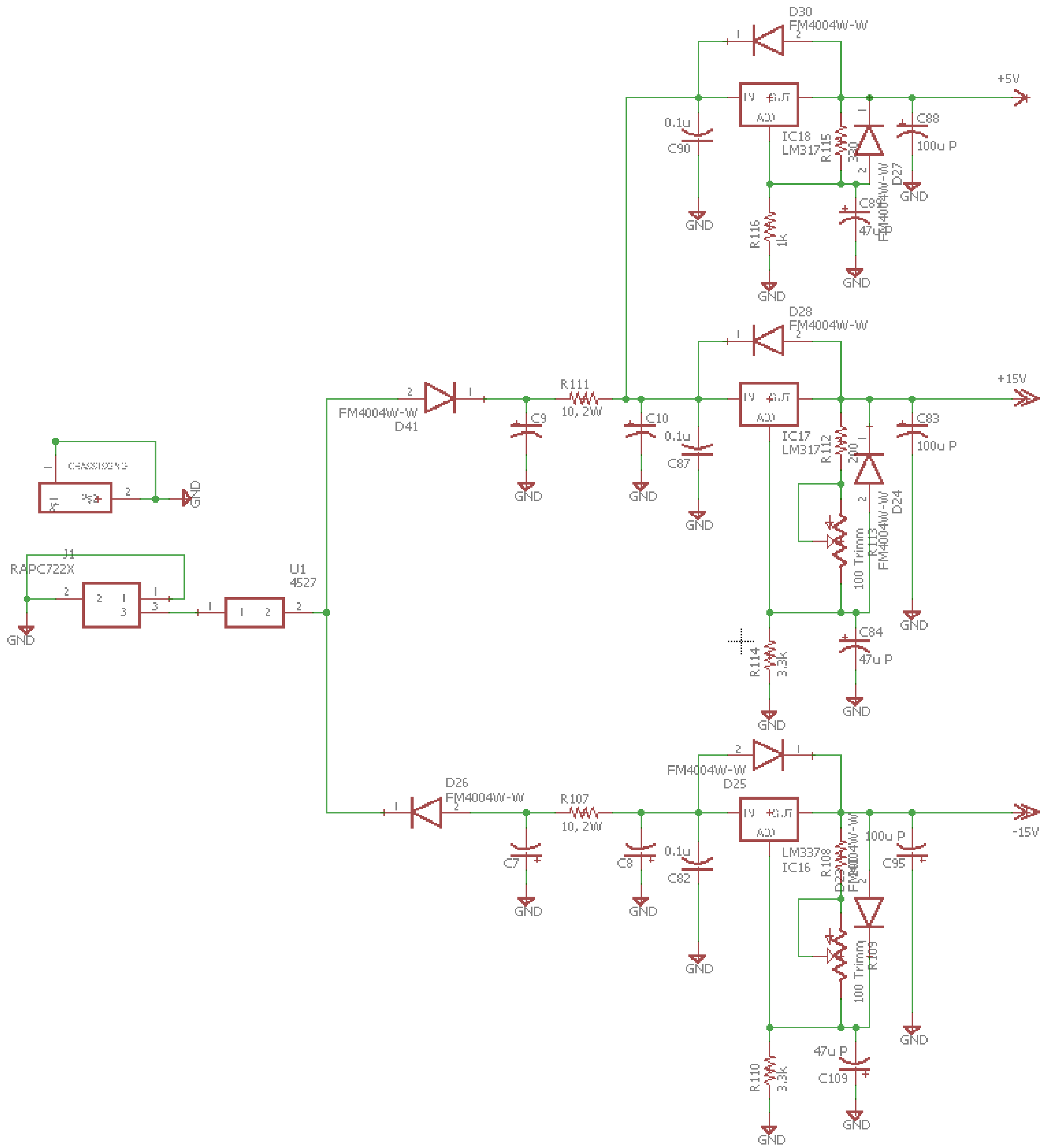

Figure 9. Analog Power Supply Schematic

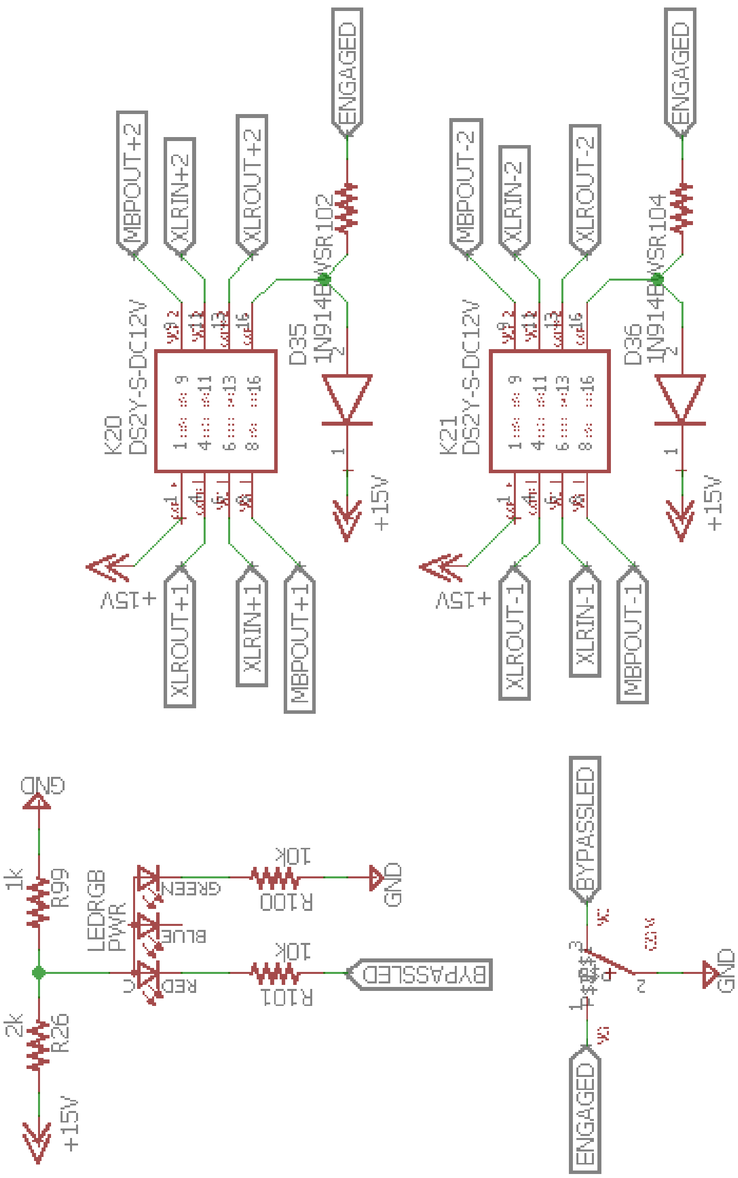
K20
DS2Y-S-DC12V
D35
1N914B
R102
ENGAGED
MBPOUT+2
XLRIN+2
XLROUT+2
XLROUT+1
XLRIN+1
MBPOUT+1
+15V
K21
DS2Y-S-DC12V
D36
1N914B
R104
ENGAGED
MBPOUT-2
XLRIN-2
XLROUT-2
XLROUT-1
XLRIN-1
MBPOUT-1
+15V
GND
R99
1k
R26
2k
LEDRGB
PWR
GREEN
BLUE
RED
R100
10K
R101
10K
BYPASSLED
BYPASSLED
ENGAGED
GND

