

Real-Time Adaptive Signal Conditioning System for Wide Dynamic Range Inputs

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I. Plain explanation

The diagram represents a Real-Time Adaptive Signal Conditioning System for Wide Dynamic Range Inputs.

The system automatically regulates the amplitude of an input signal by applying level-dependent gain control. It continuously monitors the input signal level, compares it to a predefined threshold, and dynamically adjusts the gain of a voltage-controlled amplification stage to maintain the output signal within a controlled range.

The system operates in real time using a feed-forward control architecture, enabling fast response to changes in input amplitude without directly feeding back the output signal.

II. Detailed explanation of how the system works

1 Signal Input

The system receives an analog input signal whose amplitude may vary significantly over time.

2 Voltage-Control

The input signal is fed directly into a Voltage-Controlled Amplifier. This block applies a gain to the signal, where the gain value is controlled by an external control voltage. The VC is responsible for increasing or decreasing the signal amplitude in real time.

At this stage: The signal path remains continuous No frequency modification is intended Only amplitude scaling is applied

3 Envelope Detector

In parallel with the main signal path, the input signal is routed to an Envelope Detector. The purpose of this block is to extract a representation of the signal's amplitude (or level), independent of its frequency content. This is typically achieved through rectification followed by low-pass filtering, producing a slowly varying control signal. This block provides the system with real-time information about how "strong" the input signal is.

4 Signal Comparator

The output of the Envelope Detector is fed into a Signal Comparator, where it is compared against a predefined reference threshold level. If the detected signal level is below the threshold, no gain reduction is required. If the detected signal level exceeds the threshold, the comparator generates a control signal indicating that gain reduction should be applied. This block implements the decision logic of the system.

5 Control Signal Generation

The output of the Signal Comparator is converted into a control voltage that determines how much gain reduction is applied by the VC. The magnitude and timing of this control signal govern: How quickly the system responds to increases in input level How smoothly

the gain returns to normal when the input level decreases. This behavior defines the system's dynamic response characteristics.

6 Signal Output

The processed signal exits the system through the output block. As a result of the adaptive gain control, the output signal exhibits a reduced dynamic range compared to the input, remaining within a controlled amplitude range even when the input varies significantly.

7 System block illustration

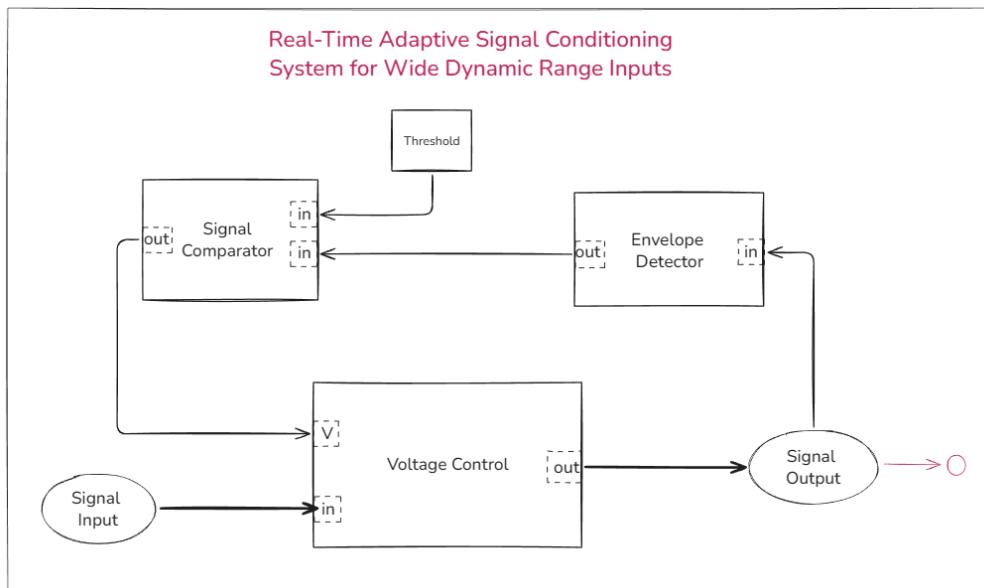


Figure 1: Block diagram

III. Deployment

1 Voltage-Control

Available methods -Multi Variable Resistors Low Pass filtering -Diode ladder filtering
 Chosen Method: Diode ladder filtering this method consists combining a multi set 1N4138 diodes in series will act as a variable resistance in function of the control-voltage applied to the input of the CV (V). this method will cause less distortion and more control of the CV and its generally more cost-effective and easy to assemble.

1.1 functioning

I have selected the diode technique, which involves utilizing many diodes as resistors. It functions by supplying symmetric voltages to the diode ladder's beginnings and a non-inverted buffered input at the center.

This is the fundamental idea behind the diode ladder. The output signal is picked as is from the middle of the ladder if the symmetric voltages are zero. If the symmetric

voltages are not equal to zero, there will be a current flowing from the positive rail to the negative rail and simultaneously dragging some of the current from the input signal, so the output signal will be the same as the input but lower in amplitude (volume).

Therefore, the more the symmetric voltages increase, the lower the input will become.

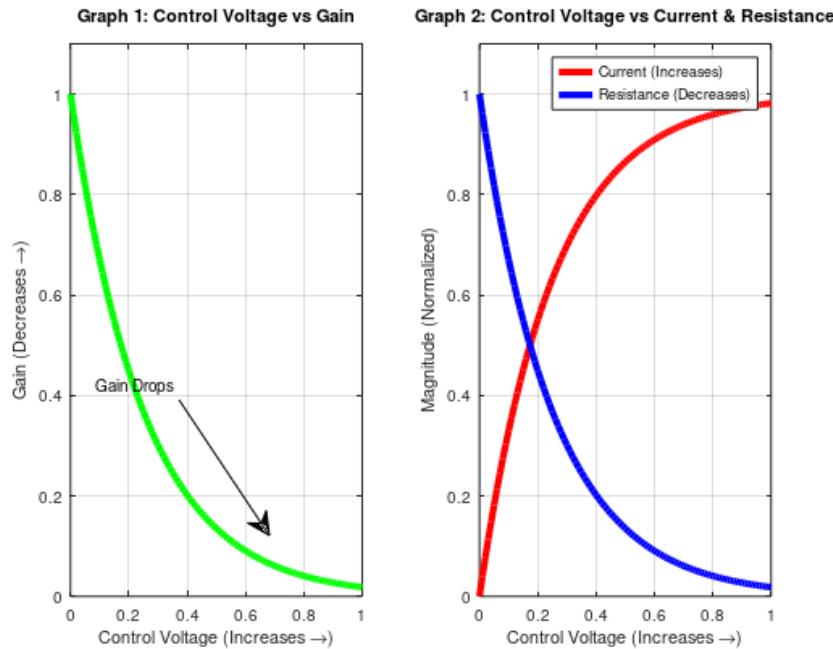


Figure 2: Diode Ladder Control Characteristics

1.2 Schematic

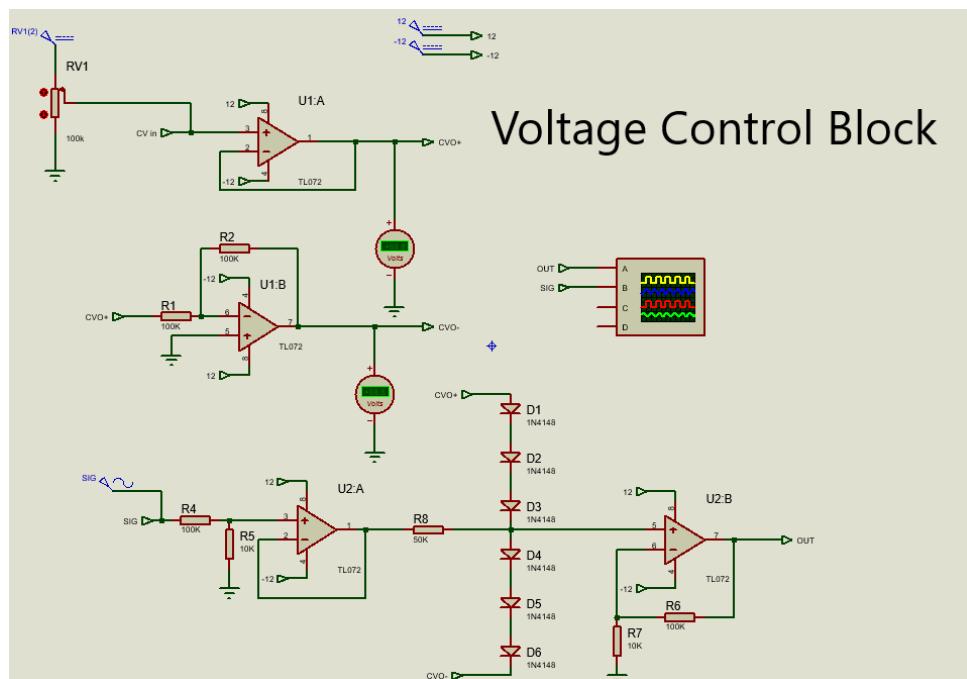


Figure 3: Voltage Control Block schematic

1.3 Simulation

$CV = 0 \rightarrow \text{Gain} = 1$

$CV = 2 \rightarrow \text{Gain} < 1$

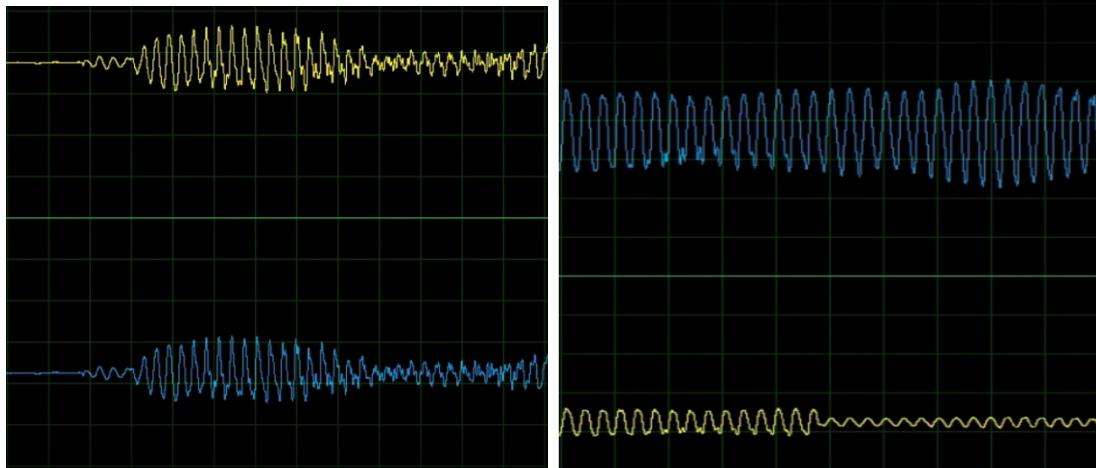


Figure 4: Simulation 1 and Simulation 2

2 Peak Detector

Available Methods

There are several approaches for peak detection in circuits, and these are a few of them:

1. Diode-capacitor Circuit
2. Diode-capacitor-Amplifier
3. Diode-capacitor-RC Coupling

Chosen Method

diode-Capacitor-RC coupling is the technique I have selected because of its simple circuit, high efficiency, and high response time.

