Luka Pkhaladze and Luka Balanchivadze

Senior Project

Analog-Digital Modular Synthesizer

Contents

List of Tables, Graphs, Formulas, and Figures

Annotation

This senior project focuses on the design and development of an **Analog–Digital Modular Synthesizer** that integrates traditional analog sound synthesis techniques with modern digital control and user interfaces. The system is composed of several key analog modules, including **three Voltage-Controlled Oscillators (VCOs)**, **two Mixers**, a **Voltage-Controlled Filter (VCF)**, an **Envelope Generator**, a **Voltage-Controlled Amplifier (VCA)**, and a **Wavefolder**. Each module is designed using discrete analog circuitry to preserve the characteristic warmth and expressiveness of analog sound. The modular design allows the user to freely interconnect components through **3.5 mm patch jacks**, offering a flexible and experimental environment for sound creation and manipulation.

In addition to the analog synthesis section, the project incorporates advanced digital components that expand the system's functionality and control precision. A **two-octave piano keyboard**, implemented using an **ESP32 microcontroller**, serves as the main control interface for pitch and note triggering. The ESP32 generates **control voltage (CV)** and **gate signals** to interface with the analog modules, providing stable and programmable digital control over analog sound sources.

A **Raspberry Pi 4** equipped with a **7-inch touchscreen display** functions as an interactive **drum pad and looper station**. This subsystem enables users to trigger percussive sounds, record short loops, and layer rhythmic sequences in synchronization with the analog synthesizer. The drum pad interface provides real-time visual feedback and allows intuitive interaction, bridging tactile and digital performance elements.

The project's hybrid approach highlights the synergy between analog and digital technologies in modern music systems. The analog section delivers continuous, organic sound shaping, while the digital section offers precision control, versatility, and user-friendly interaction. Together, they form a modular platform for **experimental sound design, electronic music production, and research in audio electronics**.

This work demonstrates the integration of **analog circuit design**, **digital signal control**, and **embedded systems programming**, showcasing a comprehensive understanding of both hardware and software aspects of electronic musical instrument development. The result is a versatile synthesizer that embodies the creativity, technical knowledge, and engineering precision required in contemporary sound technology.

Introduction

In recent years, the fusion of analog and digital technologies has significantly advanced the field of electronic music, enabling musicians and producers to create complex, customizable sounds with both warmth and precision. Modular synthesizers, which allow flexible interconnection of sound-generating and processing modules, have become increasingly popular due to their versatility and hands-on control. The project presented here focuses on the design and development of an **Analog–Digital Modular Synthesizer**, integrating both traditional analog synthesis components and modern digital interfaces to create a highly interactive musical instrument.

The motivation behind this project stems from a desire to explore the intersection of analog sound design and digital control while providing a functional platform for experimentation and music creation. Existing synthesizers often require expensive commercial solutions or offer limited customization, which can restrict creative possibilities for musicians, students, and hobbyists. This project aims to provide a modular, hybrid system with three **Voltage-Controlled Oscillators (VCOs)**, two **Mixers**, a **Voltage-Controlled Filter (VCF)**, an **Envelope Generator**, a **Voltage-Controlled Amplifier (VCA)**, and a **Wavefolder**, along with a two-octave **ESP32-based piano keyboard** and a **Raspberry Pi 4 touchscreen interface** for drum pads and looping functionality.

The novelty of this project lies in its hybrid architecture, which combines the warmth and expressiveness of analog circuits with the precision, programmability, and user-friendly interaction of digital components. The synthesizer enables flexible routing of audio and control signals via patchable jacks while providing real-time digital interfaces for performance, sequencing, and rhythm creation. In addition, it addresses challenges related to signal synchronization, control voltage generation, and integration between microcontrollers and analog modules, demonstrating a comprehensive understanding of both electronic circuits and embedded systems.

The primary goal of this project is to create a **fully functional hybrid synthesizer** capable of supporting a wide range of musical experimentation, from sound design to performance. By combining analog circuitry, digital control, and interactive interfaces, the project offers a versatile platform for musicians, educators, and hobbyists. Moreover, it highlights the potential of modular systems to bridge traditional analog synthesis with modern digital innovation, providing an accessible, cost-effective, and expandable solution for creative sound production.

Problem Definition and Methodology

Research Conducted in Connection with the Topic of the Project

In recent years, the integration of analog and digital technologies in electronic musical instruments has transformed the landscape of music production, performance, and sound design. Modular synthesizers, in particular, have gained attention due to their flexible architecture, which allows users to interconnect individual modules for sound generation, processing, and modulation. This section provides the necessary background to understand the purpose, relevance, theoretical, and practical value of this project, highlighting key aspects of the field and summarizing the research conducted in connection with the project topic.

Technologies in the Field and Market Overview: Analog synthesizers remain highly valued for their characteristic warmth and expressiveness, while digital systems offer precision, programmability, and extended control capabilities. In recent years, hybrid synthesizers combining analog and digital components have become increasingly popular, enabling musicians to exploit the advantages of both worlds. The market for modular synthesizers is growing steadily, with commercial systems ranging from high-end professional units to affordable DIY kits. However, high costs, limited modular flexibility, and complex digital integration continue to restrict access for students, hobbyists, and emerging musicians.

Advancements in microcontrollers, embedded systems, and digital interfaces have made it possible to integrate features such as programmable keyboards, drum pads, sequencers, and loopers into analog systems. These technologies allow real-time interaction, performance recording, and expanded sound design capabilities, making hybrid modular systems more versatile and user-friendly.

Challenges in the Field: Despite technological progress, several challenges remain. Analog modules require careful calibration and synchronization, while digital interfaces must communicate reliably with analog circuits for seamless operation. Modular systems often involve complex signal routing, control voltage management, and timing synchronization, which can complicate design and increase costs. In addition, integrating multiple modules with varying voltage and signal requirements demands careful planning to maintain stability and sound quality.

Development Prospects in the Field: The future of modular synthesizers lies in hybridization and digital augmentation. By combining analog circuitry with microcontroller-based control and touchscreen interfaces, it is possible to create highly flexible instruments that are accessible, affordable, and performance-ready. Educational applications, experimental sound research, and home studio production represent areas of particular relevance for such systems.

Task Definition: The project aims to develop a hybrid analog–digital modular synthesizer capable of real-time sound synthesis, sequencing, and interactive performance. The system integrates three VCOs, two Mixers, a VCF, an Envelope Generator, a VCA, a Wavefolder, an ESP32-based piano keyboard, and a Raspberry Pi 4 touchscreen drum pad with looper. The

synthesizer enables flexible patching, sequencing, and digital control while preserving the analog character of the sound.

Innovative Aspects of the Project:

- **New and Innovative Idea:** The project combines analog warmth with digital precision and interactive performance features, creating a versatile hybrid modular synthesizer.
- **Innovative Problem-Solving:** By integrating affordable microcontrollers and touch interfaces, the project addresses common accessibility and usability issues in modular systems.
- **Process Optimization:** The project optimizes signal routing, control voltage management, and real-time digital interaction to ensure seamless operation between analog and digital modules.

Technical Task of the Project: The technical objectives of this project include:

- Designing and assembling functional analog modules for sound generation and processing.
- Implementing digital interfaces for keyboard control, drum pads, and looping.
- Ensuring reliable communication and synchronization between analog and digital components.

Material and Technical Tools Needed: The project will utilize the following components:

- ESP32 microcontroller for keyboard control and digital interfacing.
- Raspberry Pi 4 with touchscreen for drum pad and looper functionality.
- Discrete analog components for VCOs, VCF, VCA, envelope generators, mixers, and wavefolders.
- Patchable 3.5 mm jacks for modular interconnections.
- Sequencer module and related software for performance control.

Need/Relevance of the Project: With increasing interest in experimental music, home studios, and electronic sound design, there is a need for affordable, flexible, and interactive modular synthesizers. This project addresses that gap by providing a hybrid analog–digital system suitable for both performance and research applications.

Potential Commercialization of the Project: The hybrid modular synthesizer developed in this project could find applications in music education, experimental sound research, independent music production, and hobbyist communities. Its affordability, expandability, and versatility make it a potential product for emerging musicians, home studios, and educational institutions seeking an interactive platform for sound exploration.

Technical Side of the Project
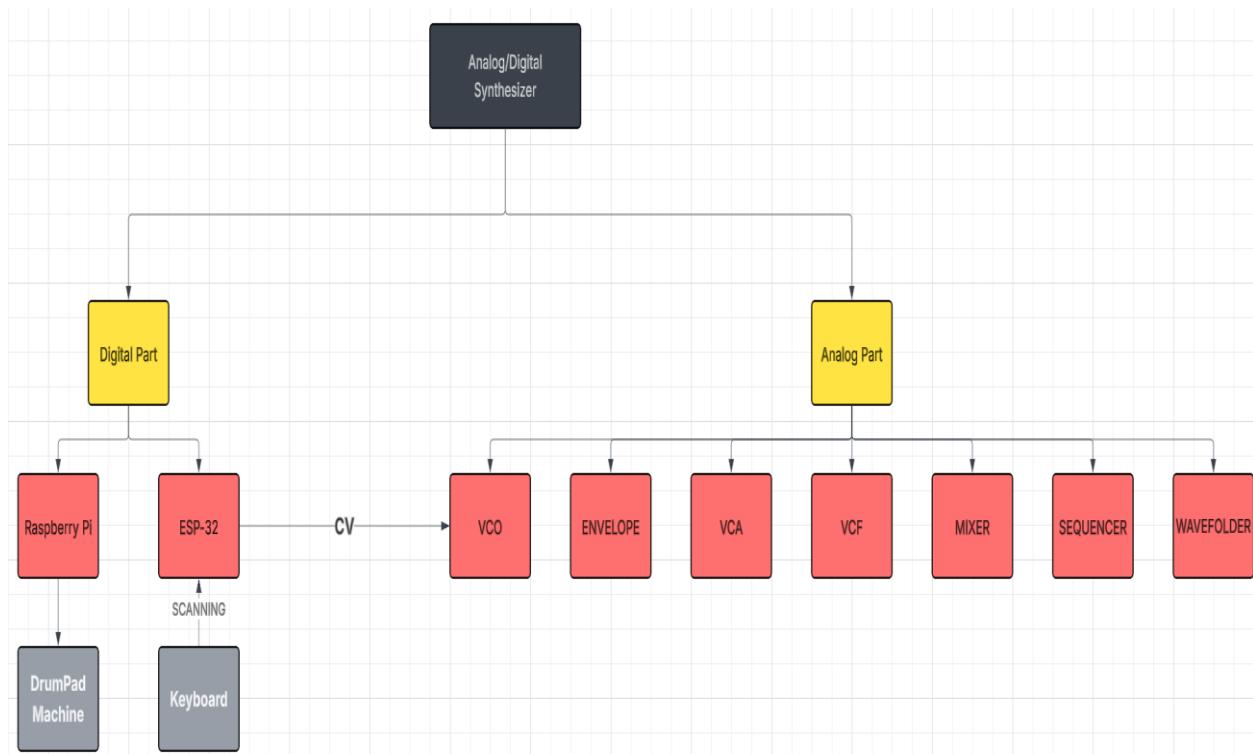
This section outlines the comprehensive technical aspects of the **Analog–Digital Modular Synthesizer** project, detailing the methodologies employed, analyses conducted, visual representations, hardware and software components, challenges encountered, and the solutions implemented. Each stage of the project is described to provide clarity on the technical tasks and their execution.