Figure 10. Analog Hardware-Bypass Schematic

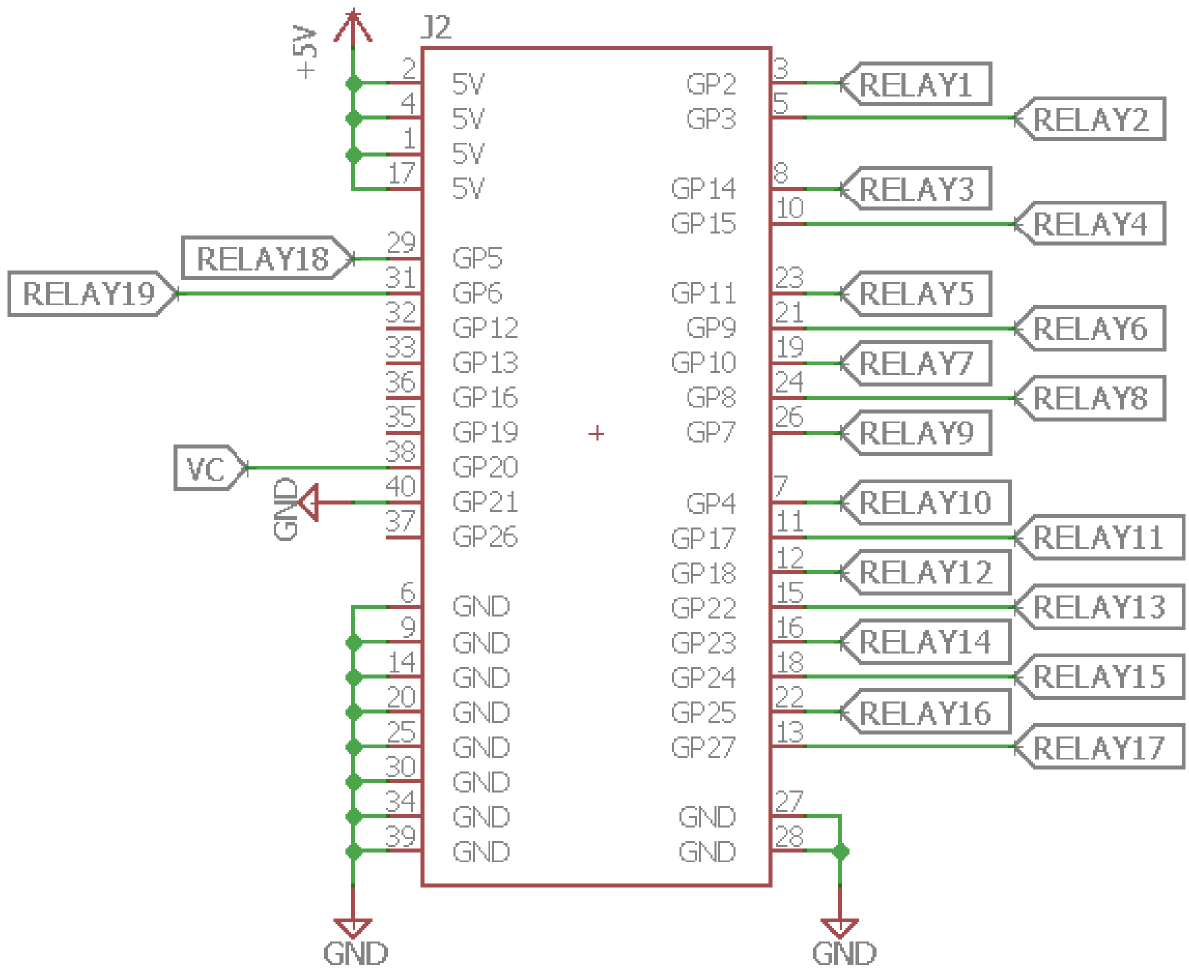

Figure 11. Analog Digital-Connector Schematic

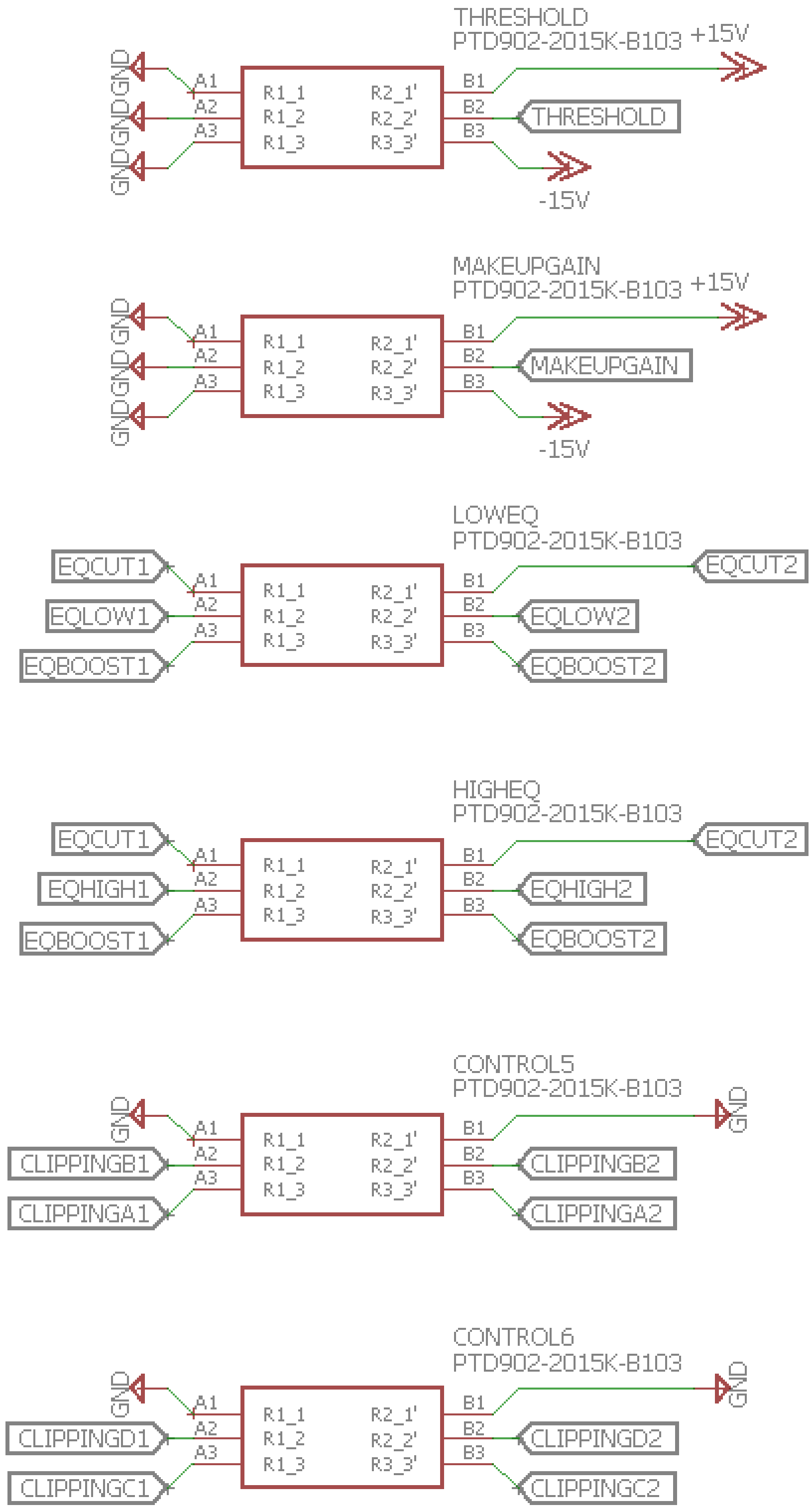

Figure 12. Analog Controls Schematic

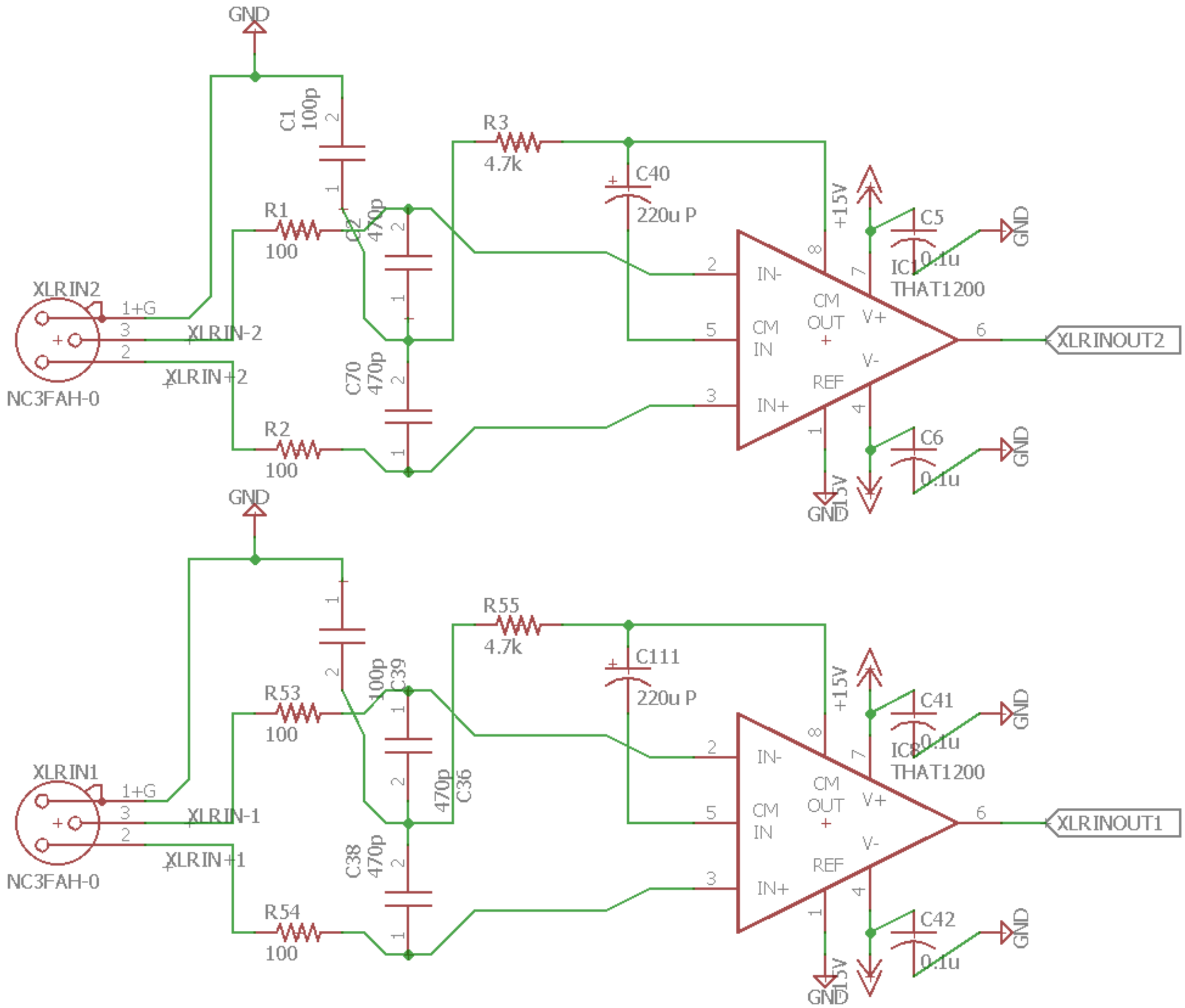

Figure 13. Analog Inputs Schematic