2.1 functioning

We can create a peak detector by wiring a buffer op amp through a diode and an RC coupling.

When the input signal increases, the capacitor charges, and when the input signal decreases, the current flowing from the capacitor will drain through the resistor to ground (the diode blocks the other sense of current flow).

This allows us to detect the output from the resistor.

2.2 Schematic

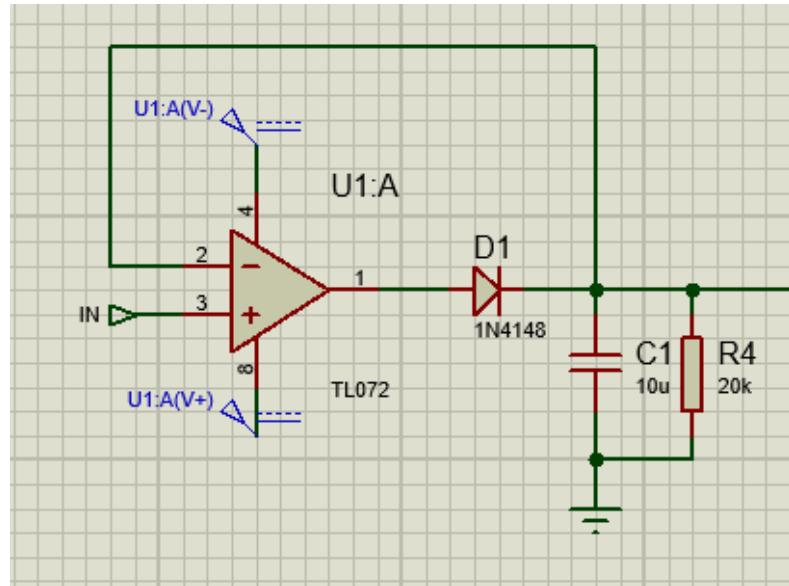


Figure 5: Schematic Peak detector

2.3 Simulation

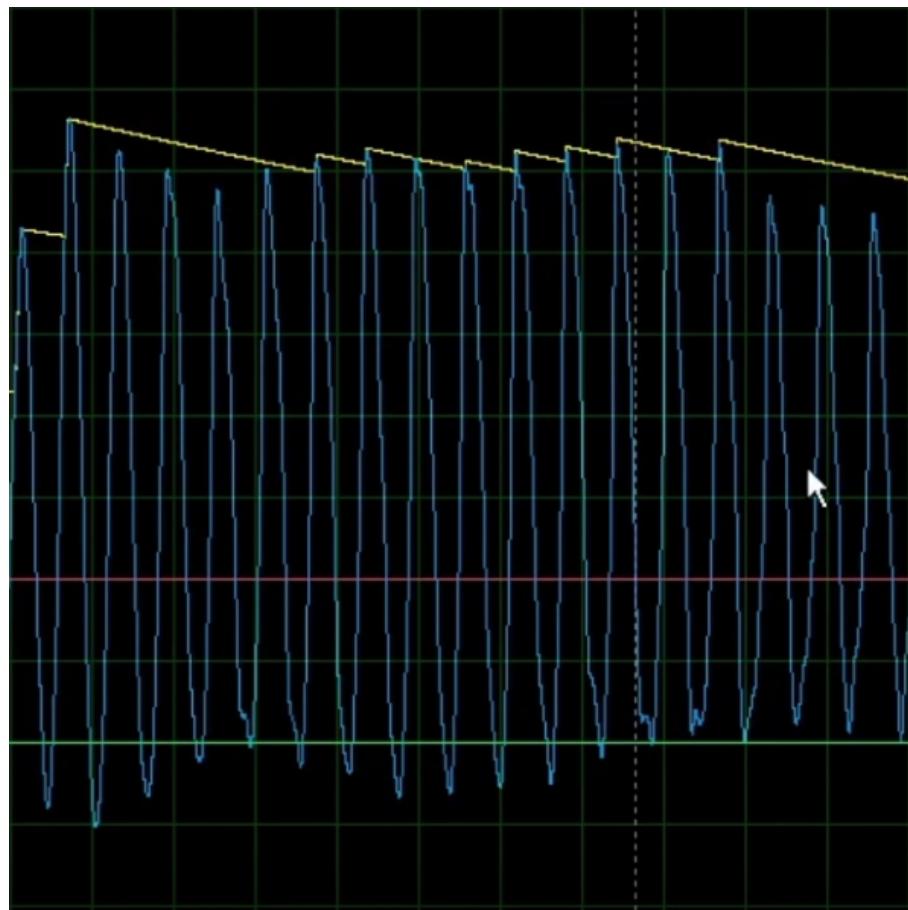


Figure 6: Simulation Peak detector

Note

Because of its orientated diodes, our control voltage block (built on the preceding block) does not require the negative peaks. In any case, since all of the signals will be somewhat sinusoidal, we do not require the negative sections.

3 Signal Comparator Block

3.1 functioning

The comparator block's operation is really simple, and we do it by utilizing a differential amplifier with gain 1.

The threshold voltage is wired to the amplifier's non-inverting input, so a negative output indicates no change in the signal because the input is below the threshold, and a positive output indicates a decrease in the signal because it is above the threshold.

The output of the comparator block will be the input of the VC block.

Since our input is maximum at 12 volts peak to peak, the threshold element will be a variable voltage that swings between 0 and 6 volts.

3.2 Schematic

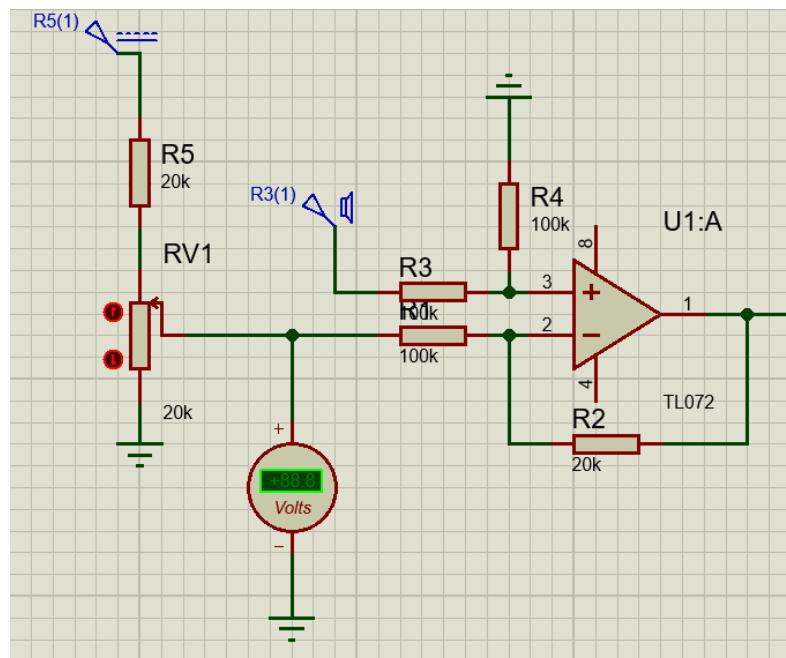


Figure 7: Comparator Block

4 Assembling

The assembly process is straightforward, combining the previous blocks together and fine-tuning the wiring and input/output pins.

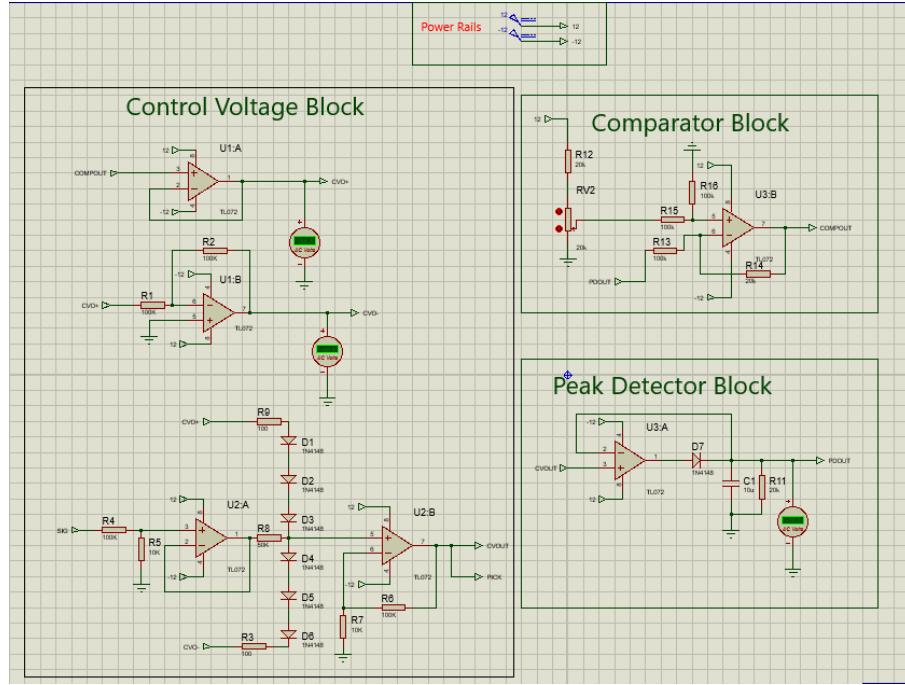


Figure 8: Assembled Blocks

5 Initial Performance Analysis

From the tests that I have made through the simulation and my own thinking, I identified a few problems that have caused the system not to fail completely, but it is not behaving as we would like.