Our project consists of two main components. The first component focuses on the **design, construction, and testing of the analog modules**, including VCOs, VCF, VCA, Envelope Generator, Mixers, and Wavefolder. This involves circuit design, module assembly, signal calibration, and performance evaluation to ensure accurate sound generation and modulation capabilities.

The second component involves the **digital interfaces and control systems**, including the ESP32-based two-octave piano keyboard and the Raspberry Pi 4 touchscreen drum pad with looper. This part covers key scanning, control voltage (CV) and sequencing, loop recording, and real-time digital interaction with the analog modules.

Finally, the integration of these two components involves **synchronizing digital controls with analog modules**, establishing seamless communication, and creating a fully functional hybrid system. This step also focuses on optimizing patchable signal routing, module interconnection, and ensuring real-time responsiveness during live performance and experimentation.

Picture 1: Block Diagram

Voltage-Controlled Oscillator (VCO)

A **Voltage-Controlled Oscillator (VCO)** is a fundamental component in analog and modular synthesizers, responsible for generating periodic waveforms whose **frequency can be controlled by an input voltage**. VCOs serve as the primary sound source in most analog synthesis systems, producing audio signals that can be shaped, modulated, and combined with other modules to create complex sounds.

Working Principle: The output frequency of a VCO is directly proportional to the control voltage applied to its input. Increasing the control voltage typically increases the oscillation frequency, while decreasing it lowers the frequency. This property allows musicians to control pitch dynamically using keyboards, sequencers, or other modulation sources.

Exponential Voltage-to-Frequency Conversion: In analog synthesizers, musical pitch is logarithmic: **each octave doubles the frequency** of the previous one. To achieve correct musical intervals, the VCO uses an **exponential relationship** between control voltage (CV) and frequency.
- 1 Volt per Octave Standard (1V/Oct): Each increase of 1 volt in control voltage doubles the oscillator frequency, raising the pitch by one octave.
- Mathematical Relationship:
$$f_{out} = f_{base} \cdot 2^{V_{in}}$$

Where f_{out} is the VCO output frequency, f_{base} is the base frequency at 0V input, and V_{in} is the control voltage in volts.

This ensures that **equal voltage steps correspond to equal musical intervals**, enabling keyboards and sequencers to produce accurate notes across octaves. Exponential conversion also ensures coherent detuning and modulation when using multiple VCOs.

Waveforms Produced: VCOs can generate various standard waveforms, each with distinct timbral characteristics:
- **Sawtooth Wave:** Rich in harmonics, bright and buzzy.
- **Square Wave:** Hollow, woody sound suitable for leads or pulse-width modulation.

Applications in Modular Synthesizers
- **Primary Sound Source:** Provides raw audio signals for synthesis.
- **Modulation Source:** Can function as a low-frequency oscillator (LFO) to modulate other modules like VCF or VCA.
- **Sequencing and Control:** Converts control voltages from keyboards or sequencers into musical notes.
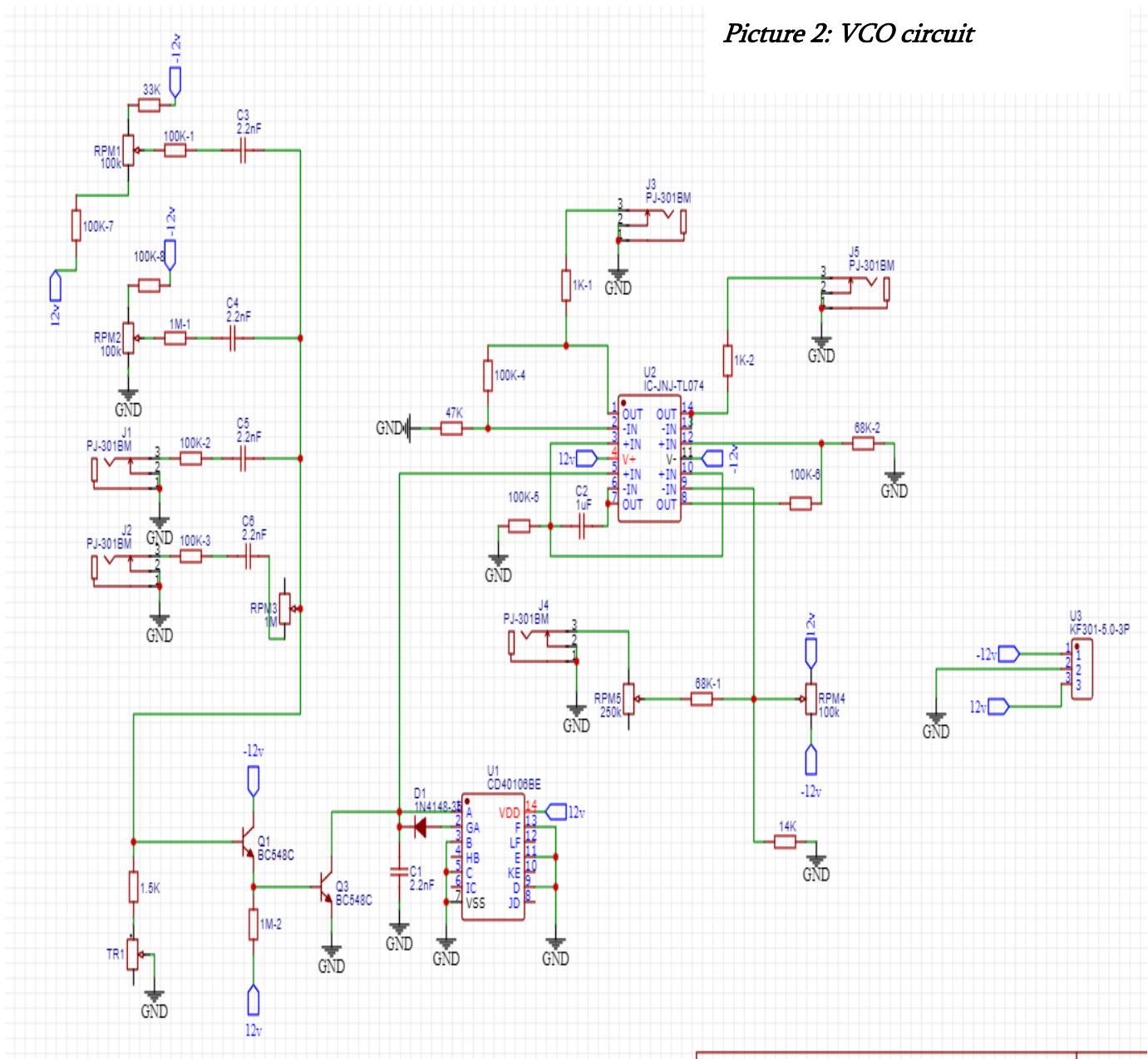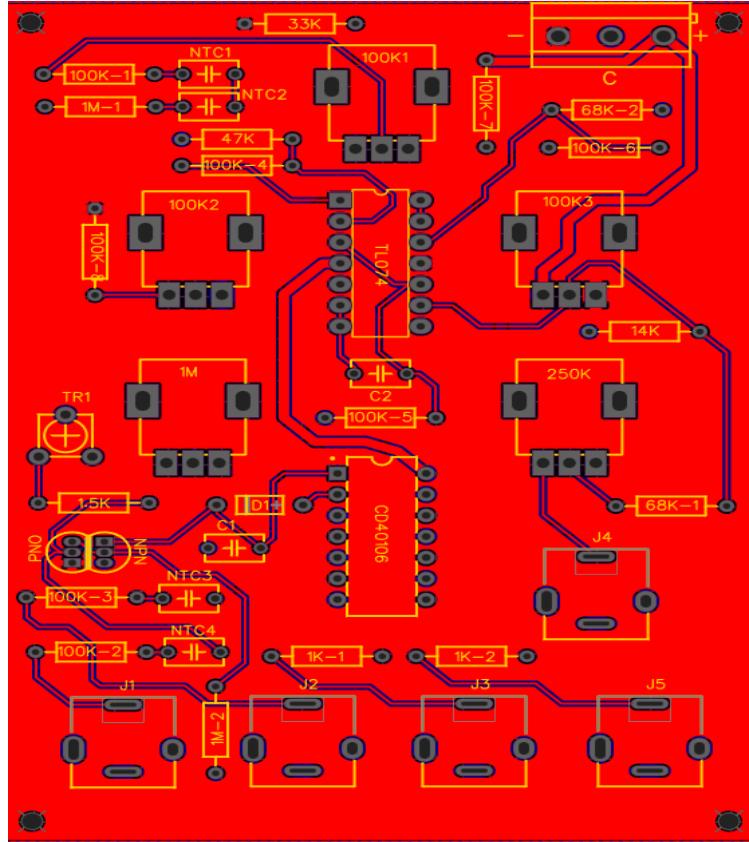
Key Parameters
- **Frequency Range:** Defines the pitch limits of the VCO.