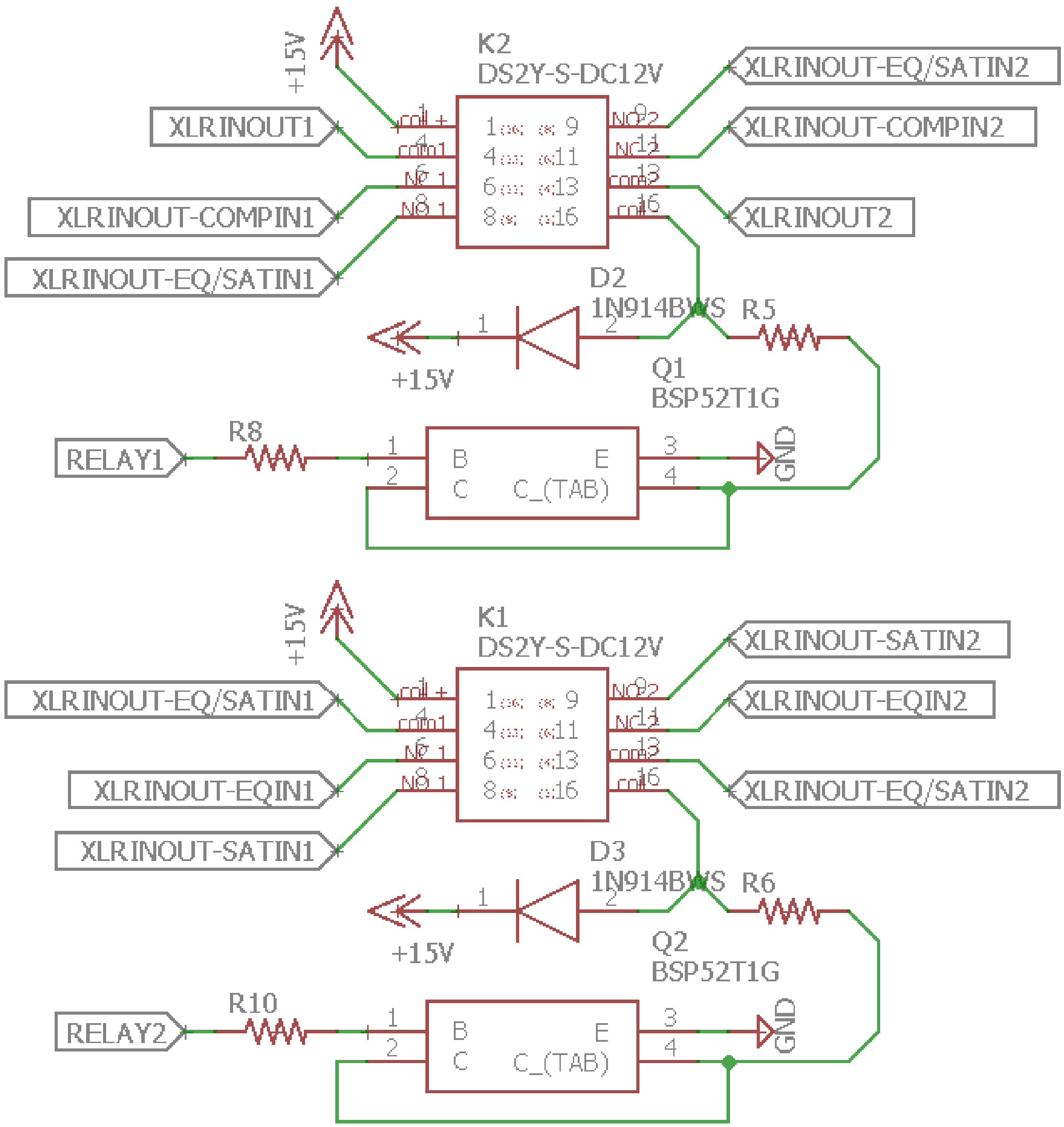

Figure 14. Analog Input Relays Schematic

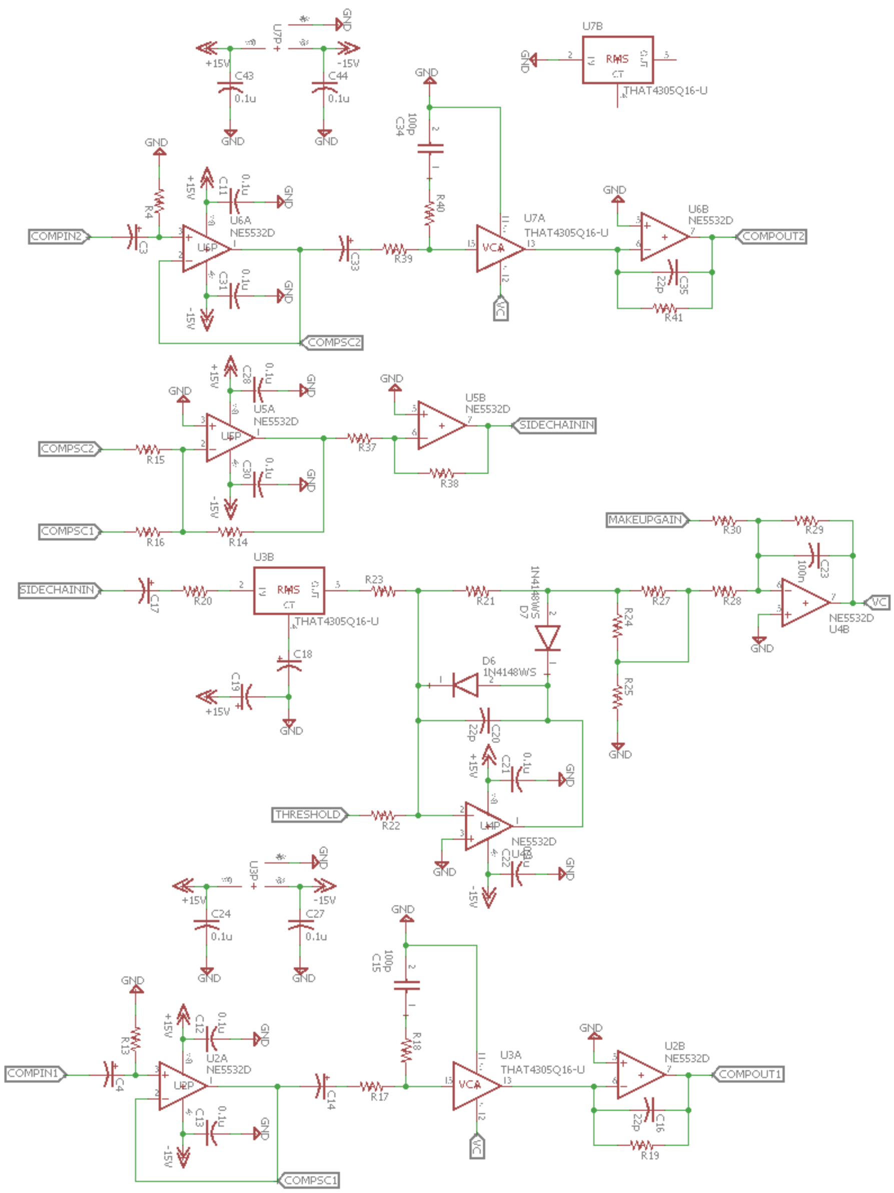

Figure 15. Analog Compressor Schematic

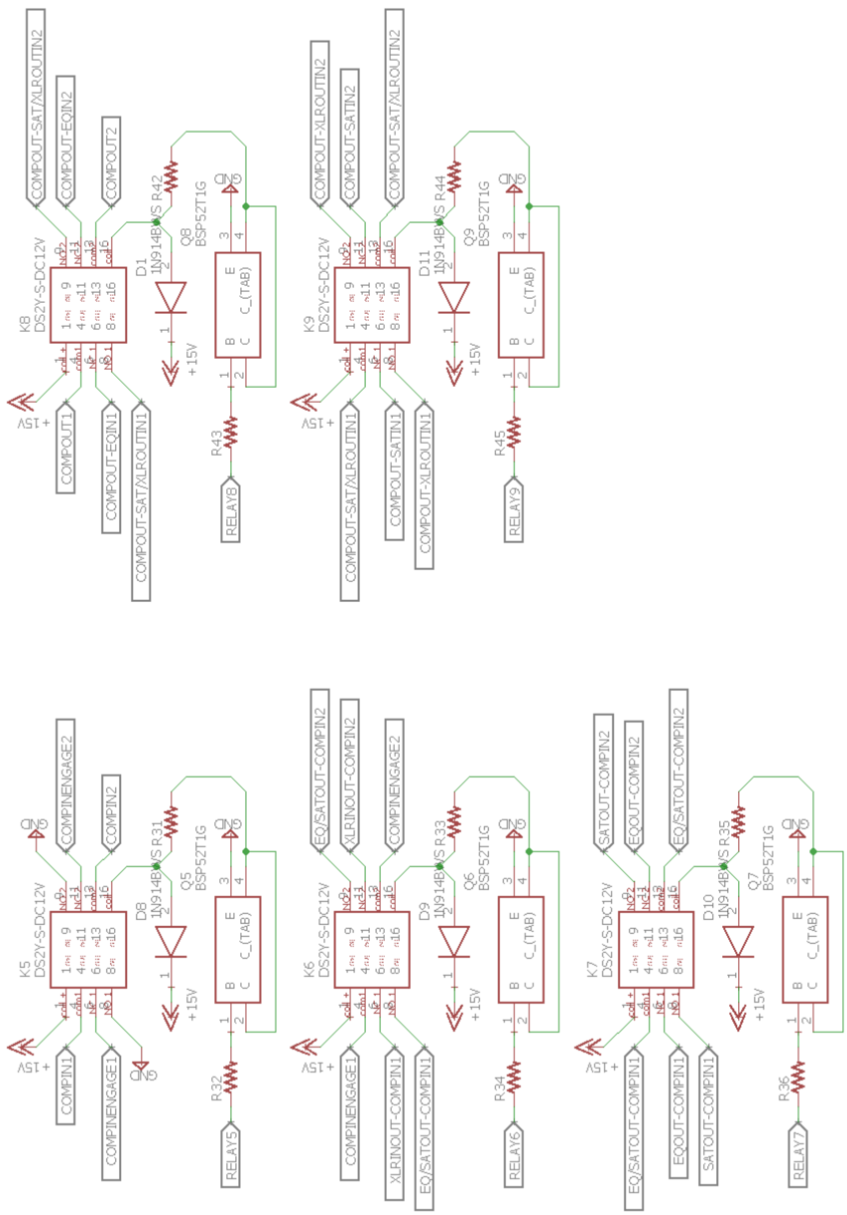

Figure 16. Analog Compressor Relays Schematic