First, the control voltage inputs (same as the comparator outputs) are always positive even when the threshold is set at 0 volts, so the output signal from the CV will always be shrunk down by some unwanted factor.

I also noticed that in the CV input, if the input difference went above 2 volts, the output will be completely silenced, and the signal in the output is somewhat distorted.

6 Proposed Solutions

The main issue with the output being silenced is that the CV input is becoming far too high (approximately 2.5 volts), which will widely open the diodes and drain the output signal completely to ground.

My solution to this is to connect a voltage divider of 1/2 between the comparator output and the CV input.

Through experimentation, I discovered that using a 30K resistor and a 10K resistor with a variable potentiometer works best for our desired work.

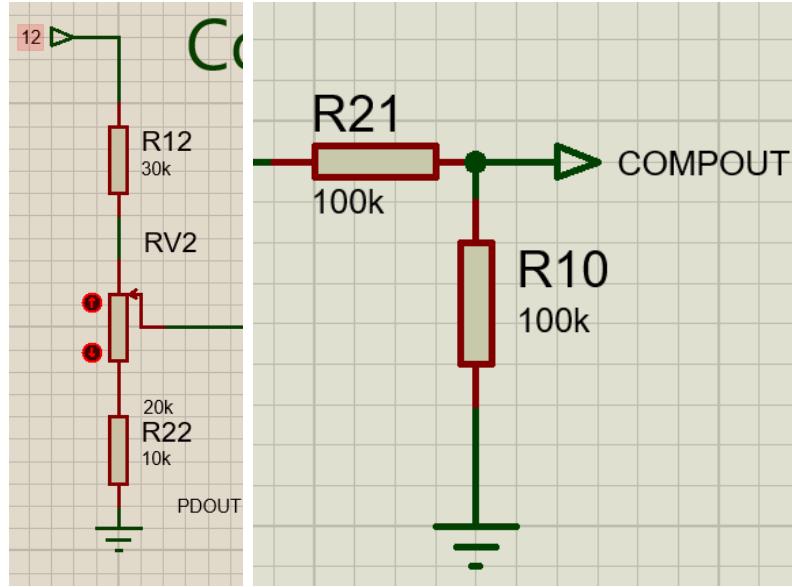


Figure 9: Refined POT and Comparator Output

7 Adding features

7.1 Attack

Definition

Attack is how quickly the system starts reducing volume after a signal exceeds the desired threshold. In other words, it is how much the system should wait before reducing the volume of the input.

Explanation

During the testing and debugging phase of the project and its simulation, I identified a simple and effective method for implementing the attack control. This approach is based on manipulating how quickly the peak detector capacitor responds to the incoming signal peak.

By slowing the charging rate of the capacitor, the peak detector responds more gradually, which automatically reduces how quickly peak information is passed to the comparator. As a result, replacing the fixed resistor between the diode and the capacitor with a variable resistor provides a practical solution for implementing the attack feature. In this design, a 100 k Ω potentiometer was used for this purpose.

7.2 Release

Definition

When the input signal level drops below the threshold, the release time is the amount of time needed for the control system to eliminate gain reduction and return to its nominal condition. It controls how the system recovers after attenuation.

Explanation

The release time is implemented using a simple RC-based approach. The release time constant is defined as $\tau = RC$, where 10 μ F is the fixed value of the capacitor.

The release time is controlled by varying the resistance in the discharge path using a 100 kΩ potentiometer.

To prevent the discharge path from being shorted to ground when the potentiometer is set to its minimum value, a 5 kΩ fixed resistor is placed in series with the potentiometer. This ensures a non-zero minimum resistance and provides safe, stable operation.

As a result, the release time constant is adjustable over a range defined by:

$$\tau \in [5 \text{ k}\Omega \times 10 \mu\text{F}, 105 \text{ k}\Omega \times 10 \mu\text{F}] = [50 \text{ ms}, 1.05 \text{ s}]$$

Schematics After adjustment

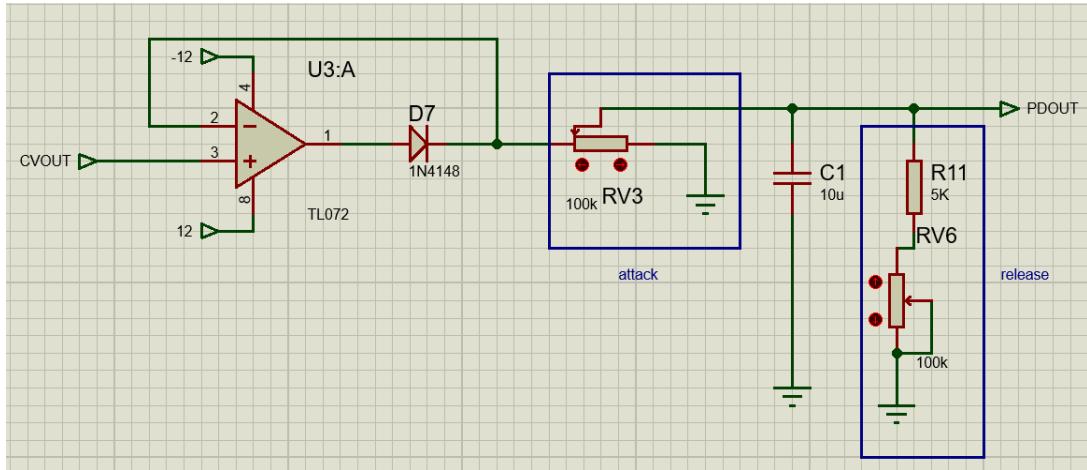


Figure 10: Attack Release

7.3 Ratio

Definition

Compression ratio defines how much the system reduces the output signal level relative to the amount by which the input level exceeds a defined threshold.

Explanation

The ratio determines the relationship between input level exceedance and the resulting gain reduction applied by the system. In the proposed design, the ratio is implemented by scaling the comparator output using a variable voltage divider.

By attenuating the control voltage that drives the gain-control stage, the system adjusts how aggressively gain is reduced once the threshold is exceeded. Higher divider output results in stronger gain reduction (higher ratio), while lower divider output produces gentler compression behavior (lower ratio).

Schematics After Adjustment

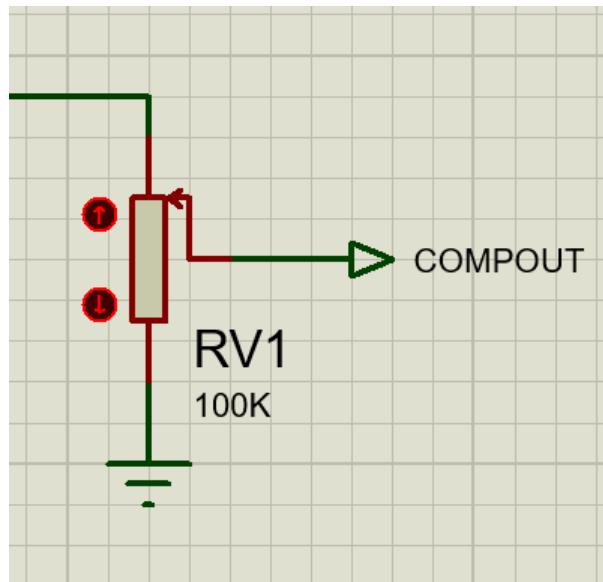


Figure 11: Ratio control circuit after adjustment

7.4 Gain Amplifier

Definition

I wanted to include a feature that may have a gain amplifier in case the input is a bit too quiet. There will be two types: either the output remains unchanged or it is amplified using a variable resistor.

Explanation

Adding a non-inverting amplifier with variable gain and controlling it with a variable resistor in series with a constant one will make the gain application quite simple.

As a result, the gain is only an amplifier and cannot function as an attenuator.

Schematics After Adjustment

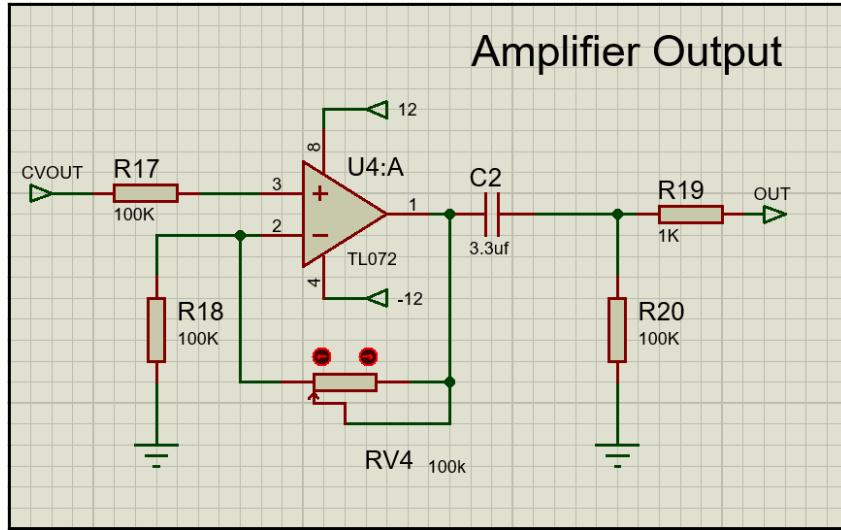


Figure 12: Gain amplifier circuit

8 Design Refinement Additional Features

According to my observations, the existing circuit is usage of a negative threshold to force the signal to zero will not result in smooth attenuation, instead it will appear to be a cutoff point that the user may not be comfortable with.