- **Control Voltage Sensitivity:** Determines frequency response to voltage changes.
- **Waveform Selection:** Chooses or blends output waveforms.
- **Pulse Width:** Adjusts harmonics in square/pulse waves.

In our modular synthesizer, the three VCOs act as the **primary tone generators**, producing the raw signals that will be shaped by mixers, filters, envelopes, and other modules. Exponential conversion ensures **accurate pitch scaling**, enabling layering, detuning, and modulation while maintaining musical harmony and responsiveness to the ESP32-based keyboard and sequencer.

Picture 2: VCO circuit

Picture 3: VCO PCB

Linear Mixer Module

A **Linear Mixer** is a core component in modular synthesizers, designed to **combine multiple audio or control voltage (CV) signals** while preserving their linear amplitude relationships. In your project, the mixer features **three input channels**, each with an independent **level control**, and **three output options**: standard, clipped, and inverted.

Working Principle: The mixer sums the input signals linearly according to the **individual level controls**. This allows precise adjustment of the contribution of each source, such as multiple VCOs, external signals, or modulation sources. The **linear summing** ensures that the combined output maintains the proportional amplitudes of all inputs without distortion, unless the clipped output is used intentionally.

Input and Output Configuration
- **Inputs:**
  - **Input 1, 2, 3:** Each input has its own level knob to control the amplitude of the signal being mixed.
- **Outputs:**
  - **Standard Output:** Linearly summed signal, preserving the combined amplitude of all inputs.
  - **Clipped Output:** The output signal is intentionally limited or clipped, introducing mild harmonic distortion or saturation for creative sound design.

        o   **Inverted Output:** Produces a phase-inverted version of the mixed signal, useful for phase cancellation, stereo effects, or modulation routing.

Applications in Modular Synthesizers
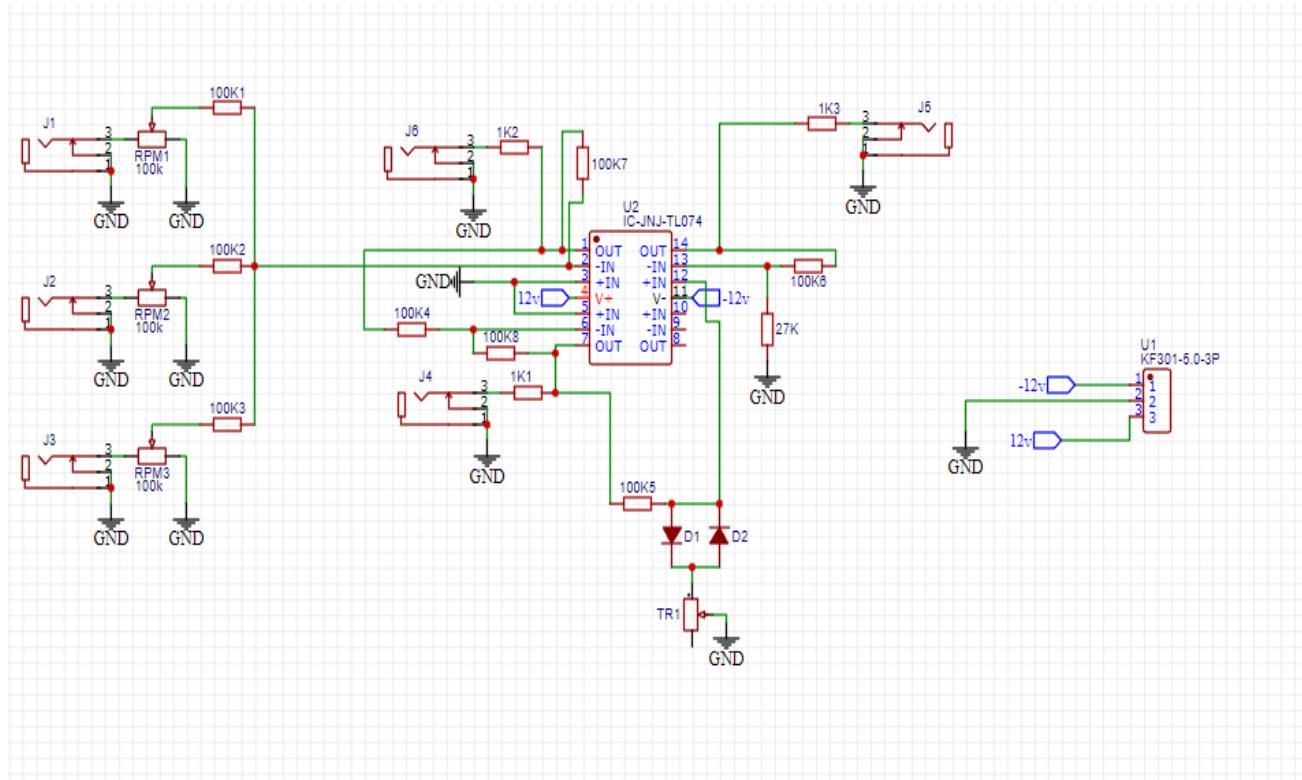
- **Audio Layering:** Combines signals from multiple VCOs or sound sources to create complex textures.
- **Control Voltage Mixing:** Blends modulation signals such as LFOs or envelope outputs for dynamic parameter control.
- **Sound Design Flexibility:** The multiple outputs (standard, clipped, inverted) provide additional sonic options for experimentation and routing to other modules like VCF, VCA, or effects.
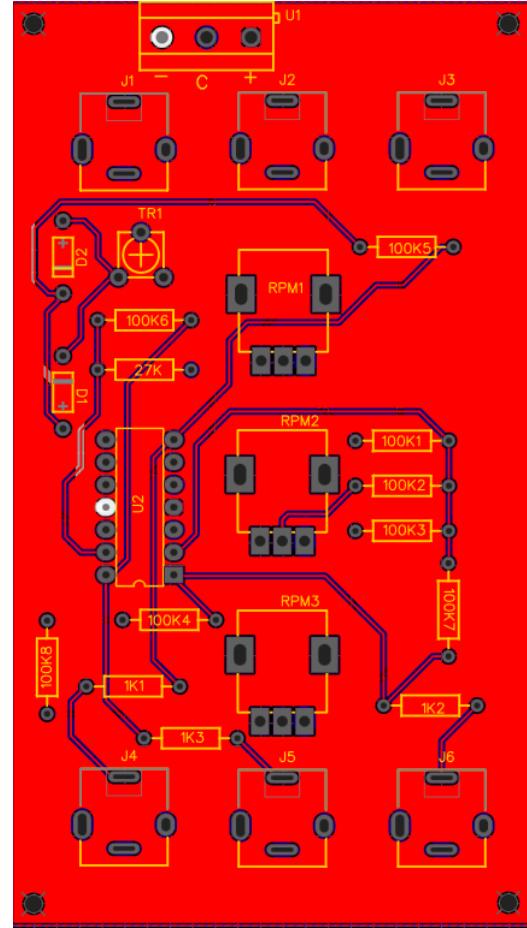
Key Parameters

- **Input Level Controls:** Adjust the contribution of each input to the mixed output.
- **Output Type Selection:** Standard, clipped, or inverted, each offering distinct sonic characteristics.
- **Linearity:** Maintains proportional amplitude relationships between inputs in standard output.

In our modular synthesizer, the **3-input linear mixer** is central to **signal routing and tonal shaping**. By combining three VCO signals or other sources and providing multiple output options, it allows **layered, harmonically rich sounds** and expands the creative possibilities of the system. The clip and inverted outputs enable additional **sound design techniques**, such as harmonic saturation, phase manipulation, and modulation experimentation, enhancing the expressiveness of your synthesizer.

Picture 4: MIXER circuit

Picture 5: MIXER PCB

Sequencer Module

A **sequencer** is a module in modular synthesizers that generates **control voltages (CV) and gate signals in a stepwise sequence**, allowing for rhythmic, melodic, or modulation patterns. In your project, the sequencer is a **5-step unit** with an internal clock, adjustable step count, gate outputs, and external control options, making it a versatile tool for both performance and experimentation.

Working Principle: The sequencer advances through its steps either via its **internal clock** or an external **clock input (CLK IN)**. Each step produces a corresponding **CV output** and a **gate output**, which can be used to control oscillators, filters, VCAs, or other modules. A **reset input** allows the sequence to return to the first step at any time, providing synchronization and repeatability for musical patterns.

Input and Output Configuration
- **Inputs:**
  - **CLK IN:** Accepts an external clock signal to advance the sequencer steps.
  - **Reset:** Resets the sequence to the first step.
- **Outputs:**
  - **CV Out:** Sends the control voltage corresponding to the current step, used to control pitch, filter cutoff, or other CV-controllable parameters.

- o **Gate Out:** Produces a gate signal to trigger envelopes, VCAs, or other time-based events.