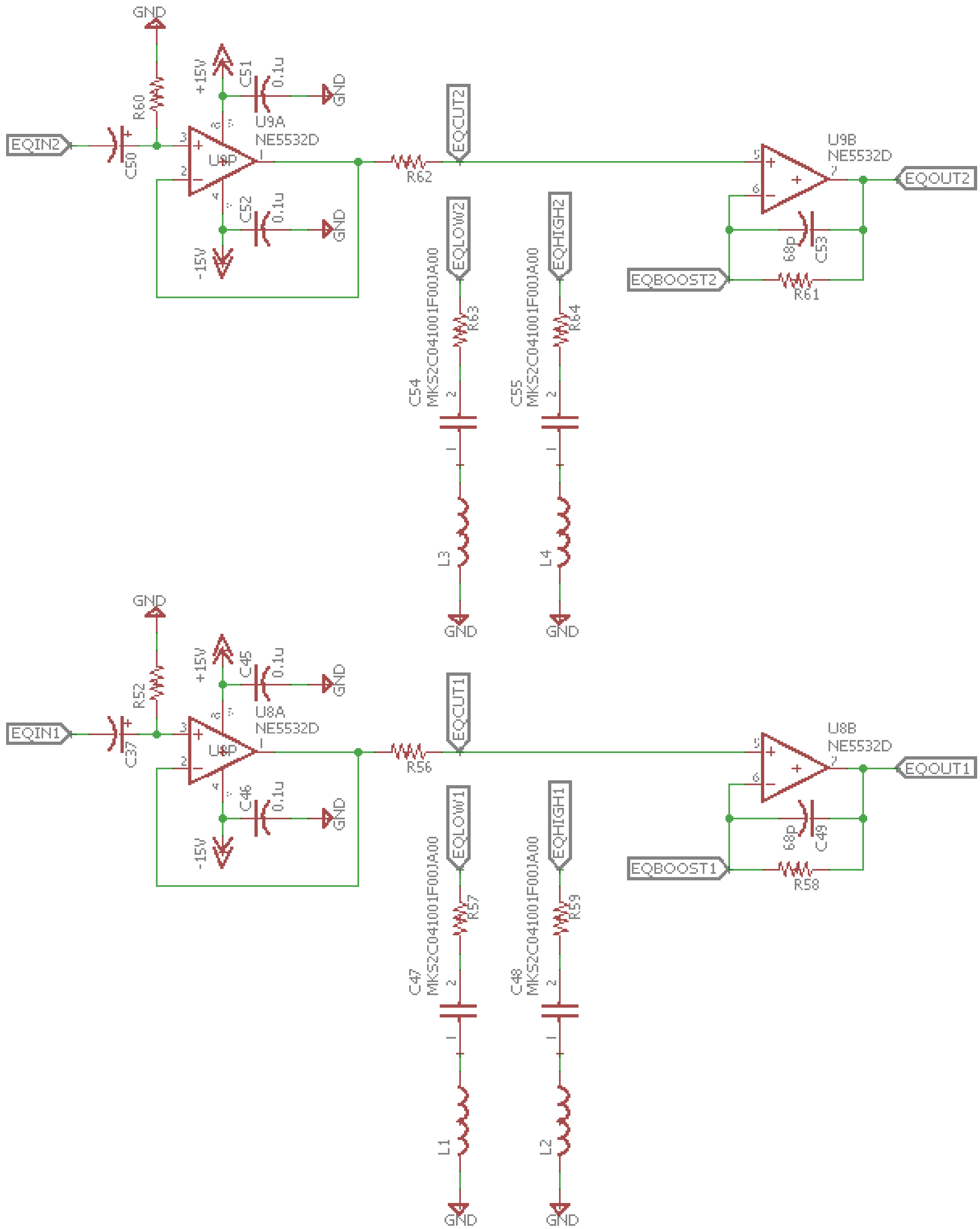

Figure 17. Analog Equalizer Schematic

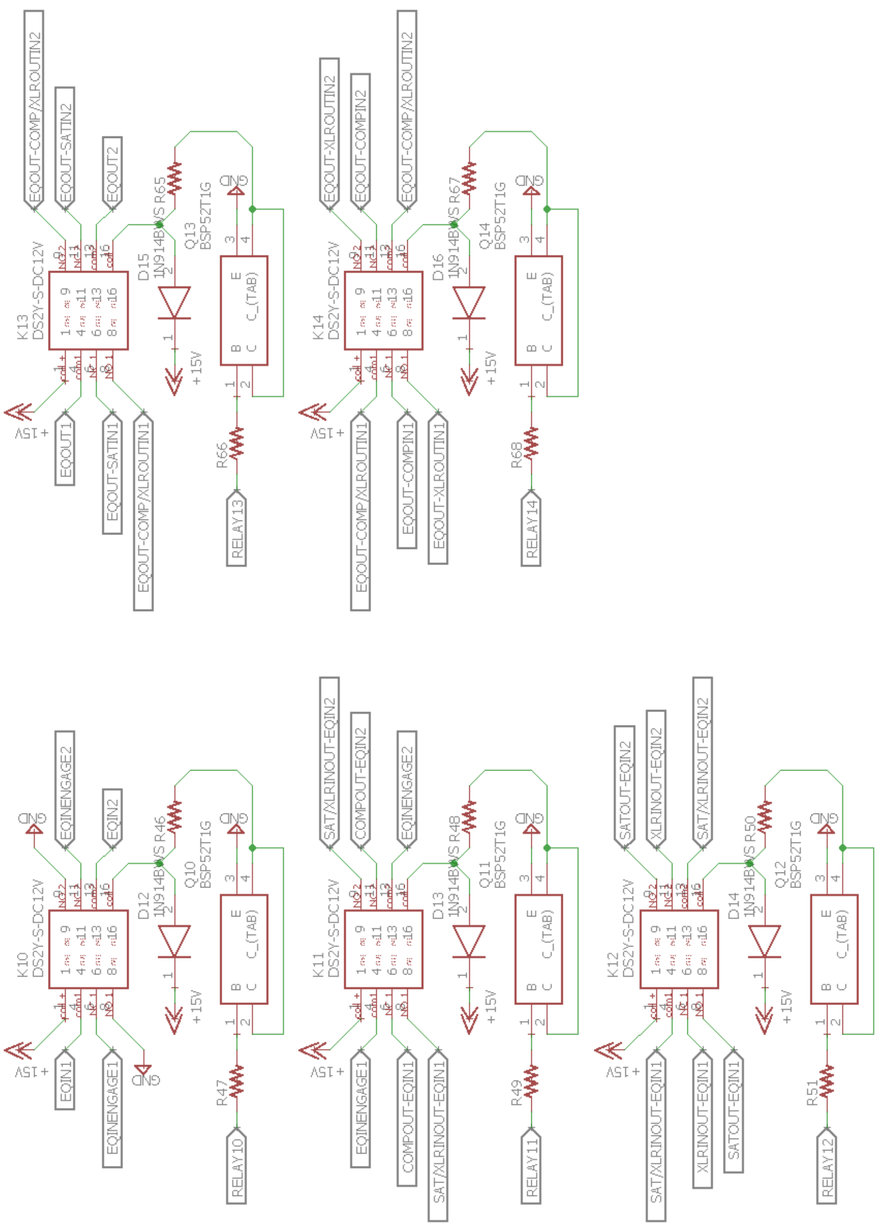

Figure 18. Analog Equalizer Relays Schematic

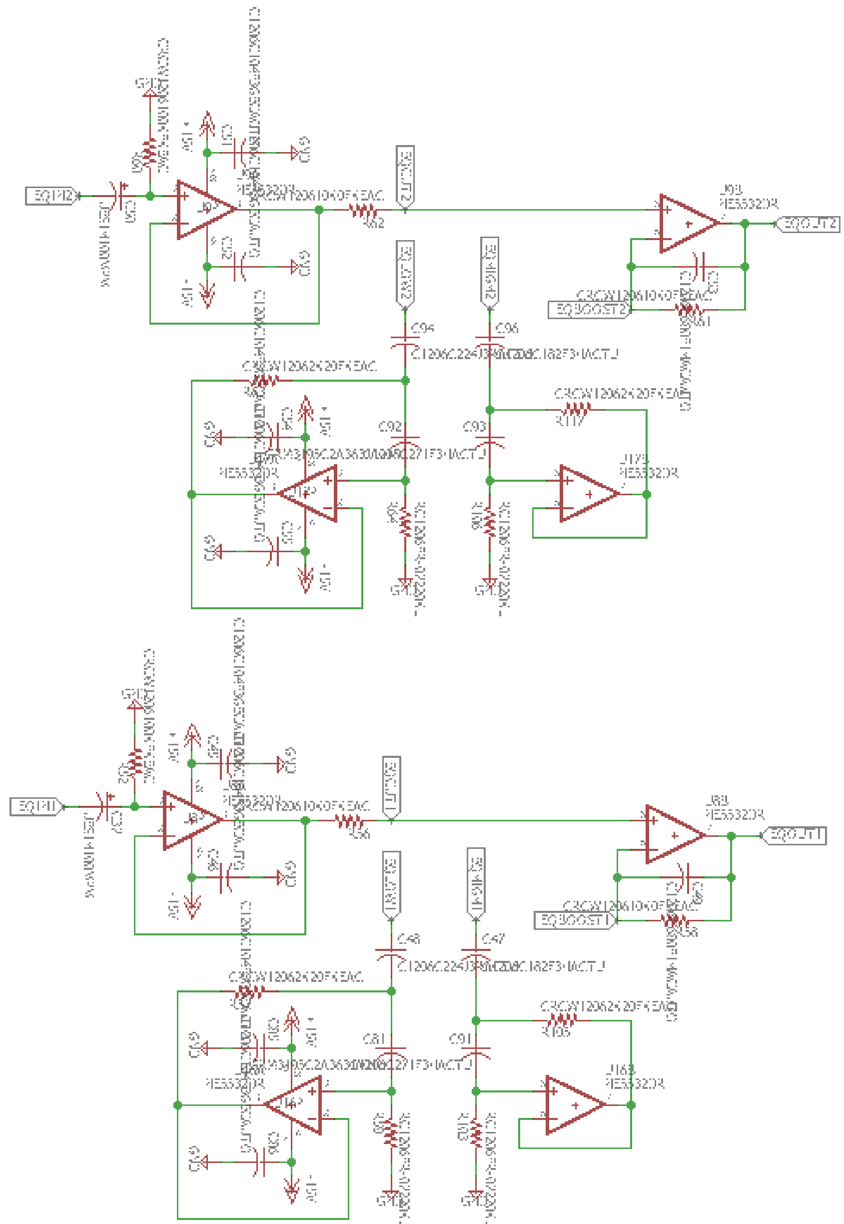

Figure 19. Analog Saturator Schematic

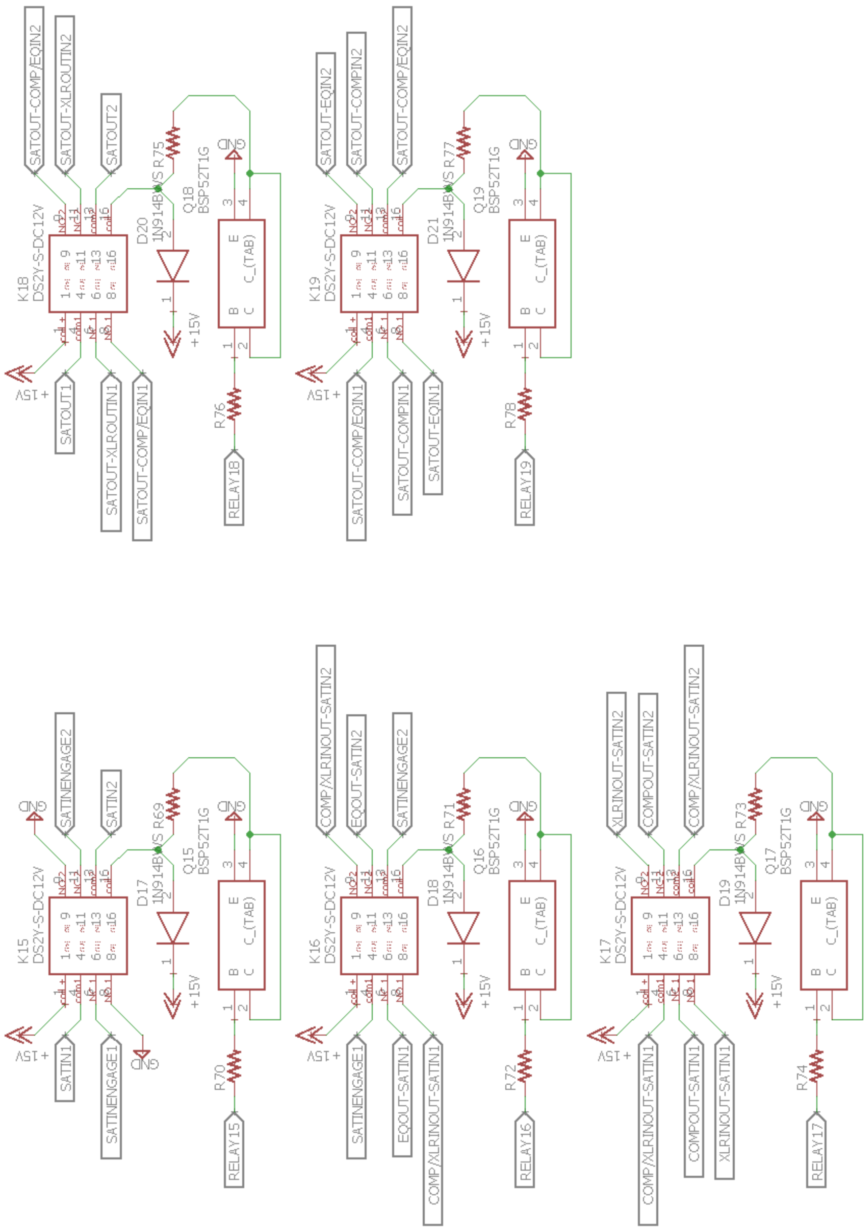