I also want to add a led indication or an LED-follower for a basic led visualisation on the output, which would be a wonderful addition.

I have also noticed that, given the current state of the project, I have decided to separate the amplifier and LED visulizer blocks as an addition because the system has become unaffordable and those two blocks are not necessary for the core system. Therefore, they will function as a subsystem to the core, and whether or not to obtain them is completely optional

Since our threshold is set at 6 volts, I would add a system that would clamp the input at a maximum of 6 volts, or 12 volts peak to peak, to ensure that the system operates flawlessly and without distortion or damaging the components.

8.1 LED-Follower

Explanation

I utilized a couple of 2N2222 transistors for the LED follower block. Since the peak detector is already operational, we can use it, amplify it and detect the opening and shutting of certain LEDs with a level utilizing potential voltage dividers for each level.

Schematics After adjustment

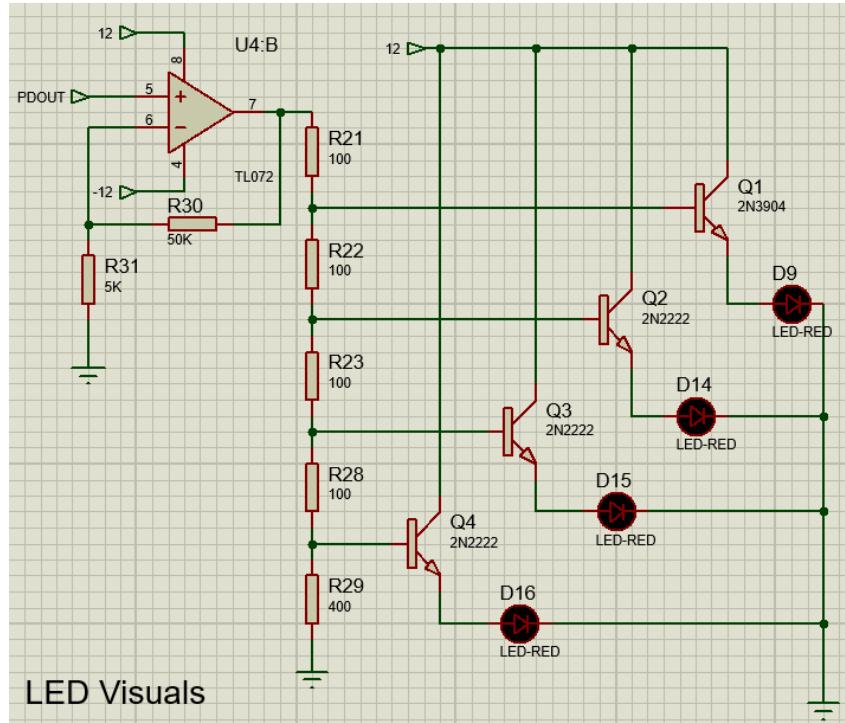


Figure 13: LED-Follower circuit

8.2 Attenuation problem

This is a simple solution. The issue vanished after I replaced the linear potentiometer with a logarithmic one.

8.3 Maximum input

This is a simple solution. Since our threshold is about 6 volts, I will be adding a zener diode clamp to the system's input.

After a brief search, I discovered that a zener diode using two 1N5232B diodes will clamp the input to a maximum of about 6.2 volts, which is acceptable in our situation and should make the input clamped to that voltage and ensure good system functioning.

Schematics After adjustment

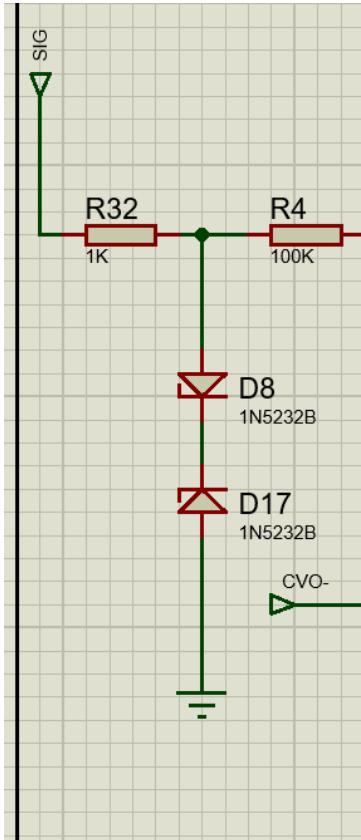


Figure 14: Input Clamping

9 Changing the CAD

Since the CAD program I have been using (PROTEUS or "ISIS") from LabCenter is a paid program, I wanted this project to be open source, accessible to everyone in the community, and available on a free CAD. For this reason, I chose KICAD, the most popular and widely used program.

9.1 Changes

Since this is the final revision to the schematics, a number of changes had to be made before moving on to the layout:

- all inputs are now made to receive an external signal.
- Three connectors for +12, -12 volts for power, and ground
- To ensure that the system is powered on, an indicator LED connected to 12 volts was added.
- Two audio jacks were added, one for input and one for output.
- I added a switch to alternate between amplified output and raw output because our system has optional sub blocks (you can tie the other switch pin to ground if the sub amplifier system is not in use).
- As the LED follower and amplifier inputs are subsystems that are optional to use, there

will be two pinheads that will ensure the connection between them and the system using jumper wires. I attached these pinheads to the peak detector input and CV output pins so they can be used.

- Since our core system has six amplifiers in total, I used one TL074 quad amplifier and one TL072 amplifier instead of three TL072 dual amplifiers, which would have cost money and taken up space. The sub blocks (LED follower and amplifier) that are connected together will be powered by a single TL072 dual amplifier. - Adding two pins for the 12V and -12V for the subsystems standalone.