Controls and Features
- **Internal Clock:** Allows autonomous sequencing without external timing sources.
- **Step Count Switch:** Adjusts the sequence length between 3, 4, or 5 steps for rhythmic variation.
- **Step Gate Switches:** Five individual switches allow enabling or disabling the gate for each step, creating customized rhythmic patterns.
- **Step Level Controller:** Fine-tunes the output voltage of each step or adjusts the overall sequence level.
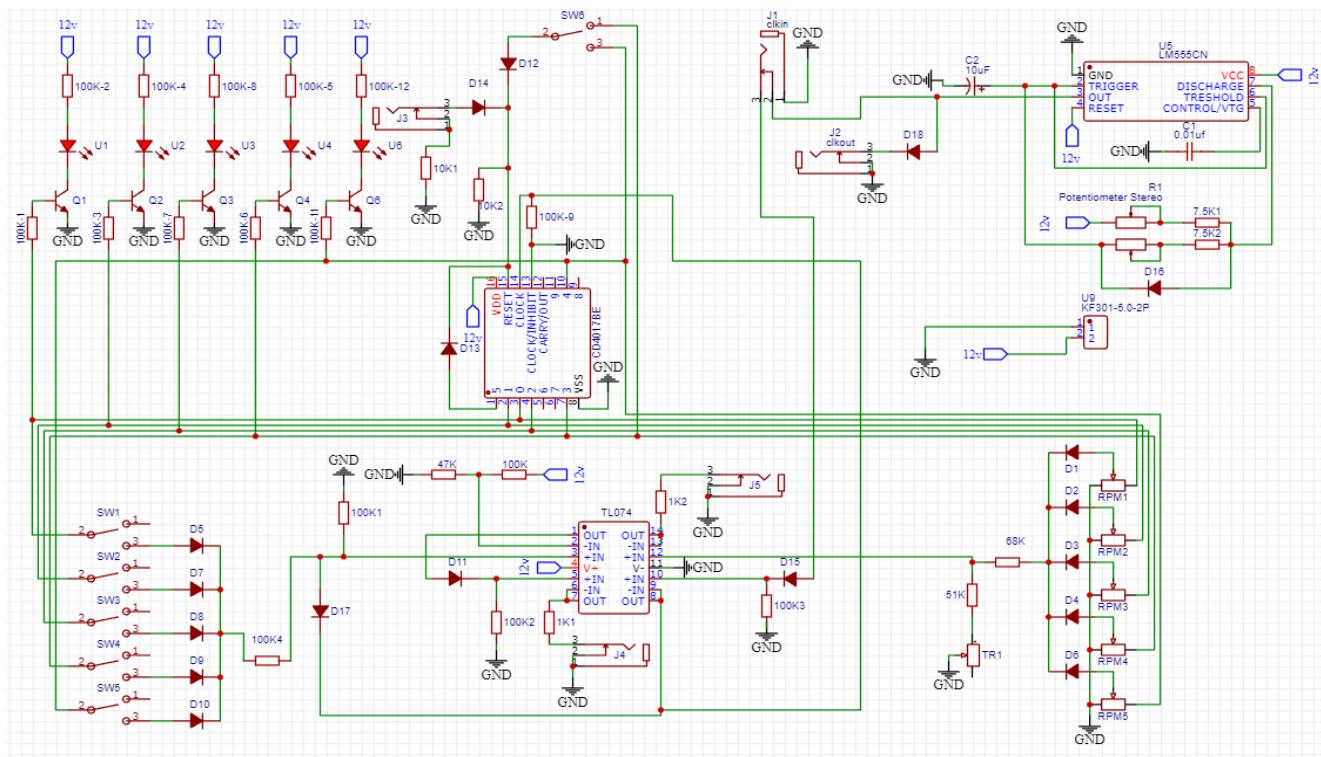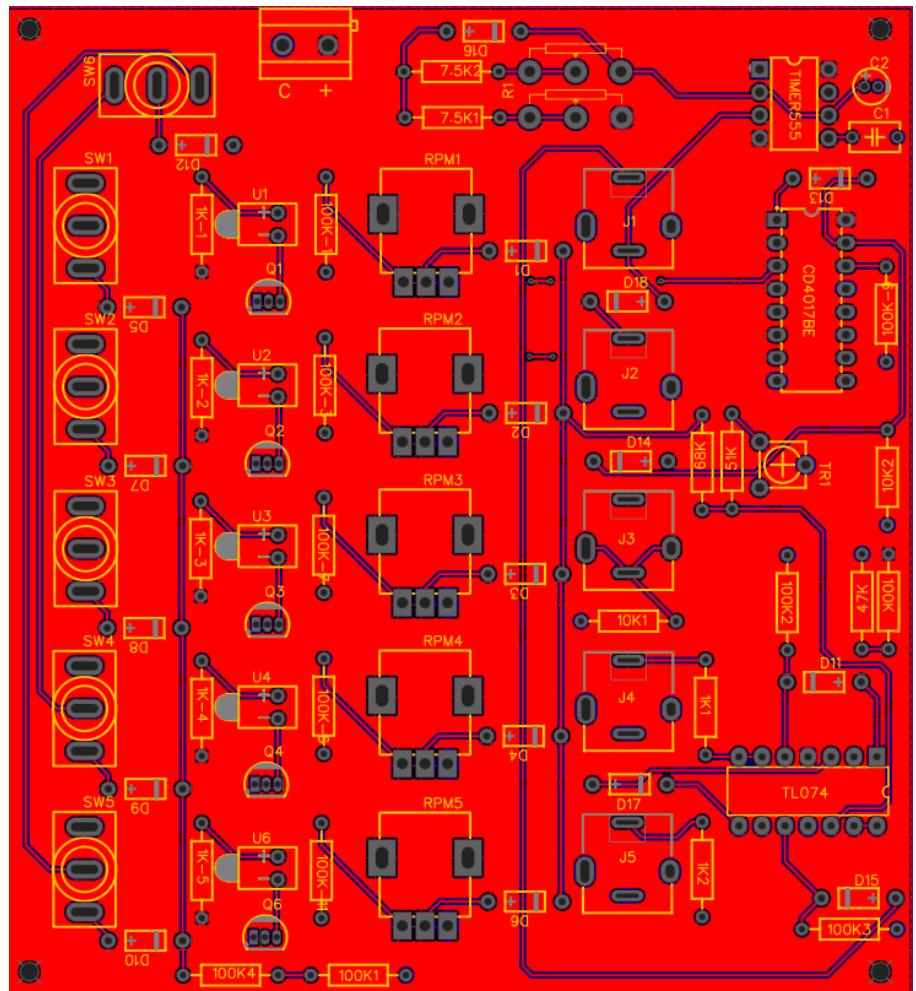
Applications in Modular Synthesizers
- **Melodic Sequences:** Generates pitch sequences for VCOs via the CV output.
- **Rhythmic Control:** Triggers envelopes, VCAs, or percussion modules using the gate output.
- **Modulation Patterns:** Can sequence LFOs or other CV-controllable parameters for evolving sounds.

In our modular synthesizer, the **5-step sequencer** allows precise, programmable control over **melody, rhythm, and modulation**. Its combination of internal clock, adjustable step count, step gate switches, and dual outputs provides **flexibility for live performance and sound experimentation**, making it a key component for creating dynamic and evolving musical patterns.

Picture 6: SEQUENCER circuit

Picture 7: SEQUENCER PCB

Wavefolder Module

A **Wavefolder** is an analog synthesis module that **adds harmonic complexity to an input signal** by "folding" the waveform when it exceeds a certain amplitude. This process transforms simple waveforms, such as sine or triangle waves, into richer, more harmonically complex sounds, making it a powerful tool for creating evolving timbres in modular synthesizers.

Working Principle: The wavefolder monitors the amplitude of the input signal. When the signal exceeds a predefined threshold, the waveform is **folded back on itself**, producing additional harmonics. The degree of folding is controlled by a **level knob**, which adjusts the input amplitude or the intensity of the folding effect.
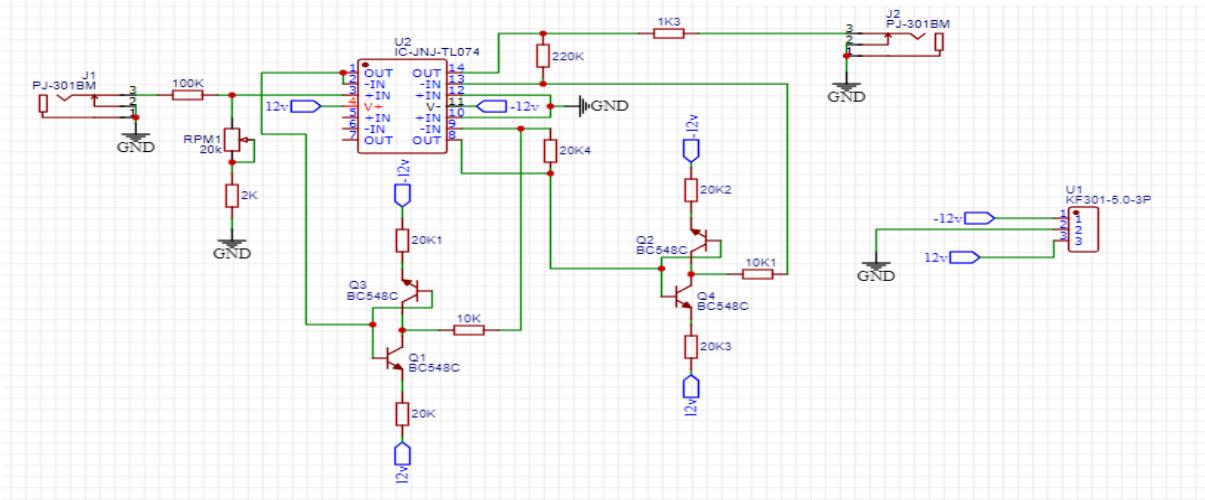
Input and Output Configuration
- **Input:** Receives an audio or CV signal, typically from a VCO or other waveform source.
- **Output:** Delivers the processed signal with added harmonic content, ready to be routed to filters, VCAs, mixers, or directly to an audio output.
- **Level Control:** Adjusts the input gain or folding intensity, allowing the user to control the amount of harmonic enrichment applied to the waveform.

Applications in Modular Synthesizers
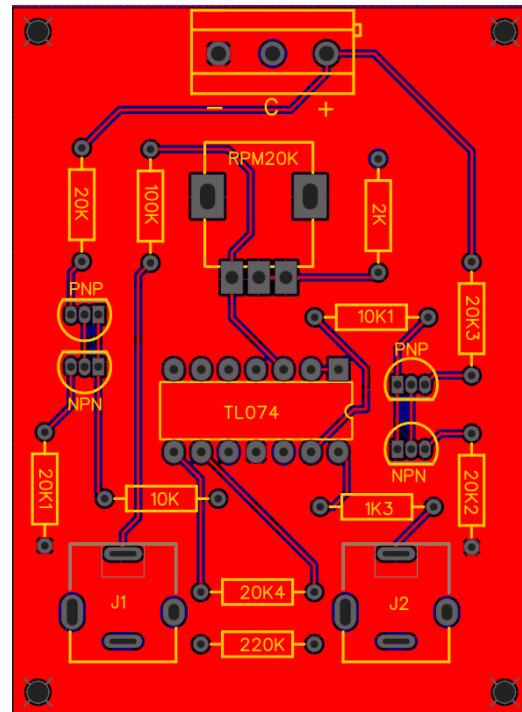
- **Harmonic Enhancement:** Transforms simple waveforms into more complex, richer sounds.
- **Sound Design:** Used to create aggressive, evolving, or metallic timbres for leads, pads, and effects.
- **Signal Shaping:** Can be combined with filters and envelopes to produce dynamic and expressive textures.