Figure 20. Analog Saturator Relays Schematic

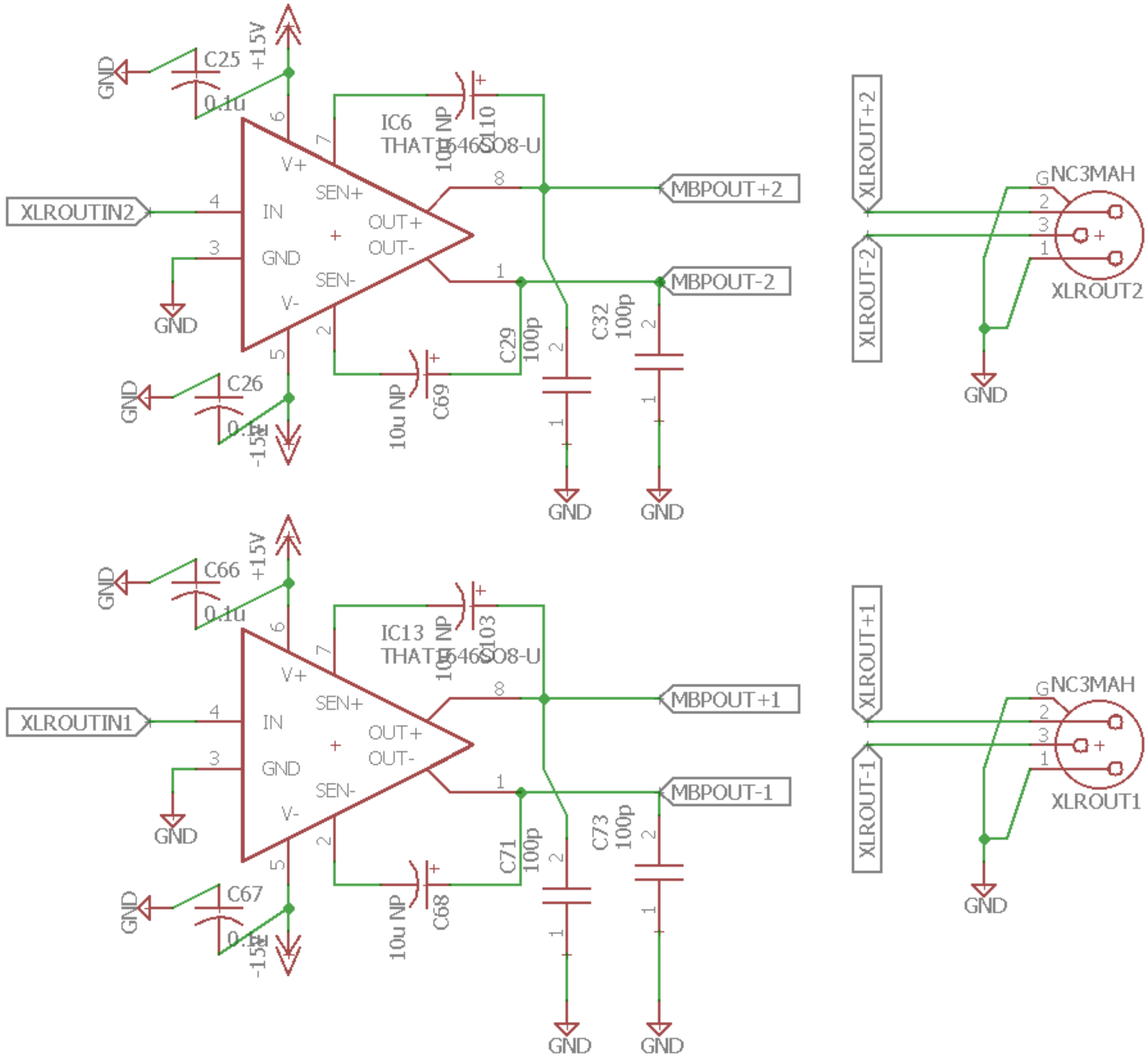

Figure 21. Analog Outputs Schematic

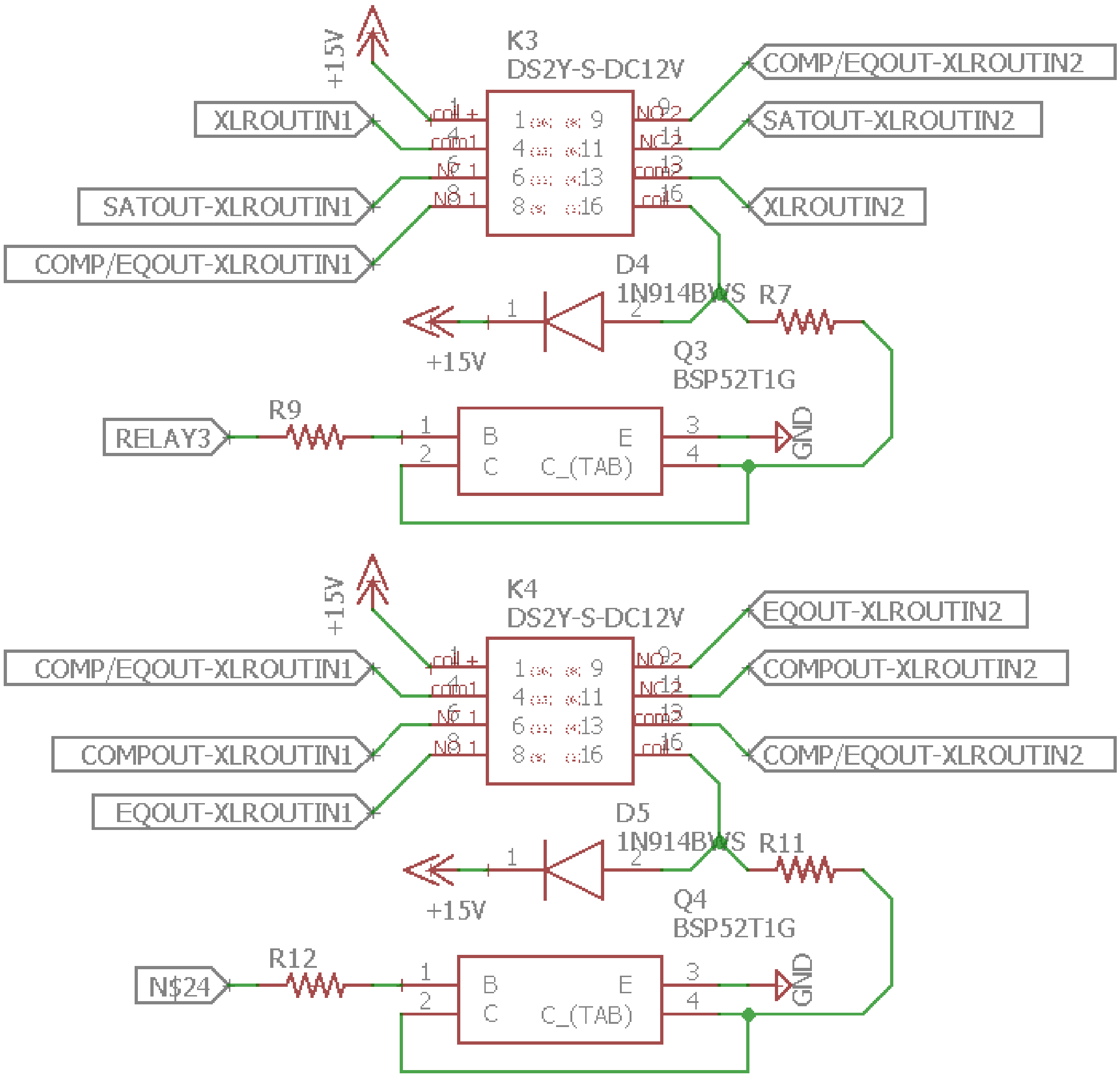

Figure 22. Analog Output Relays Schematic

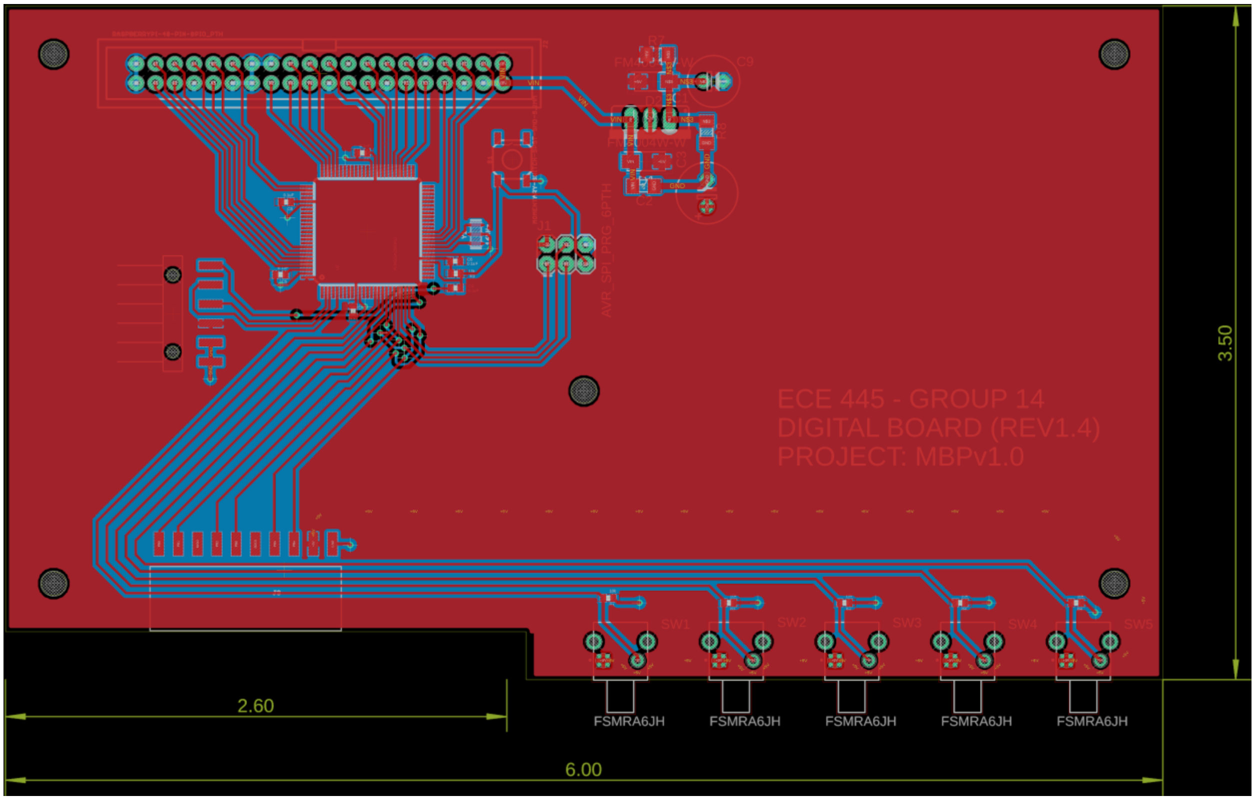

Figure 23. Digital Control Board PCB