9.2 Schematics after changes

Control Voltage Block

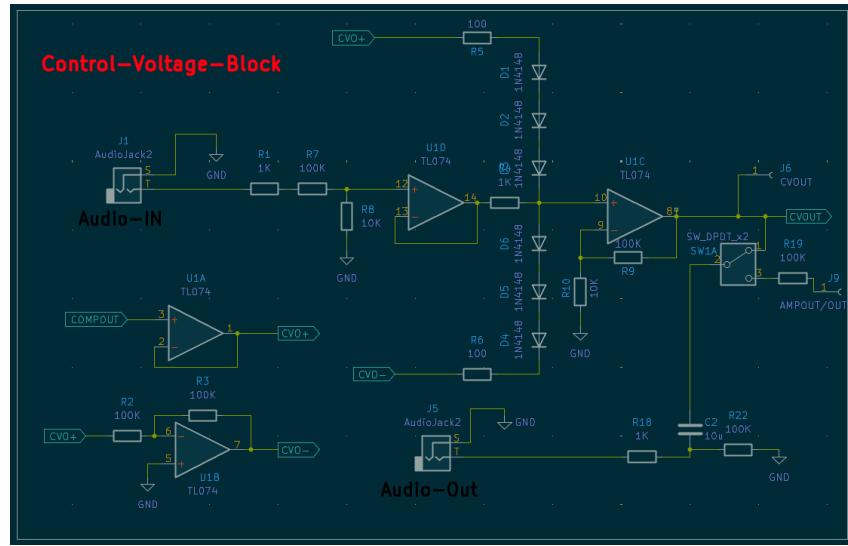


Figure 15: CV with KiCad

Peak Detector Block

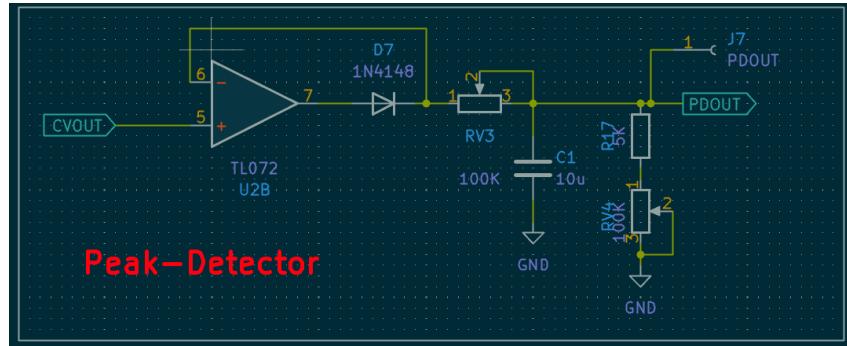


Figure 16: Peak Detector with KiCad

Comparator

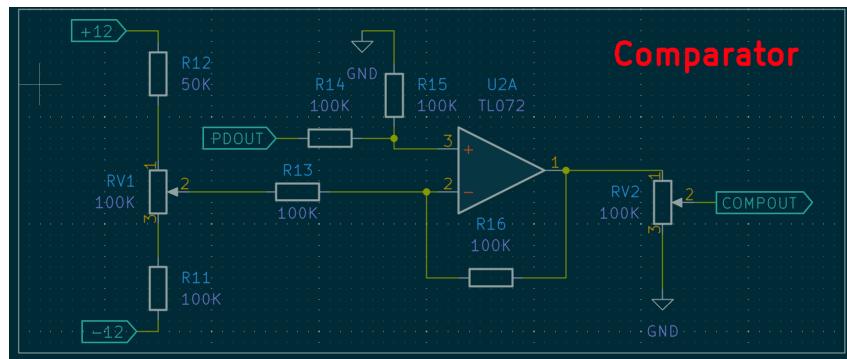


Figure 17: Comparator with KiCad

Power Rails

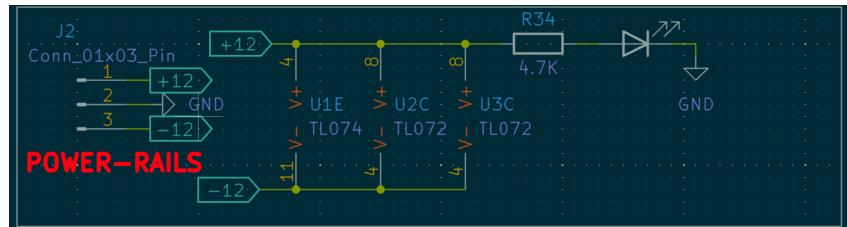


Figure 18: Power Rails with KiCad

Amplifier

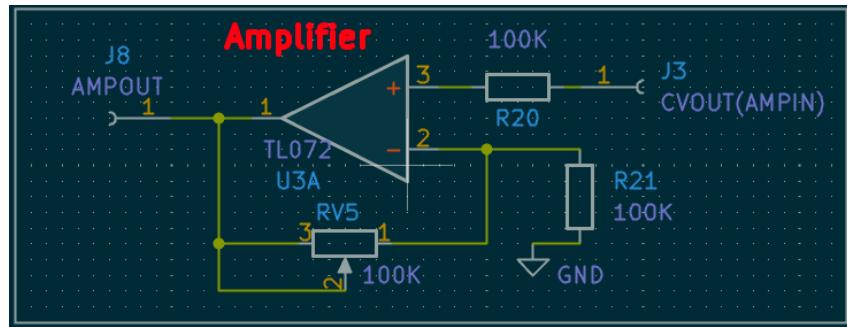


Figure 19: amplifier with KiCad

LED Follower Block

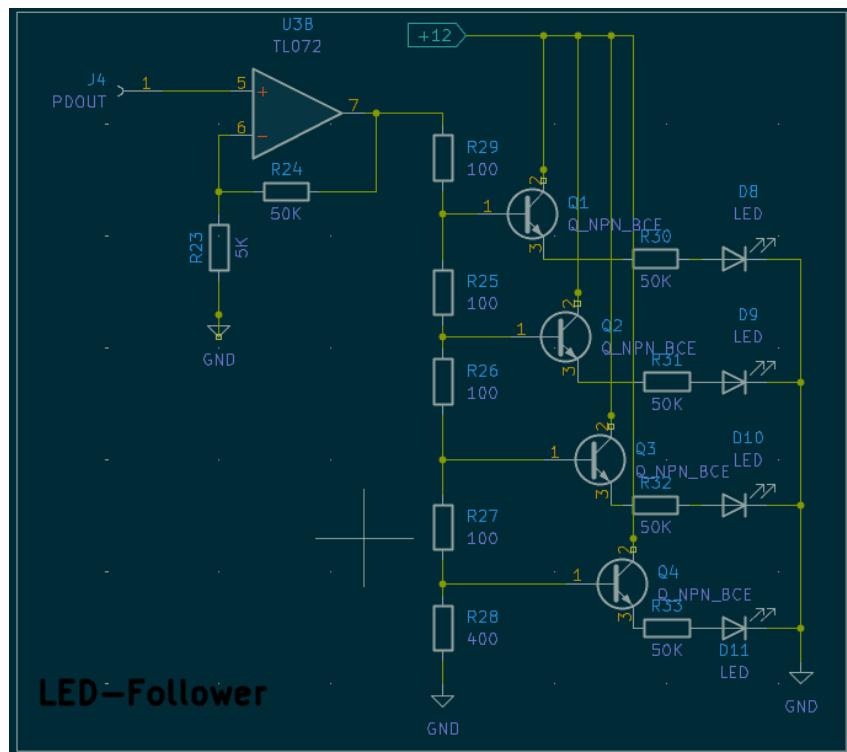


Figure 20: LED Follower Block with KiCad

Full schematics

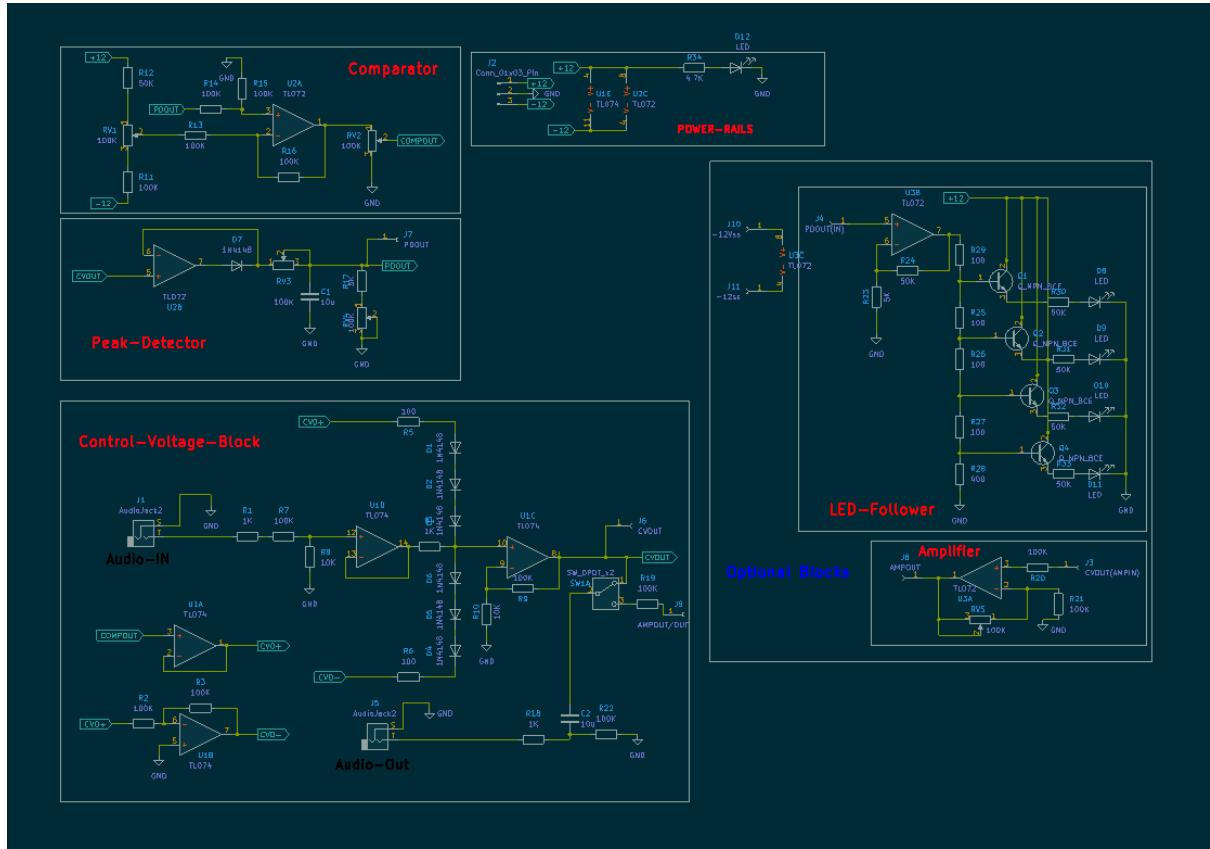


Figure 21: Full schematics with KiCad

10 Preliminary Bill of Materials and Cost Analysis

10.1 Bill of Materials

Reference(s)	Qty	Component Description	Value / Part
C1, C2	2	Electrolytic capacitor	10 μ F
D1–D7	7	Signal diode	1N4148
D8–D12	5	Indicator LED	3 mm LED
J1, J5	2	Mono audio jack (TS)	6.35 mm
J2	1	Power connector	3-pin (+12 V / GND / 12 V)
J3–J11	7	Pin header / test point	1×1
Q1–Q4	4	NPN transistor	General-purpose BJT
R1, R4, R18	3	Resistor	1 k Ω
R2, R3, R7, R9, R11, R13–R16, R19–R22	13	Resistor	100 k Ω
R5, R6, R25–R27, R29	6	Resistor	100 Ω
R8, R10	2	Resistor	10 k Ω
R12, R24	2	Resistor	50 k Ω
R17, R23	2	Resistor	5 k Ω
R28	1	Resistor	400 Ω
R34, R30–R33	3	Resistor (LED limiter)	4.7 k Ω
RV1–RV5	5	Trimmer potentiometer	100 k Ω
SW1	1	Toggle switch	DPDT
U1	1	Operational amplifier	TL074
U2, U3	2	Operational amplifier	TL072

Table 1: Bill of Materials

The bill of materials was generated from the finalized schematic in KiCad. Package footprints and PCB-specific details are omitted, as the BOM represents the schematic-level design prior to PCB layout and routing.

10.2 Cost Analysis

Item	Qty	Unit (USD)	Subtotal (USD) / (TND)
TL074 (quad op-amp)	1	1.31	1.31 / 3.82
TL072 (dual op-amp)	2	1.04	2.08 / 6.05
Trimmer potentiometer Bourns 3386P	5	2.20	11.00 / 32.02
Neutrik NJ2FD-V mono jack (TS)	2	2.05	4.10 / 11.93
Phoenix Contact 3-pos power connector (1836309)	1	1.23	1.23 / 3.58
C&K JS202011CQN DPDT switch	1	0.74	0.74 / 2.15
2N3904 (or similar) NPN transistor	4	0.15	0.60 / 1.75
1N4148 diode	7	0.10	0.70 / 2.04
3 mm LED (indicator)	5	0.40	2.00 / 5.82
10 μ F electrolytic capacitor	2	0.21	0.42 / 1.22
Resistors (axial, $\frac{1}{4}$ W)	34	0.01*	0.34 / 0.99
1×1 pin headers / test pins	7	0.05*	0.35 / 1.02
Estimated total (components only): \$24.87 72.38 TND			

Table 2: Estimated Component Cost Analysis

The cost estimation is based on low-quantity distributor pricing for representative parts. Passive components (resistors, basic headers) are costed using typical bulk pricing. This estimate excludes PCB fabrication, shipping, taxes, and assembly.