In our modular synthesizer, the **Wavefolder** adds **timbral richness and sonic complexity** to the outputs of your VCOs. By adjusting the level control, users can shape the harmonic content to suit a wide variety of sounds, from subtle overtones to heavily processed textures. Its single input, single output, and intuitive level control make it a versatile and easy-to-use module that enhances both melodic and experimental sound design.

Picture 8: WAVEFOLDER circuit

Picture 9: WAVEFOLDER PCB

Envelope Generator (ADSR)

An **ADSR envelope generator** is an essential analog synthesis module that shapes the **amplitude or other controllable parameters** of a sound over time. It defines how the sound evolves from the moment a key is pressed until it is released, allowing dynamic and expressive modulation of voltage-controlled modules such as VCAs or VCFs.

Working Principle

The envelope generator produces a voltage output that changes over time according to four stages: **Attack, Decay, Sustain, and Release (ADSR)**.

- **Attack (A):** Determines the time it takes for the voltage to rise from zero to its maximum level after a key press.
- **Decay (D):** Controls the time for the voltage to decrease from the peak to the sustain level.
- **Sustain (S):** Sets the steady voltage level maintained while the key is held.
- **Release (R):** Defines the time it takes for the voltage to return to zero after the key is released.

By adjusting these parameters, users can create sounds ranging from sharp, percussive hits to slow, evolving pads.

Input and Output Configuration
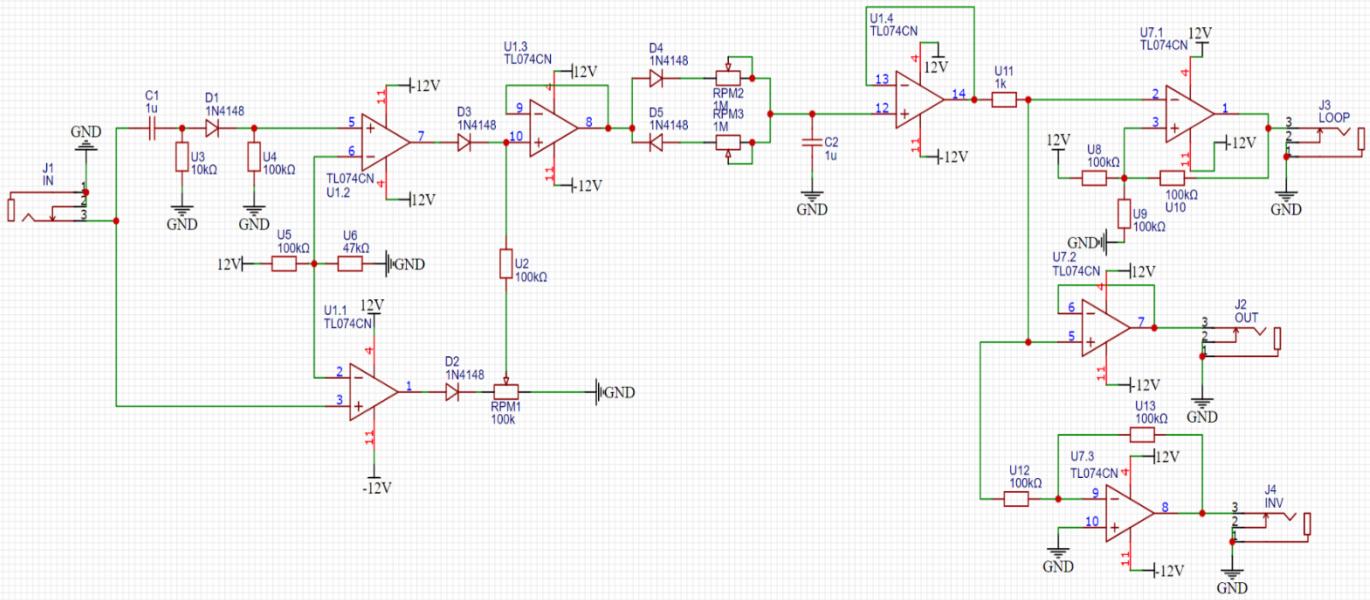
- **Input:** Receives a trigger or gate signal, typically from a keyboard, sequencer, or drum pad.
- **Output:** Delivers a voltage envelope to VCAs, VCFs, or other modules to control amplitude, filter cutoff, or other modulation destinations.
- **ADSR Controls:** Knobs or sliders allow real-time adjustment of attack, decay, sustain, and release times for expressive sound shaping.

Applications in Modular Synthesizers
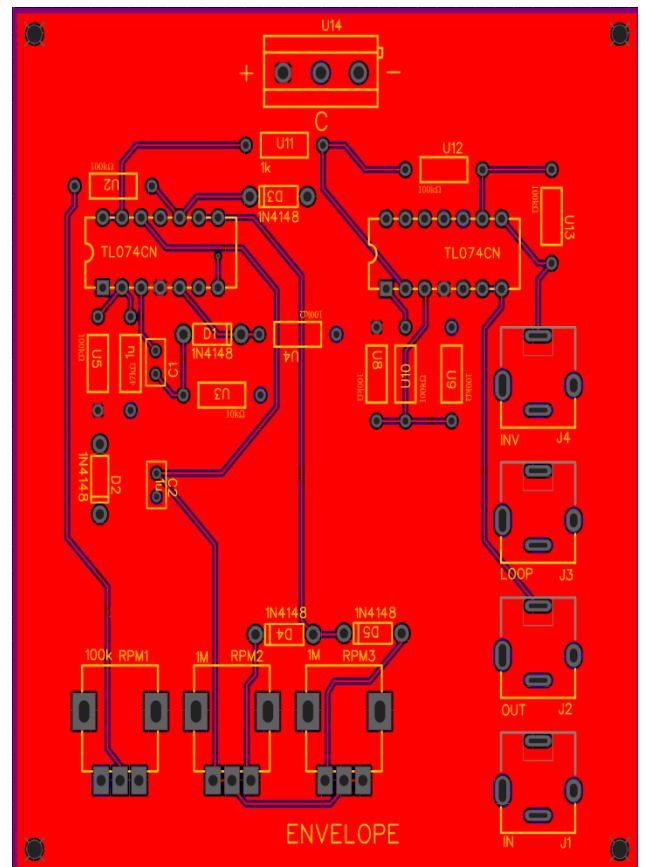
- **Dynamic Shaping:** Controls the amplitude contour of notes, giving sounds a natural evolution.
- **Filter Modulation:** Shapes filter cutoff for expressive timbral changes.
- **Expressive Performance:** Enables nuanced control over articulation, from staccato to legato playing styles.

In our modular synthesizer, the **ADSR envelope module** provides precise voltage control for shaping both amplitude and filter response. Its intuitive interface and stable output allow users to craft dynamic and expressive sounds, enhancing both melodic and experimental synthesis.
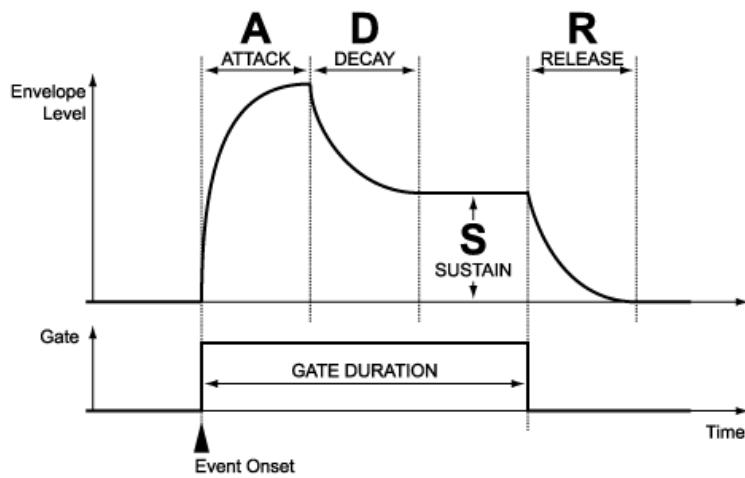
Picture 10: ENVELOPE circuit

Picture 11: ENVELOPE PCB

Picture 12: ADSR

Voltage-Controlled Amplifier (VCA)

A **Voltage-Controlled Amplifier (VCA)** is a key module in a modular synthesizer that dynamically controls the **amplitude of an incoming audio signal** based on a **control voltage (CV)** input. It allows the user to modulate the loudness of sound in real-time, making it essential for expressive performance and dynamic sound shaping.