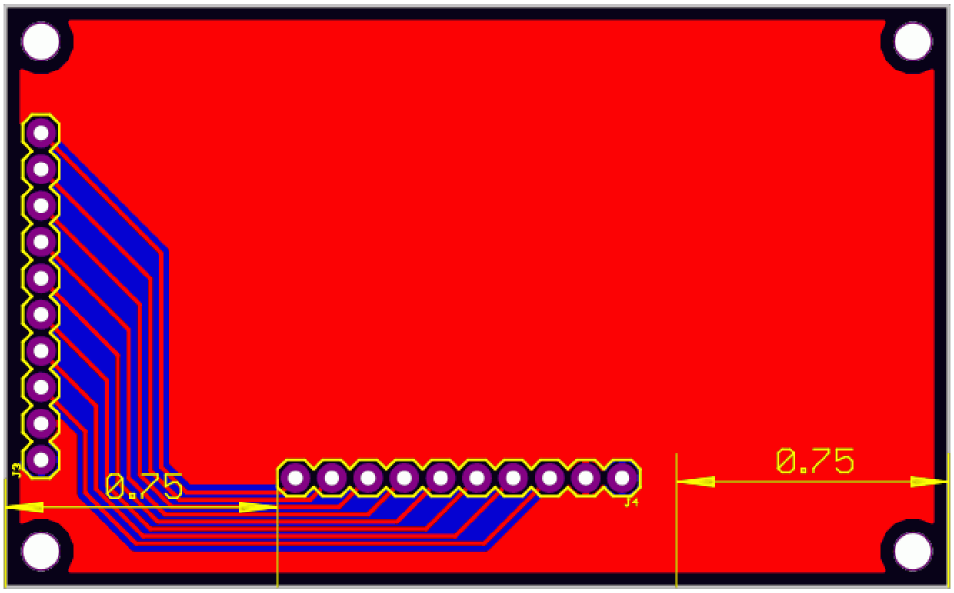

Figure 24. Display Adapter Board PCB

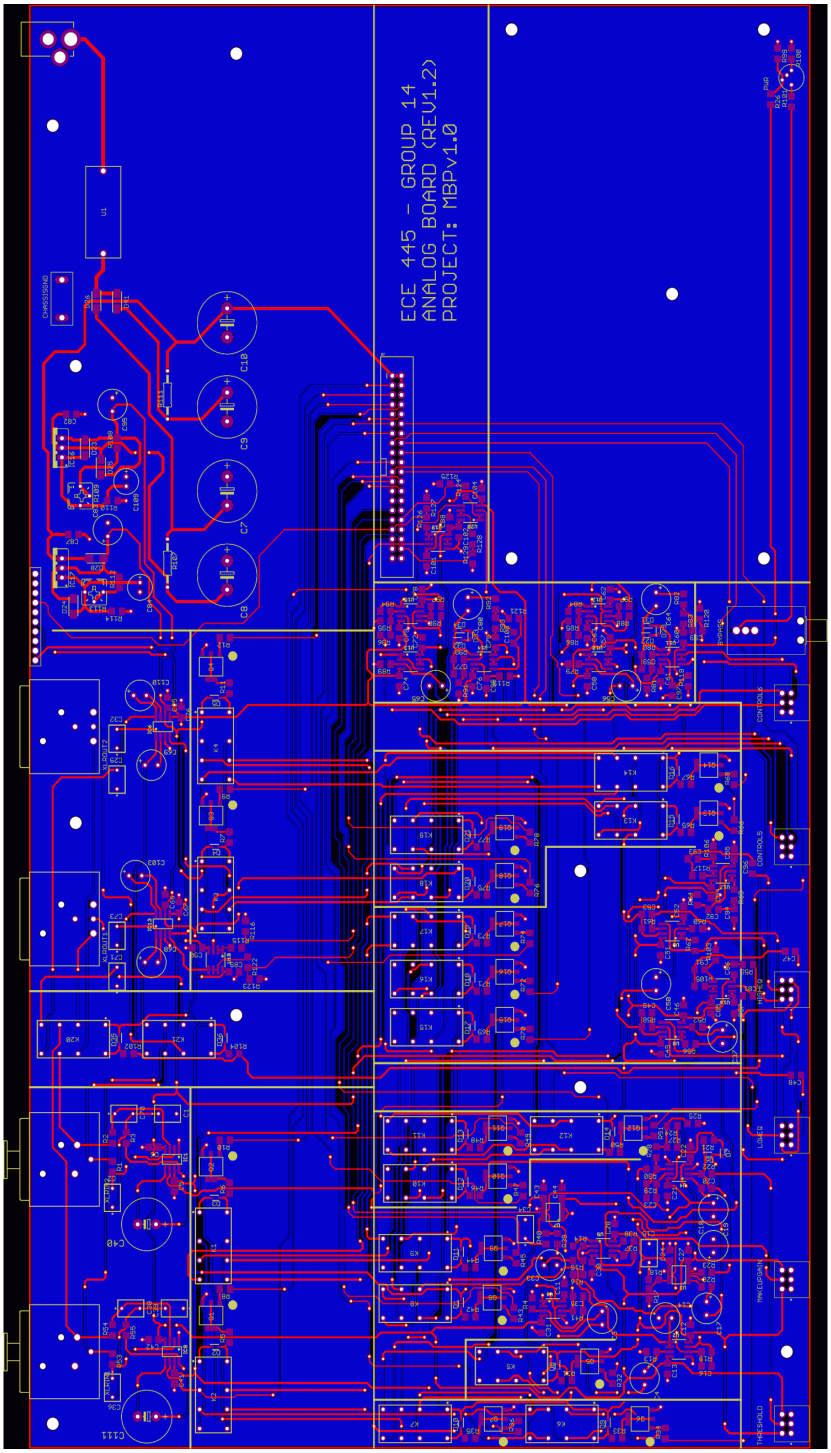

Figure 25. Analog Board PCB Overview

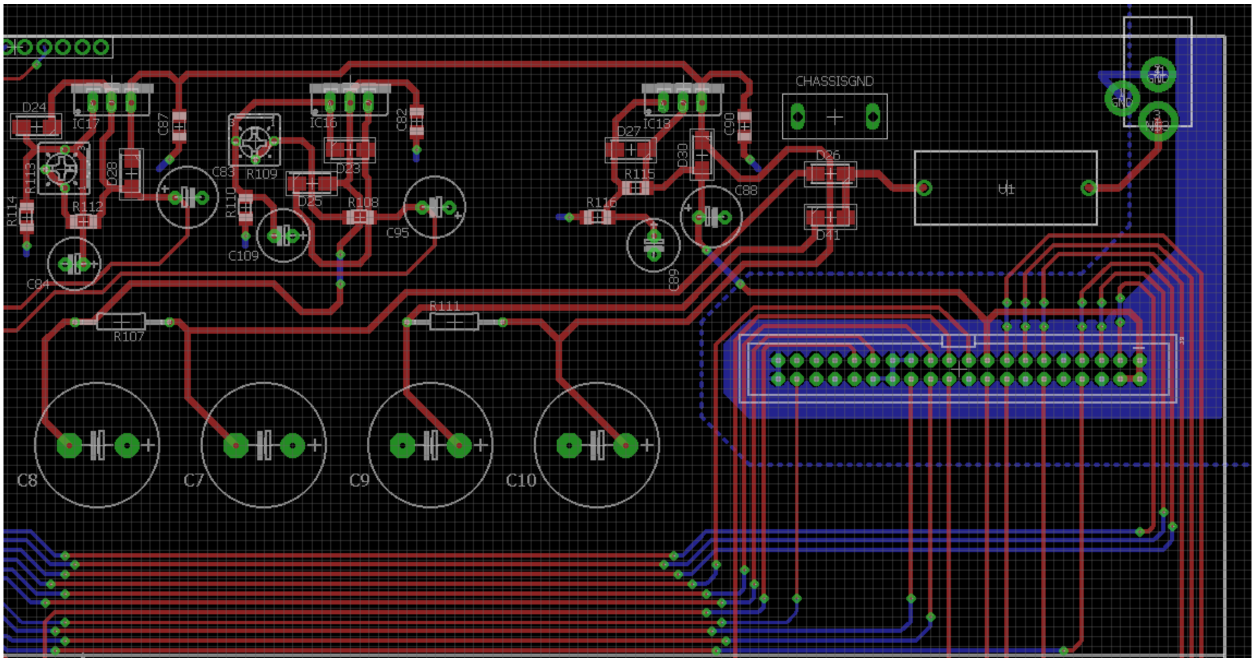

Figure 26. Analog Board: Power Supply Layout

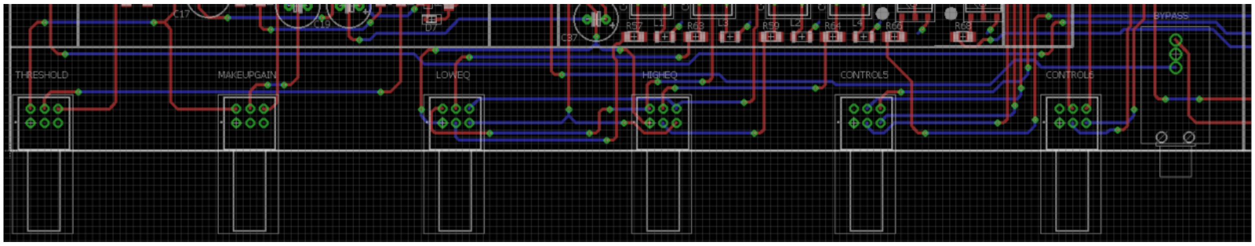