IV Power Consumption and Dissipation Analysis

Supply rails The circuit is powered from a symmetric dual supply: $V_+ = +12 \text{ V}$ $V_- = -12 \text{ V}$

Total power drawn from the supply is:

$$P_{\text{TOTAL}} = (12 \cdot I_+) + (12 \cdot I_-)$$

1 Operational amplifier quiescent current (typical)

The TL07x family datasheets specify typical supply current of approximately 1.4 mA per amplifier (no load, $T_A = 25^\circ\text{C}$).

The design includes: TL074 (quad): 4 amplifiers Two TL072 (dual + dual): 4 amplifiers total

Total number of amplifiers:

$$N = 4 + 2 \cdot 2 = 8$$

Total quiescent current for all amplifiers:

$$I_{\text{opamp,T}} \approx N \cdot 1.4 \text{ mA} = 8 \cdot 1.4 \text{ mA} = 11.2 \text{ mA}$$

For a symmetric supply, a reasonable approximation is that quiescent current is split between the rails:

$$I_{\text{opamp},+} \approx I_{\text{opamp},-} \approx \frac{11.2}{2} = 5.6 \text{ mA}$$

2 Indicator LED current and resistor dissipation

Each indicator LED is powered from +12 V with a $4.7 \text{ k}\Omega$ series resistor. Assuming a typical LED forward voltage of $V_f \approx 2.0 \text{ V}$, the LED current when ON is:

$$I_{\text{LED}} = \frac{12 - V_f}{R} = \frac{12 - 2}{4700} = 2.13 \text{ mA}$$

Worst-case LED condition (all 5 LEDs ON simultaneously):

$$I_{\text{LED,total}} = 5 \cdot 2.13 \text{ mA} = 10.65 \text{ mA}$$

Resistor power dissipation per LED:

$$P_R = I^2 \cdot R = (0.00213)^2 \cdot 4700 \approx 0.021 \text{ W}$$

Therefore, standard 0.25 W resistors provide a large safety margin.

3 Rail current estimates

Worst-case (all LEDs ON):

$$I_+ \approx I_{\text{opamp},+} + I_{\text{LED,total}} = 5.6 + 10.65 = 16.25 \text{ mA}$$

4 Total power drawn from the supply

$$P_{\text{TOTAL}} = 12 \cdot (I_+ + I_-) = 12 \cdot (0.01875 + 0.0081) = 12 \cdot 0.02685 = 0.322 \text{ W}$$

5 Conclusion

The circuit is low-power in design. With a typical TL07x quiescent current of ~ 1.4 mA per amplifier and worst-case LED activity, the total power drawn from a ± 12 V supply is around 0.32 W.

The maximum resistor dissipation in LED limit resistors is approximately 0.021 W, which is significantly lower than the standard 0.25 W rating.

As a result, no special thermal measures are required for normal operation, and the chosen component ratings provide adequate margins.

V Layout and Routing

Introduction

The next step in the design process is to physically realize the circuit in the form of a printed circuit board (PCB) after the schematic design has been validated and the preliminary bill of materials, cost estimation, and power consumption analysis have been completed. In order to maintain signal integrity and guarantee dependable operation, this step attempts to convert the logical schematic into a manufacturable layout. Because the circuit is analog and audio-frequency, additional consideration is given to component location, grounding technique, and routing sequence. In order to limit noise coupling and enable controlled placement of sensitive signal pathways, manual routing is preferred over automatic routing. The layout strategy and design considerations used during the PCB creation process are explained in the next section.

1 PCB Design Without Optional Blocks

The system will be divided into a modular architecture because the PCB design incorporates a number of additional functional blocks outside the necessary signal-processing path. Initially, a PCB specifically intended for the core system will be created, with the bare minimum of circuitry needed to ensure proper and comprehensive performance of the primary function. This strategy guarantees that the system's core features are still accessible and working regardless of the auxiliary blocks. Users are therefore not needed to install or buy the entire system if they do not need all the features. Thus, the LED follower stage and the extra amplification block, which might be added later as optional extensions, will not be included in the initial PCB designing phase, which will only concentrate on the core circuit. Throughout the PCB, a filled ground plane served as a common reference. To make trace placement easier, routing was done on both the top and bottom levels. The other signal traces were routed with a conventional width of 0.2 mm, whereas power traces for the ± 12 V supply were routed with a width of 0.5 mm. For better accessibility and organization, the audio input and output connectors were positioned on opposite sides of the board, and the potentiometers were grouped together. Dedicated SMD test point pads were added for the +12 V, 12 V, CVOUT, and COMPOUT nodes to allow easier debugging and measurement if required.

1.1 Full board

The entire PCB layout of the core system is shown in the following figure. The final component placement and routing technique used for the design, including the arrangement of functional blocks, power distribution, and grounding approach, are shown in this picture.

The design preserves a clear and organized signal flow appropriate for dependable operation while reflecting the mechanical limitations imposed by user-interface elements like potentiometers and audio connectors.

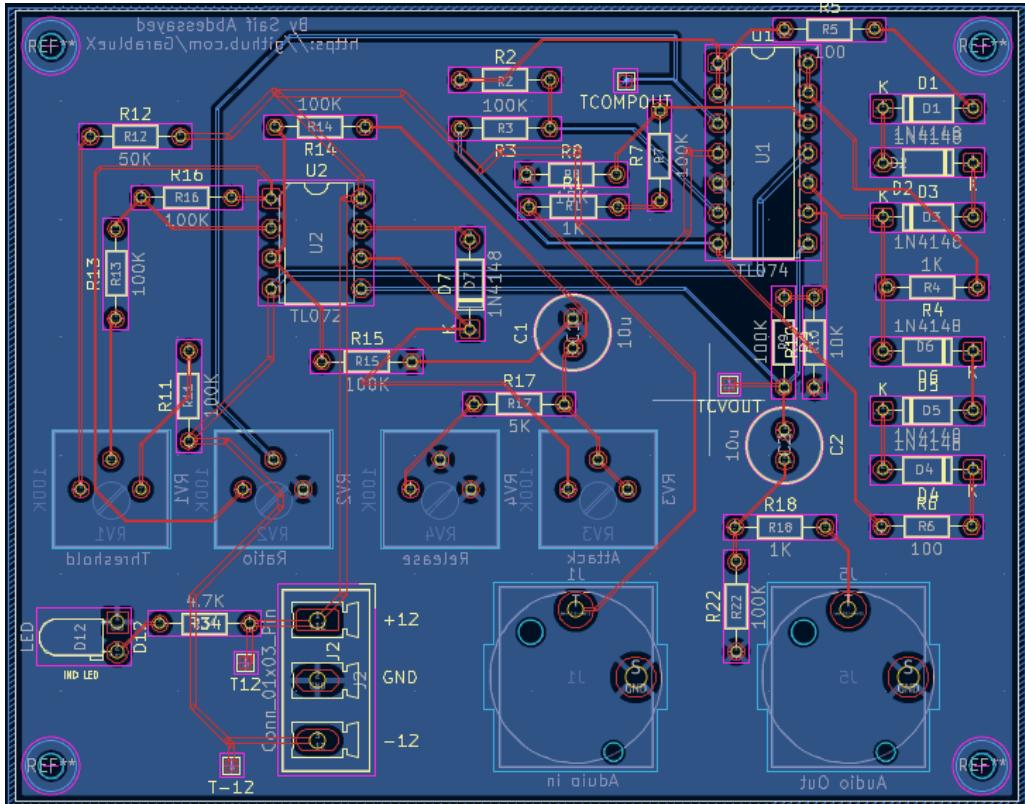


Figure 22: Full Layout

1.2 Top copper

Signal and power routing were the primary uses of the top copper layer. In order to improve reliability and reduce noise, the ± 12 V supply rails were routed utilizing wider trace widths, while critical analog routes and op-amp feedback connections were kept short and direct.

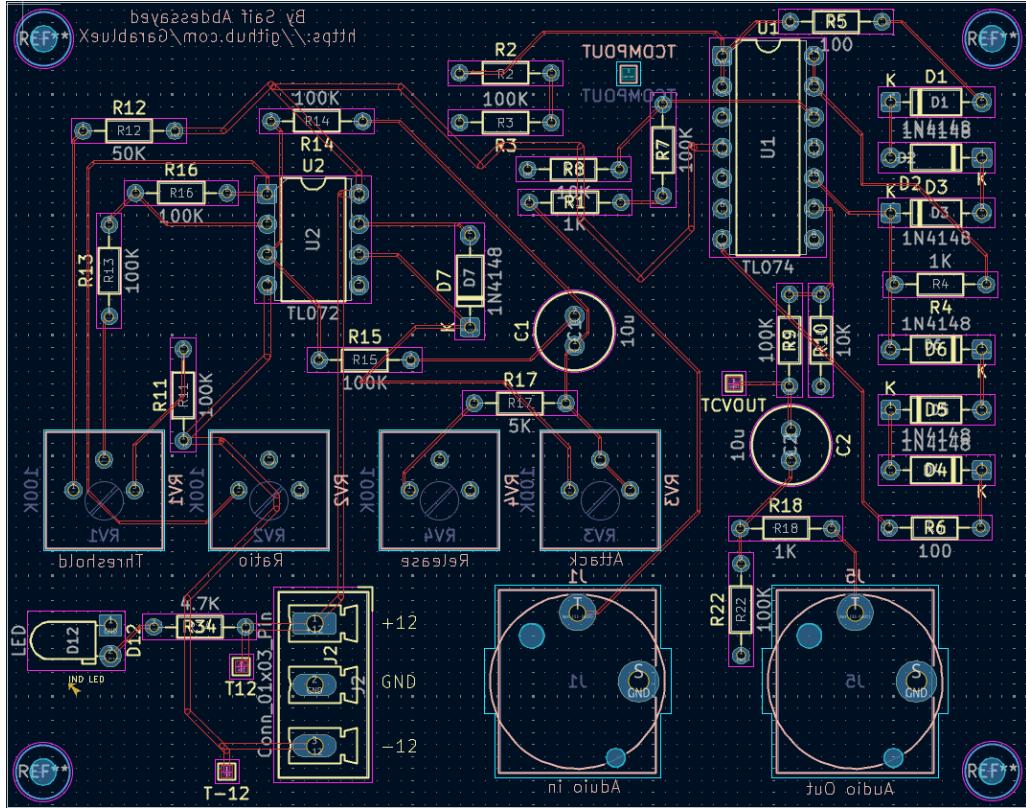


Figure 23: Top copper

1.3 Bottom Copper

The bottom copper layer was mainly used as a ground plane that was continuous throughout the PCB. For all circuit blocks, this ground plane offers a low-impedance common reference that enhances signal integrity and lowers noise coupling — two factors that are crucial for analog and audio-frequency signals. To maintain the continuity of the ground plane, very little routing was done on the bottom layer only necessary interconnections and vias. Thermal reliefs are used to preserve efficient ground connectivity while ensuring dependable soldering of through hole components.