Working Principle
The VCA takes an audio signal and multiplies it by the amplitude of the control voltage. When the CV increases, the output signal becomes louder; when the CV decreases, the output signal reduces accordingly. Typically, the control voltage is derived from modules such as **ADSR envelopes**, **LFOs**, or sequencers, enabling complex modulation patterns.
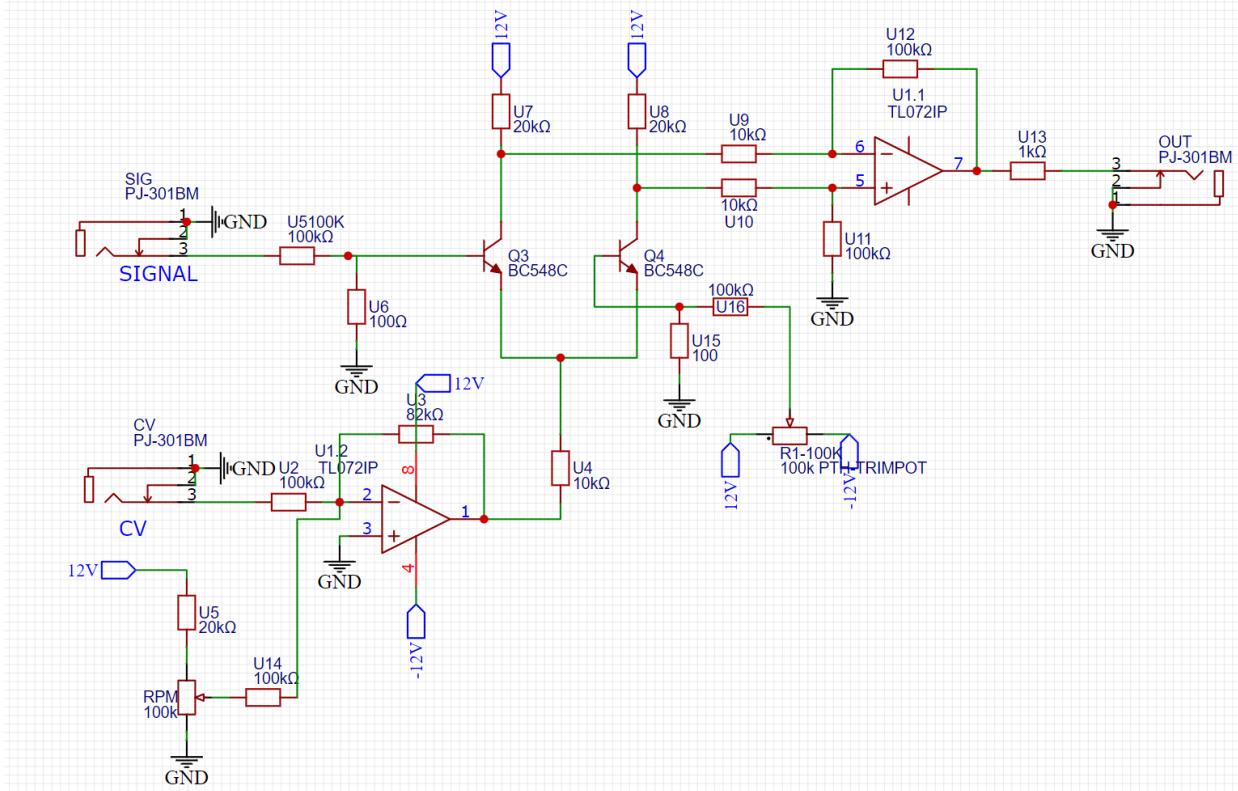
Input and Output Configuration
- **Audio Input:** Receives a waveform from a VCO, mixer, or other audio source.
- **Control Voltage Input (CV):** Accepts voltage signals that modulate the amplitude dynamically.
- **Output:** Delivers the amplified or attenuated audio signal, ready to be routed to mixers, filters, or the final audio output.
- **Level Control:** Some VCA designs include a manual gain knob to set the base amplitude independently of the CV input.
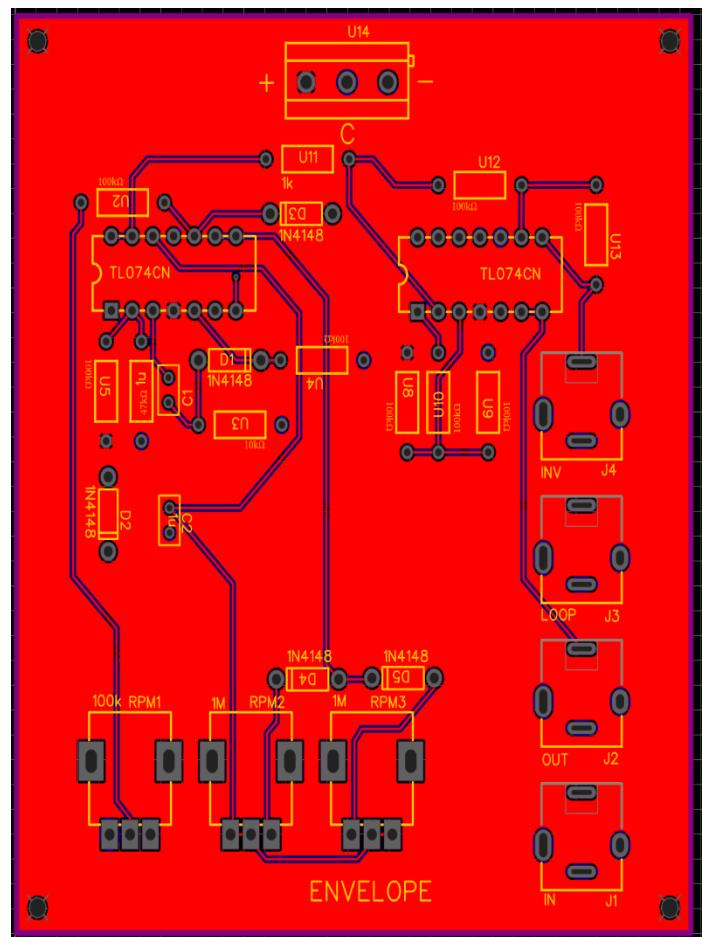
Applications in Modular Synthesizers
- **Amplitude Shaping:** Works with ADSR envelopes to create dynamic note articulation (attack, sustain, decay, release).
- **Tremolo and Modulation Effects:** Works with LFOs to produce periodic amplitude variations, adding movement and texture to sounds.
- **Signal Routing:** Enables mixing and combining multiple modulated audio signals for complex synthesis patches.

In our modular synthesizer, the **VCA module** is crucial for shaping the dynamics of the VCOs and other sound sources. By responding to envelope generators and modulation sources, it allows for expressive and nuanced sound design, supporting both subtle volume changes and dramatic, evolving textures.

Picture 13: VCA circuit

Picture 14: VCA PCB

Voltage-Controlled Filter (VCF)

A **Voltage-Controlled Filter (VCF)** is a fundamental module in a modular synthesizer that shapes the **tonal character of an audio signal** by selectively passing or attenuating specific frequency ranges. It allows the user to sculpt the sound dynamically, making it a critical component for timbral control and expressive synthesis.

Working Principle

The VCF modifies the frequency content of the input signal based on a control voltage (CV) applied to the filter's cutoff. By adjusting the cutoff frequency and resonance, the filter can emphasize or suppress particular harmonics, creating a wide variety of tonal effects. In this implementation, **three simultaneous filter types** are available:

- **Low-Pass (LP):** Passes frequencies below the cutoff and attenuates higher frequencies.
- **Band-Pass (BP):** Passes a specific range of frequencies around the cutoff while attenuating frequencies outside the range.
- **High-Pass (HP):** Passes frequencies above the cutoff while attenuating lower frequencies.

Each filter response can be **independently enabled or disabled** using toggle switches, allowing the user to combine modes for more complex tonal shaping.

Input and Output Configuration
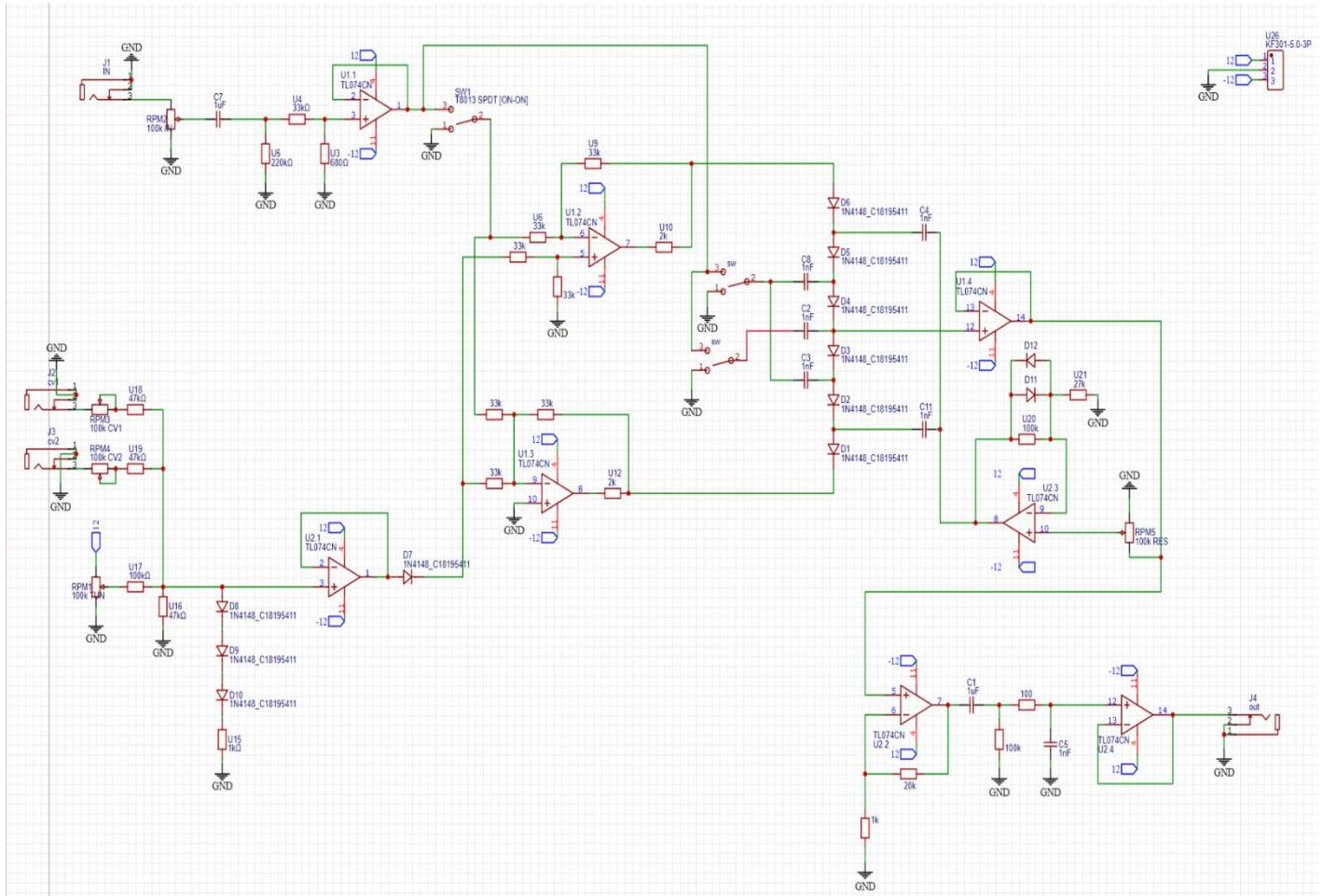
- **Audio Input:** Accepts a waveform from a VCO, mixer, or other audio source.
- **Control Voltage Input (CV):** Modulates the cutoff frequency, typically from an ADSR envelope or LFO.
- **Audio Output:** Delivers the filtered signal to other modules such as VCAs, mixers, or directly to audio output.
- **Mode Switches:** Enable or disable LP, BP, and HP simultaneously or individually.