Figure 27. Analog Board: Analog Controls Layout

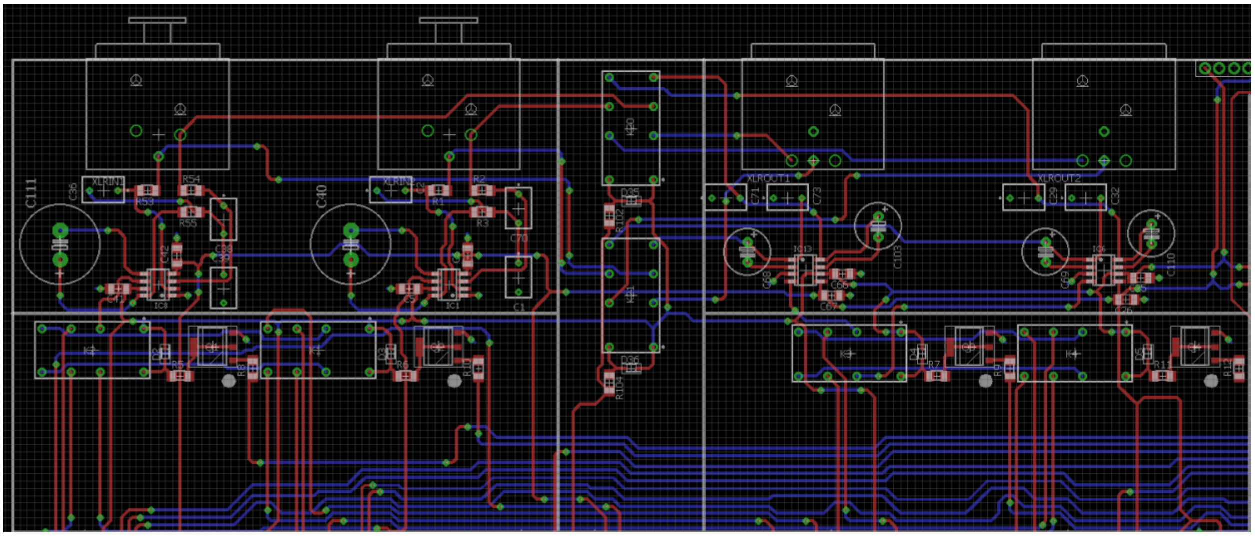

Figure 28. Analog Board: Input/Output Layout

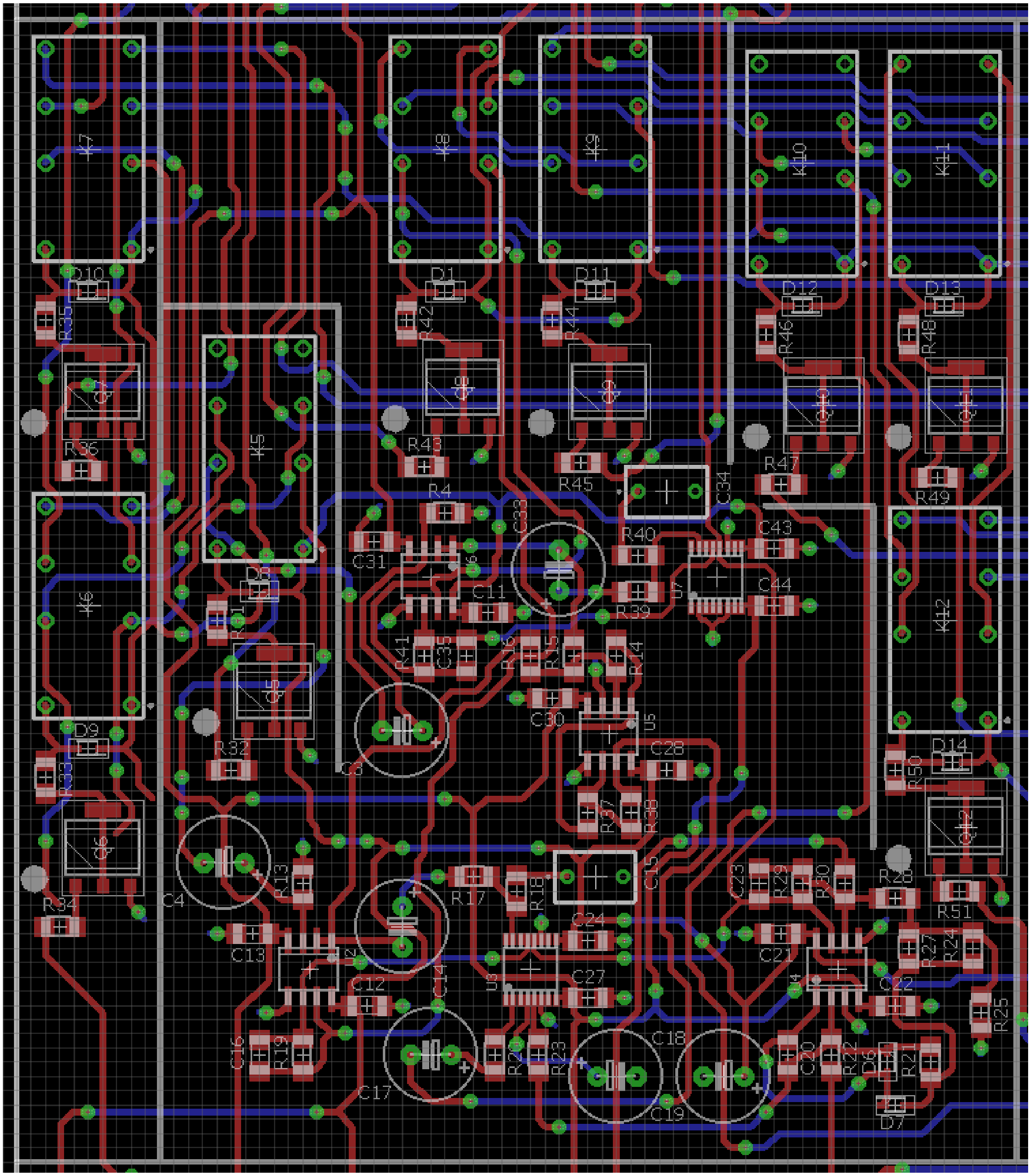

Figure 29. Analog Board: Compressor Layout

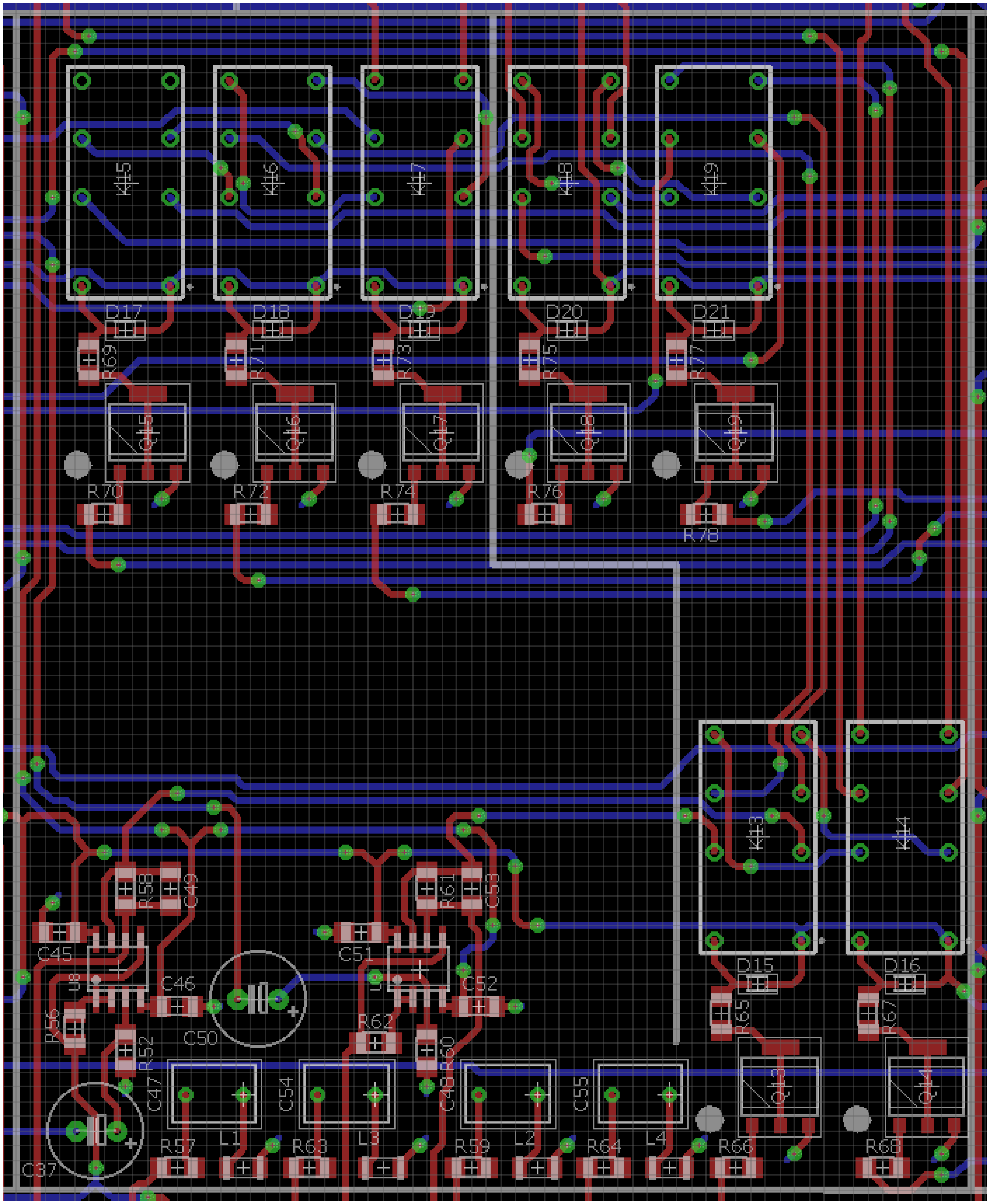