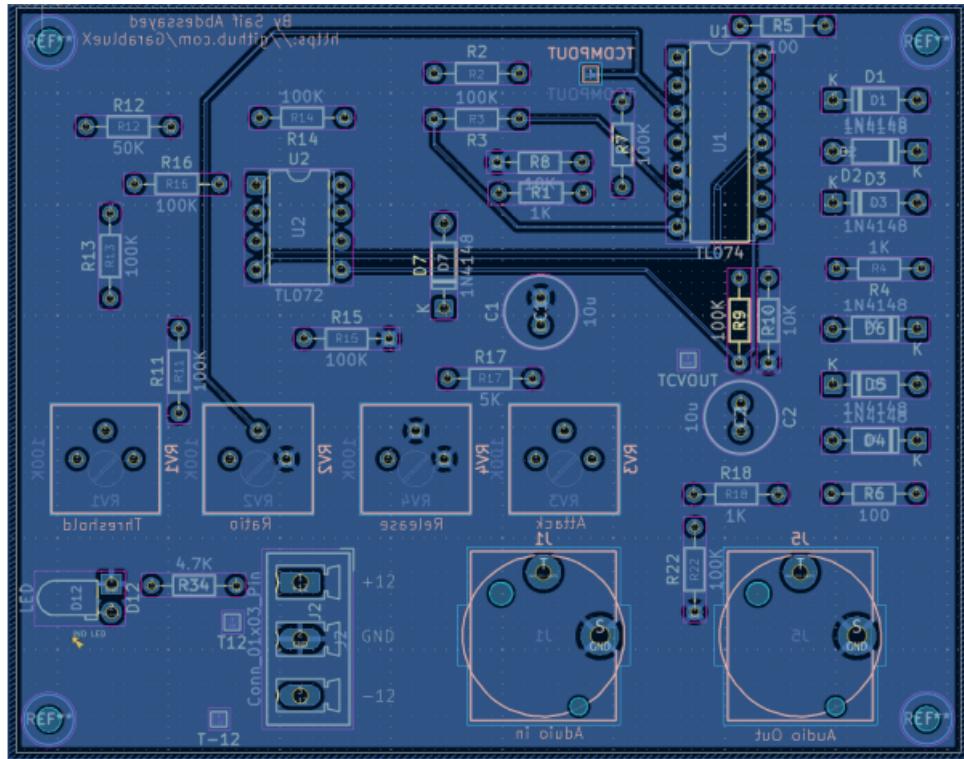


Figure 24: Bottom Copper

1.4 3D View

A three-dimensional (3D) view of the PCB was generated to verify the mechanical integrity of the design and to validate component placement prior to fabrication. This view allows visual inspection of component heights, connector alignment, and overall board geometry, ensuring that all mechanical elements fit within the board outline without interference. The 3D representation also confirms the accessibility of user-interface components such as potentiometers, audio connectors, and switches, providing confidence that the PCB can be assembled and integrated into its intended enclosure.

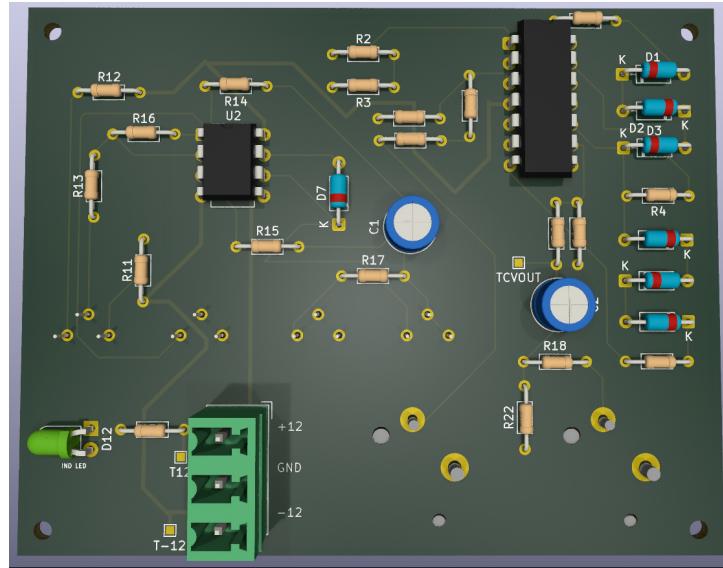


Figure 25: Back Face

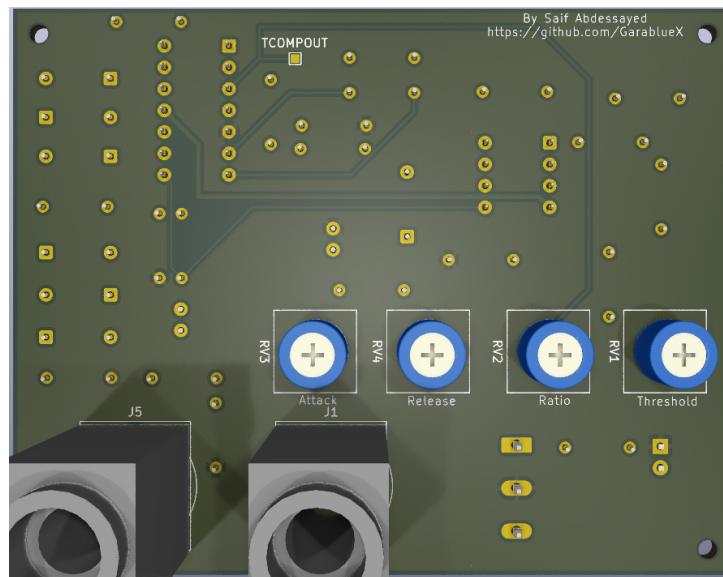


Figure 26: Front Face

2. PCB Design With Optional Blocks

A second plan iteration was created that incorporates the optional functional blocks, such as the LED follower stage and the extra amplification circuitry, in addition to the core system PCB. This expanded version increases the system's capabilities while maintaining the same grounding technique, routing principles, and mechanical limits as the basic design. The placement of the optional blocks reduces interference with the core signal channel and makes it possible to distinguish between auxiliary characteristics and critical processing steps. The system can be utilized in its most basic configuration or with more capability based on the needs of the application thanks to this modular approach's flexibility in implementation.

2.1 Full board

The full board layout is shown in this section, highlighting the overall placement of components, routing organization, and board geometry. This view provides a complete overview of the physical realization of the system

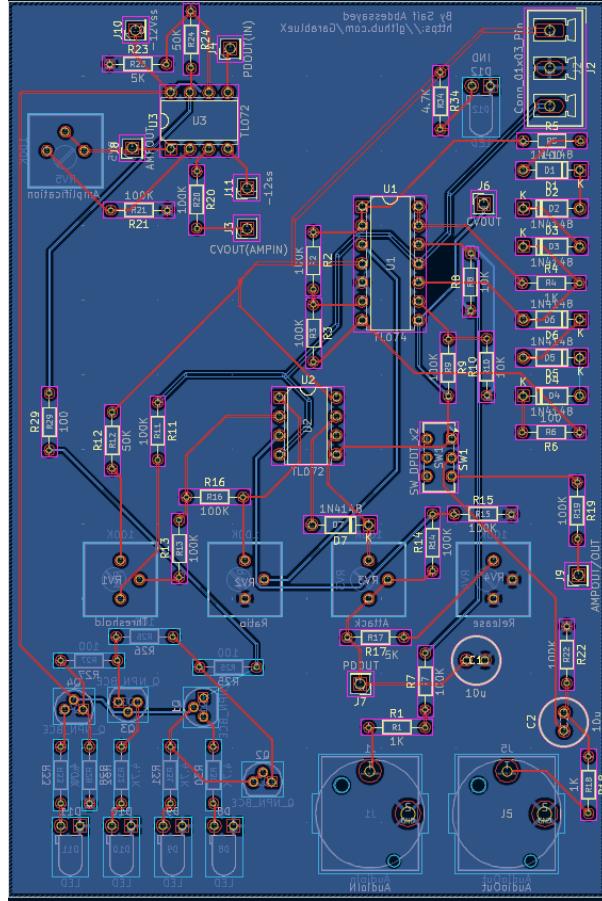


Figure 27: Full Layout

2.2 Top copper

The top copper layer was used primarily for routing signal and power traces. Critical analog paths and feedback loops were kept short and direct, while the ± 12 V supply rails were routed with wider traces to ensure reliable power distribution.