## Applications in Modular Synthesizer
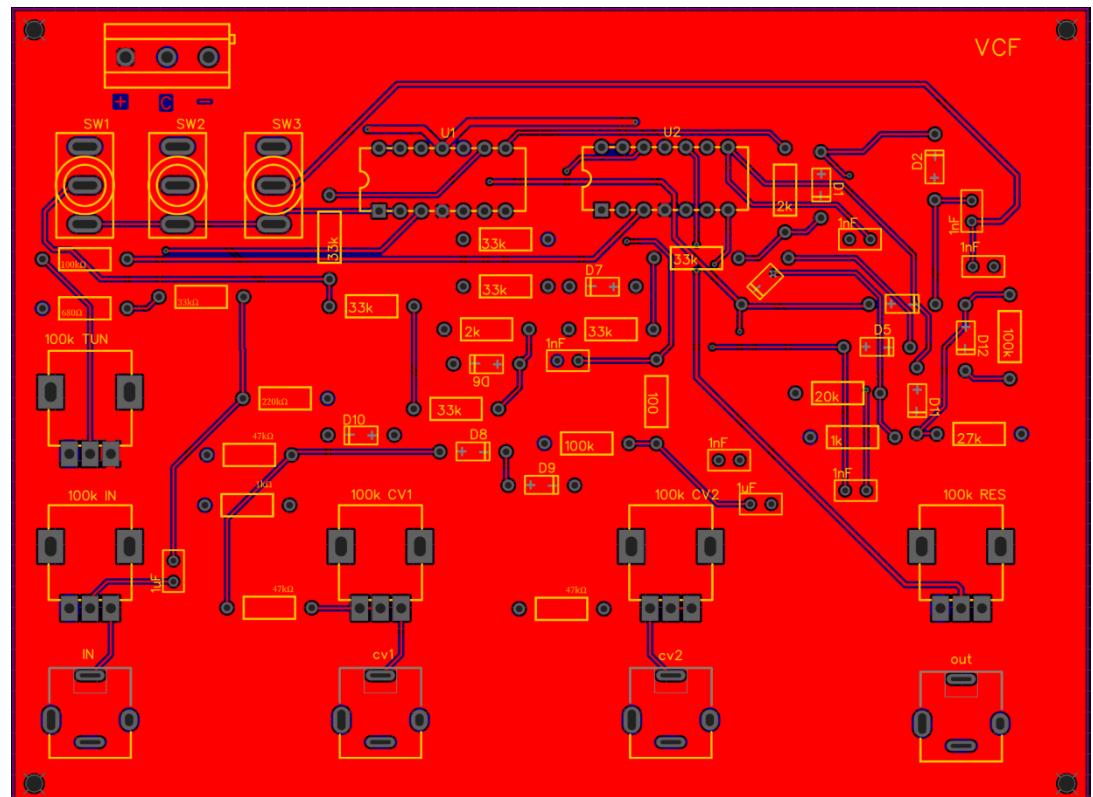
- **Tonal Shaping:** Sculpt harmonic content to emphasize or suppress specific frequencies.
- **Dynamic Modulation:** Work with envelopes and LFOs to create evolving textures, sweeps, and filter effects.
- **Sound Design Flexibility:** Combine filter modes to create unique timbres for leads, pads, basses, and effects.

In our modular synthesizer, the **VCF module** provides flexible and precise control over the harmonic content of VCO signals. Its multiple selectable modes and voltage-controlled cutoff allow for expressive and complex sound design, making it a central component in both melodic and experimental synthesis.

Picture 15: VCF circuit

Picture 16: VCF PCB

19

ESP32 Keyboard Scanning and Control

The two-octave keyboard in the modular synthesizer is implemented using an ESP32 microcontroller, which scans a matrix of keys and outputs the corresponding control voltages (CV) to the analog modules. This implementation allows multiple notes to be detected simultaneously, enabling polyphonic play and integration with the analog VCOs.

Keyboard Matrix Design

The keyboard is organized into two octaves, each with 4 rows and 3 columns, forming a 4×3 matrix per octave. This matrix reduces the number of required input/output pins while allowing each key to be uniquely identified. To prevent ghosting and ensure reliable key detection, each key in the matrix is scanned sequentially using the row-column method, where one row is activated at a time and the column inputs are read.

Code Functionality

Pin Configuration: The row pins are configured as outputs and initialized to a low state, while column pins are configured as inputs with external pull-down resistors. Two separate I2C buses are used to control three MCP4725 DACs, which output the corresponding voltage for the pressed keys.

Matrix Scanning: The scanAllMatrices() function iterates through each row of the matrix, setting it HIGH to activate it. The code then reads the state of all columns to determine which keys are pressed. After reading, the row is set LOW before moving to the next row. This ensures that multiple key presses can be correctly detected and mapped.

Note Detection: The readNote() function identifies up to three simultaneous key presses by checking the switchStates array. Each pressed key is mapped to a predefined voltage value stored in the note array, which corresponds to the pitch for the VCO. This approach allows the system to support polyphony and assign specific notes to each DAC channel.

Voltage Output: The playNote() function sends the detected note voltages to the MCP4725 DACs (dac1, dac2, and dac3) using I2C communication. Each DAC outputs a voltage corresponding to one of the three detected notes, which is then fed to the VCOs for sound generation. After output, the note variables are reset to zero to prepare for the next scanning cycle.

Timing and Responsiveness: The scanning and playback loop includes a short delay (delay(100)) to ensure stable readings while maintaining real-time responsiveness. This balance allows the synthesizer to react quickly to key presses without introducing significant latency.

Importance in the Project

The ESP32-based keyboard scanning system provides a flexible, reliable, and expandable interface for the modular synthesizer. It enables polyphonic note detection, accurate pitch control via DAC outputs, and seamless integration with the analog modules. This digital interface complements the analog components, creating a hybrid system that combines the expressive capabilities of traditional synthesis with the programmability and precision of digital control.

Picture 17: ESP32

Digital Part – Raspberry Pi Drum Pad

The digital component of the modular synthesizer project is implemented using a **Raspberry Pi 4** paired with a **7-inch capacitive touchscreen**. This subsystem functions as a **standalone digital drum-pad instrument**, providing rhythm generation, sample playback, and looping capabilities.

Working Principle

The drum pad application is written in **Python** and allows the user to trigger preloaded samples via the touchscreen interface. Each pad corresponds to a specific drum sound or sample, and multiple pads can be activated simultaneously to create complex rhythmic patterns. The system operates at a **user-defined BPM**, enabling synchronization with the rest of the synthesizer or external instruments.

Input and Output Configuration
- **Input:** Touch gestures on the capacitive screen are used to trigger drum samples.
- **Output:** Audio is routed to the synthesizer's mixer or directly to external speakers.
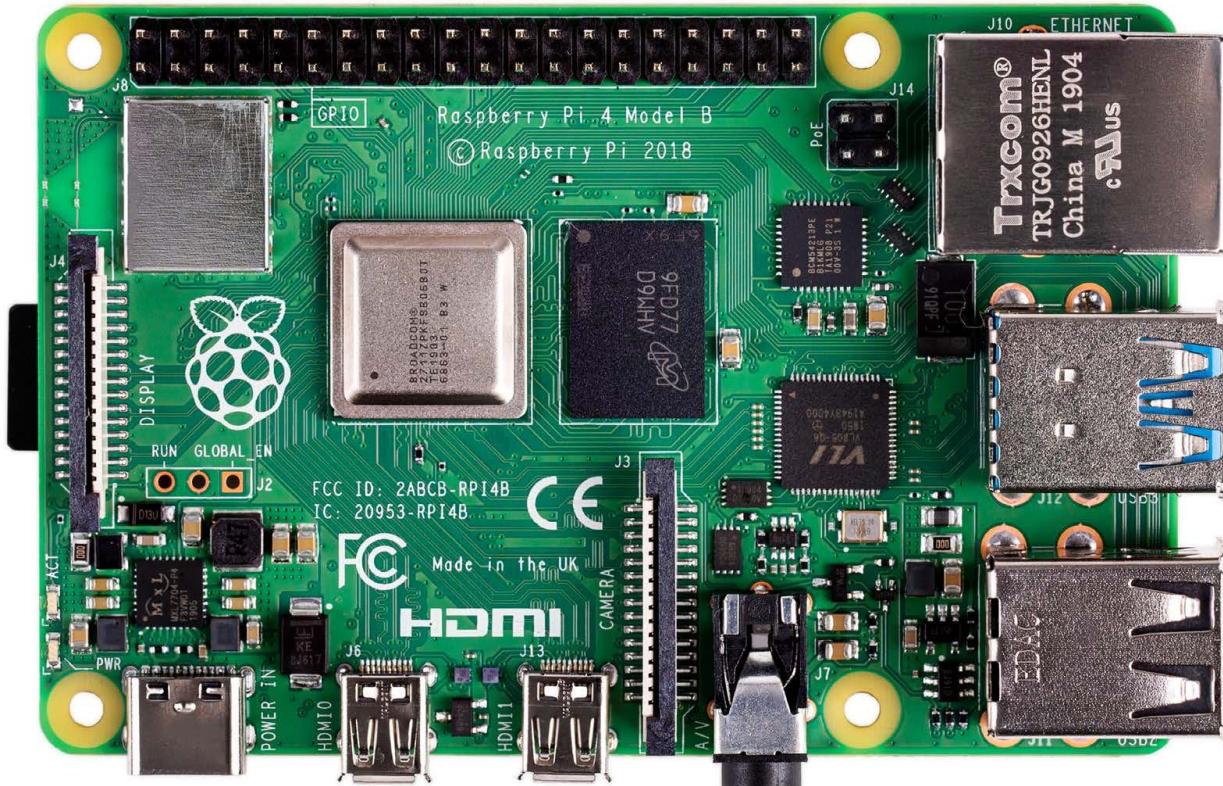
Applications in Modular Synthesizers
- **Rhythm Generation:** Provides drum and percussive patterns to complement melodic and harmonic content.
- **Sample Playback and Looping:** Enables the creation of repeating patterns, allowing live performance and experimental compositions.