Figure 30. Analog Board: Equalizer Layout

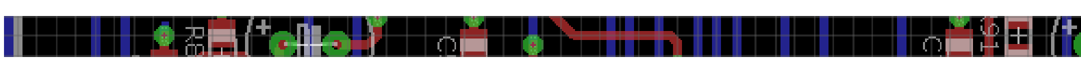

Figure 31. Analog Board: Saturator Layout

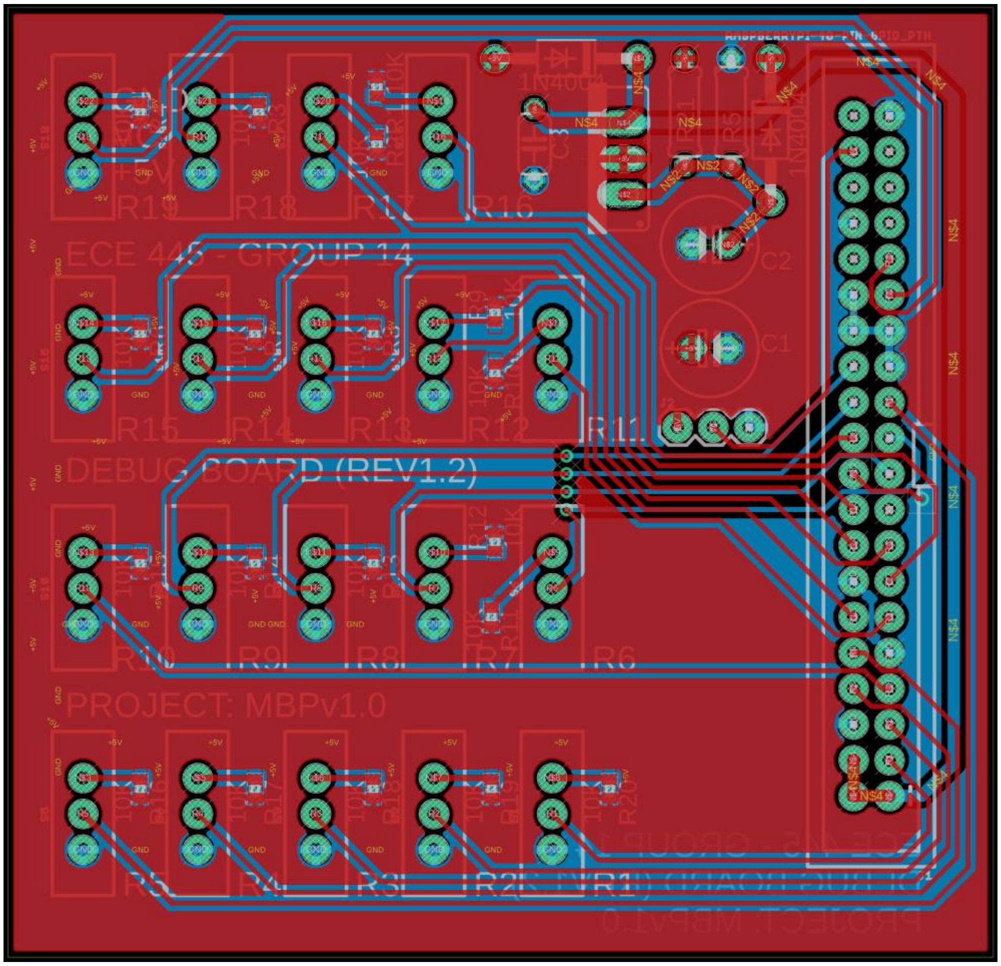

Figure 32. Debug Board

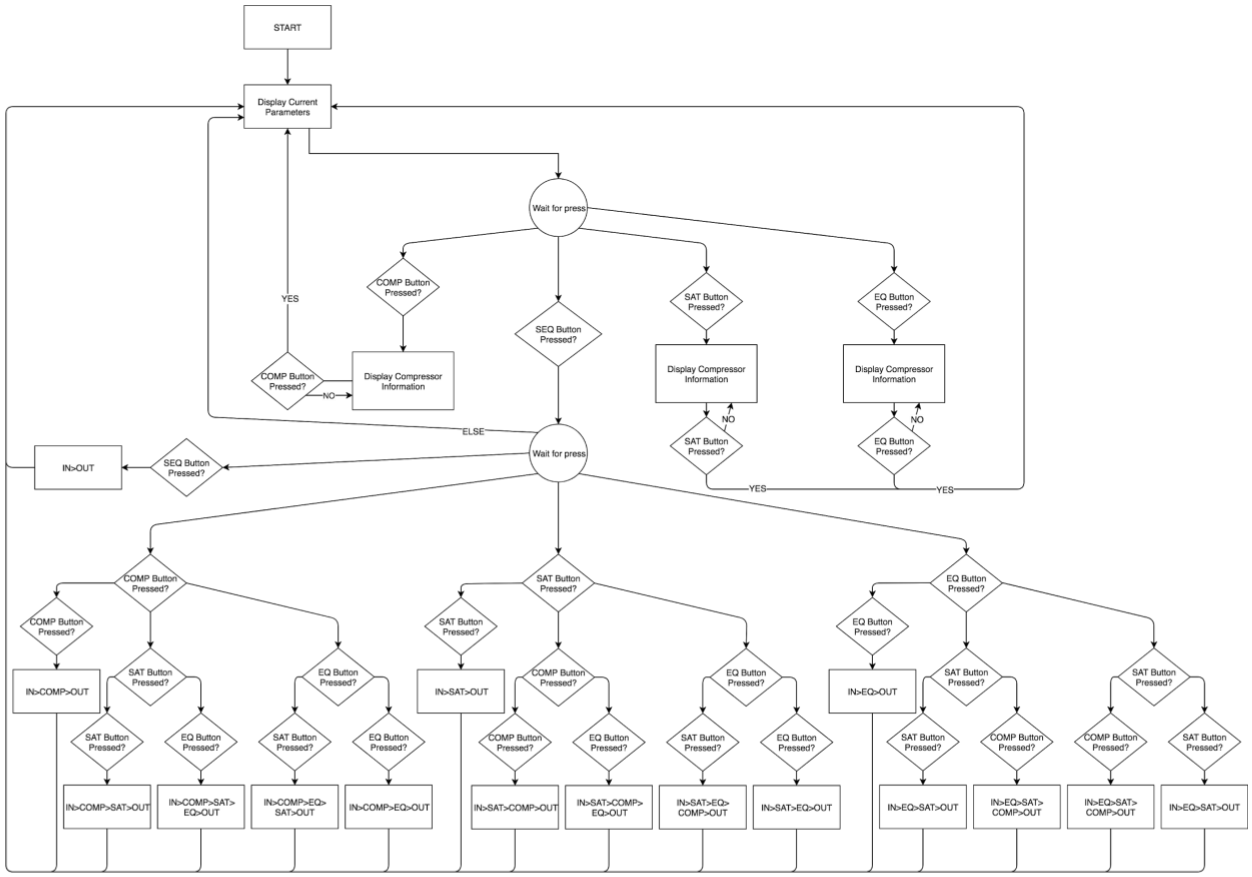

Figure 33. Microcontroller Software Flow Chart