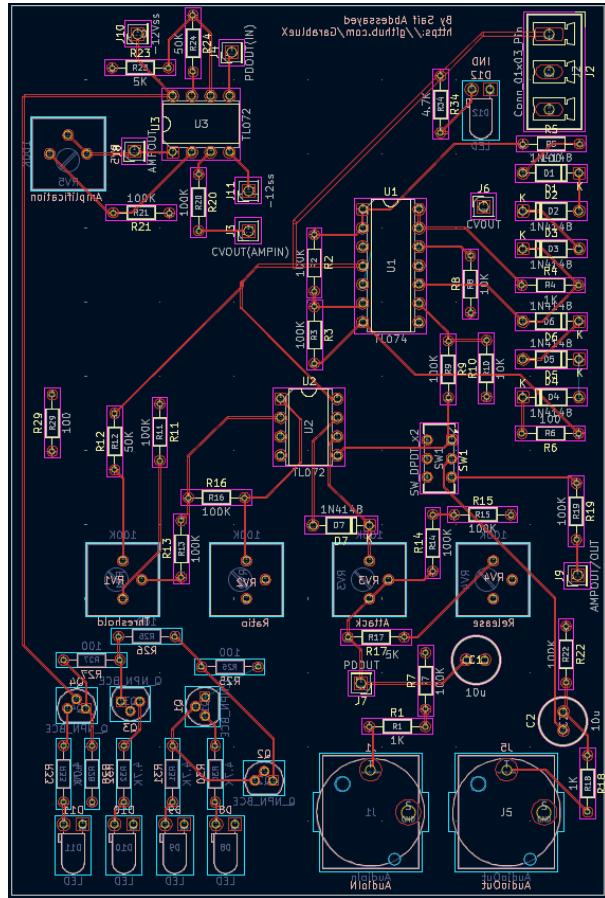


Figure 28: Top Copper Full

2.3 Bottom copper

The top copper layer contains the main signal and power routing of the PCB. Critical analog paths were kept short and direct, and the ± 12 V power rails were routed with increased trace widths to ensure reliable operation.

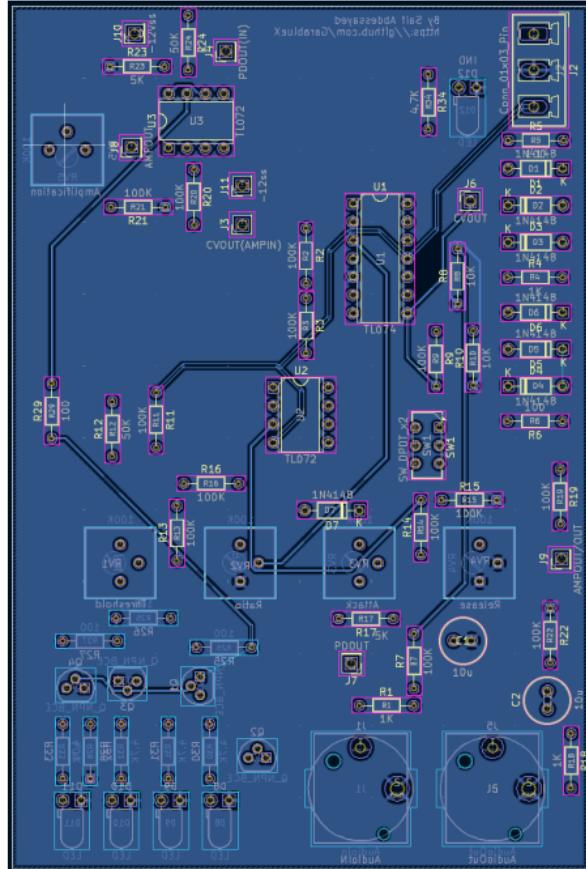


Figure 29: Bottom Copper Full

2.4 3D View

A three-dimensional (3D) view of the PCB was generated to verify the mechanical integrity of the design and to validate component placement prior to fabrication.

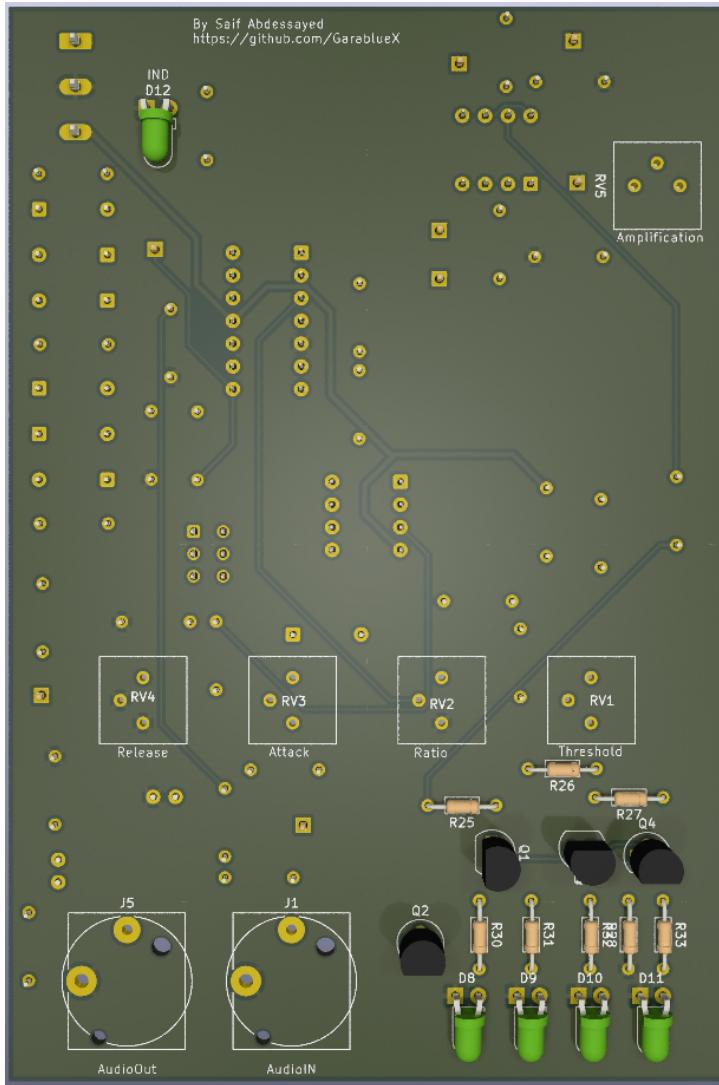


Figure 30: Back Face Full

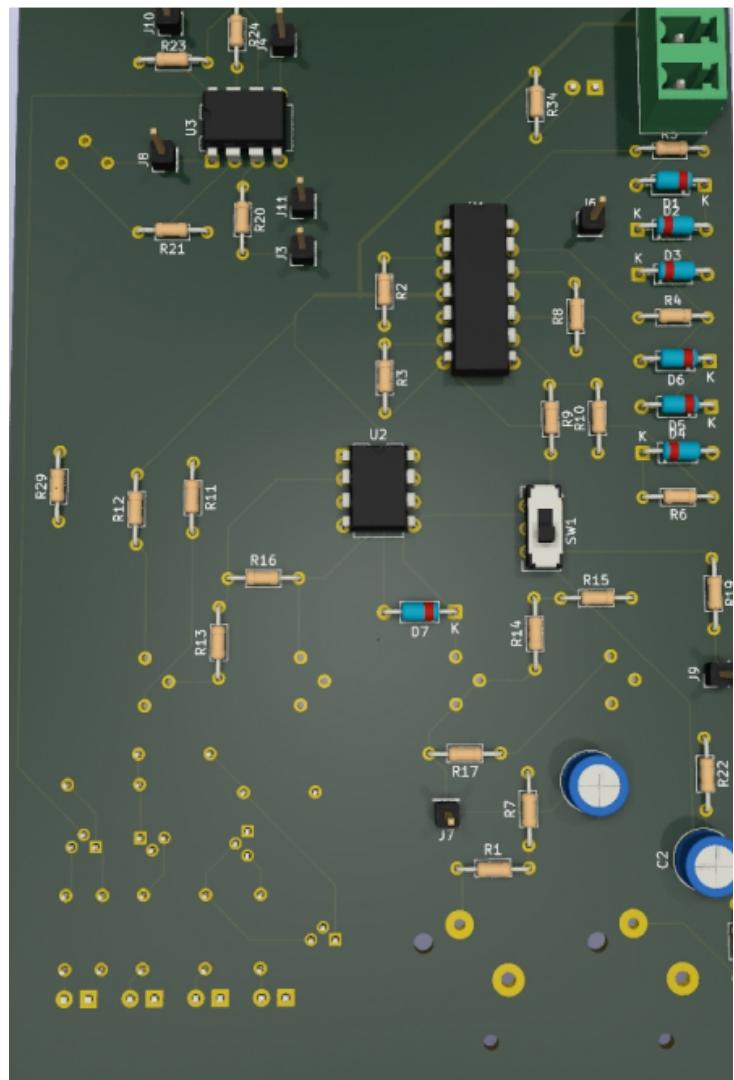


Figure 31: Front Face Full

VI Conclusion

The design and implementation of an analog system, from schematic conception to full PCB layout, was successfully accomplished in this project. After the circuit schematic validation, component selection, cost estimation, and power consumption analysis were conducted. To guarantee dependable performance of the analog circuitry, a structured PCB layout was subsequently created using KiCad, paying close attention to component arrangement, routing strategy, and grounding.

By dividing the core system from optional functional blocks, a modular design approach was used, which reduced needless complexity for users who only needed the fundamental functionality and allowed for implementation flexibility. A strong ground plane, suitable trace widths for power and signal routing, and specific test spots to aid in debugging and validation are all included in the final PCB design.

Overall, the project resulted in a full, manufacturable PCB design that fits the initial functional requirements and can be directly produced or further expanded. Physical prototyping, experimental validation, and enclosure integration are possible future projects.

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