- **Integration with Analog Modules:** Outputs can be routed through mixers and VCAs for further processing, blending digital rhythms with analog synthesis.

In this project, the **Raspberry Pi drum pad** adds a digital dimension to the modular synthesizer, enabling rhythm production and interactive performance. Its standalone operation and intuitive touchscreen interface make it a versatile tool for both live and studio applications, complementing the analog modules and expanding the overall sonic palette of the synthesizer.

Picture 18: Raspberry Pi 4

Challenges and Solutions

During the development of the Analog-Digital Modular Synthesizer, several technical and design challenges were encountered, each requiring careful analysis and problem-solving. The following outlines the key challenges faced during the project and the solutions implemented to overcome them:

- **VCO Exponential Converter Stability:** One of the major challenges was achieving a precise and stable exponential voltage-to-frequency conversion in the VCO module. The initial PCB design did not provide the expected accuracy due to transistor mismatches and temperature variations. To resolve this, the design was revised using high-precision thermistors and better-matched transistor pairs placed in close proximity to maintain equal temperature conditions. This adjustment significantly improved tuning stability, ensuring accurate pitch tracking across multiple octaves.

- **Keyboard Matrix Implementation:** Creating a responsive and reliable two-octave keyboard controlled by a single ESP32 microcontroller proved to be a complex task. The initial circuit suffered from key ghosting and inconsistent note detection due to signal overlap. To address this, a diode-based matrix circuit was implemented to isolate key signals, and the ESP32 firmware was updated with an optimized key-scanning algorithm. This solution ensured accurate key recognition, smooth voltage output for pitch control, and stable integration with the analog modules.

- **3D Modeling and System Design:** Designing the physical structure and 3D model of the modular synthesizer was another significant challenge. Achieving an optimal layout that was both ergonomic and visually cohesive required multiple design iterations. The spacing between modules, wiring accessibility, and component positioning had to be balanced with aesthetic and functional considerations. By using precise 3D modeling software and iterative prototyping, a final design was achieved that ensured easy module integration, effective heat dissipation, and a professional appearance for the complete synthesizer system.

Final Result of the Project

The culmination of our project is the successful development of a fully functional analog-digital modular synthesizer that combines traditional analog sound generation with modern digital control and interface systems. The synthesizer includes three voltage-controlled oscillators (VCOs), two mixers, a voltage-controlled filter (VCF), voltage-controlled amplifier (VCA), envelope generator, wavefolder, 5-step sequencer, and a two-octave keyboard controlled by an ESP32 microcontroller. Additionally, the system integrates a touchscreen-based drum pad with a looping function powered by a Raspberry Pi 4.

The final prototype demonstrates the effective integration of analog and digital technologies, offering a versatile sound synthesis platform with both performance and experimental capabilities. The key results of the project include:

- **Stable and Accurate Sound Generation:** The improved exponential converter design in the VCOs ensures stable pitch tracking and accurate frequency control across multiple octaves, resulting in precise and musically consistent tone generation.

- **Integrated Keyboard and Sequencer Control:** The ESP32-based two-octave keyboard and 5-step sequencer provide smooth and responsive control over pitch and timing. The diode matrix design and optimized firmware ensure accurate note detection and reliable voltage output without latency or interference.

- **Dynamic Sound Shaping and Modulation:** The inclusion of analog modules such as the VCF, VCA, envelope, mixer, and wavefolder allows for a wide range of timbral variations and complex sound sculpting. The signal routing flexibility supports both traditional synthesis and experimental sound design.

- **Drum Pad and Looper Functionality:** The Raspberry Pi 4 touchscreen interface enables real-time drum triggering and loop playback, extending the synthesizer's functionality into rhythm-based music creation and live performance.

Meeting Project Goals and Technical Task

The project successfully met its defined goals and technical requirements, resulting in a fully functional analog-digital modular synthesizer system capable of generating, shaping, and controlling audio signals through both analog circuitry and digital interfaces.

- **Goal Achievement:** The primary objective of developing a modular synthesizer that integrates analog sound generation with digital control was fully accomplished. The system demonstrates stable voltage-controlled oscillation, precise keyboard and sequencer control, and responsive sound shaping through analog processing modules. The final design also includes an interactive drum pad and looper system, extending the instrument's creative capabilities.

- **Technical Task Fulfillment:** All major technical tasks were successfully executed. This includes the design and fabrication of multiple PCBs (VCO, VCF, VCA, Envelope, Mixer, Wavefolder, and Sequencer), integration of ESP32-based digital control for the keyboard, and implementation of stable exponential conversion in the VCO for accurate frequency response. The 3D modeling and physical construction of the synthesizer ensured ergonomic layout and reliable interconnection among modules.

In summary, the project achieved a complete and operational prototype of a hybrid analog-digital synthesizer, demonstrating strong technical execution and innovative design. The system provides a versatile platform for both musical performance and sound experimentation, serving as a foundation for future expansion and refinement in modular synthesis design.

Contribution of Group Members to the Project:

Both team members were equally involved throughout the entire project, engaging in discussions about critical issues and collaboratively developing solutions. This collaborative approach allowed us to make informed decisions and contributed significantly to the project's success. However, effective distribution of work is essential in group projects, as it facilitates rapid and high-quality development.

Luka Pkhaladze:
- **PCB Design and Circuit Development:** Luka was responsible for designing the PCBs for the **Envelope, VCF, and VCA modules**, ensuring accurate signal routing, component placement, and reliable operation.

- **Keyboard Modeling and Construction:** He created the **3D model of the two-octave piano keyboard** and assembled it, integrating it with the ESP32 microcontroller for control and voltage output.
- **Drum Pad and Looper Implementation:** Luka developed the **drum pad interface on the Raspberry Pi touchscreen**, including the hardware setup and coding of the **looping functionality**, enabling real-time performance and sound experimentation.

These contributions reflect Luka's expertise in **analog circuit design, digital interface integration, and software development**, ensuring both the functionality and usability of the synthesizer system.

Luka Balanchivadze:
- **PCB Design and Circuit Development:** Luka designed and assembled the PCBs for the **VCO, Sequencer, Mixer, and Wavefolder modules**, handling both analog signal paths and control voltage routing.
- **Synthesizer Construction:** He oversaw the **physical assembly and overall construction of the modular synthesizer**, integrating all modules into a cohesive and functional system.
- **ESP32 Keyboard Code Development:** Luka wrote the **ESP32 firmware for the keyboard**, enabling accurate voltage-to-frequency translation, key scanning, and real-time control of the analog modules.

These contributions demonstrate Luka's strong skills in **analog synthesis, system integration, and firmware development**, playing a critical role in building a fully functional hybrid modular synthesizer.

Together, both team members combined **circuit design, software development, and hardware integration skills** to successfully complete the senior project, creating a versatile and interactive analog-digital modular synthesizer suitable for sound design, performance, and experimentation.

Conclusion

Main Aspects of the Project

The primary goal of our project was to design, develop, and implement a **hybrid analog-digital modular synthesizer system** capable of generating and shaping complex audio signals through both analog circuitry and digital control. The project involved creating multiple interconnected modules—including a Voltage-Controlled Oscillator (VCO), Voltage-Controlled Filter (VCF), Voltage-Controlled Amplifier (VCA), Envelope Generator, Mixer, Wavefolder, Sequencer, and Keyboard system—each serving a critical role in sound synthesis and modulation.

Key objectives included achieving **precise exponential control in the VCO**, implementing **ESP32-based digital management** for the keyboard and drum pad, and ensuring **stable analog performance** across all signal paths. The physical construction of the synthesizer required

careful PCB design, circuit optimization, and 3D modeling to create a cohesive and ergonomic layout.

This multidisciplinary project combined **analog electronics, digital programming, and hardware design**, resulting in a modular and expandable synthesizer that bridges traditional sound synthesis techniques with modern embedded control systems.

Obtained Result

The project successfully met its objectives. We developed a fully functional analog-digital modular synthesizer capable of generating, shaping, and controlling complex audio signals through a combination of analog circuits and digital control systems. The synthesizer provides a modular structure that allows users to create and modify sound through interconnected components, offering a wide range of sonic possibilities.

- The VCO modules achieved stable frequency tracking across multiple octaves using precise exponential conversion and thermal compensation.
- The ESP32-controlled keyboard and drum pad operated flawlessly, accurately detecting key presses through a diode matrix system and enabling responsive real-time sound triggering.
- The sequencer and modulation modules provided reliable timing, voltage control, and rhythmic variation, while the wavefolder and mixer enhanced tonal richness and dynamic range.
- The final assembled system, including the 3D-designed enclosure and module layout, resulted in a visually cohesive, high-performance synthesizer ready for both studio and live applications.

Knowledge and Experience Gained

Throughout the project, we gained significant knowledge and practical experience in several areas:

- **Analog Circuit Design:** We developed a deep understanding of analog audio circuitry by designing and testing modules such as the VCO, VCF, VCA, wavefolder, and mixer. This process taught us about signal flow, component selection, noise reduction, and voltage control precision.
- **PCB Design and Assembly:** We acquired hands-on experience in designing printed circuit boards for various synthesizer modules, optimizing layouts for minimal interference and stable operation.
- **Microcontroller Programming:** Working with the ESP32 microcontroller helped us enhance our skills in digital control systems. We implemented matrix scanning for the keyboard, timing synchronization, and MIDI-like control over analog modules.
- **Sound Synthesis and Modulation**: We explored principles of waveform generation, frequency modulation, and envelope shaping, gaining a solid foundation in both the theory and practice of sound synthesis.

- **3D Modeling and Construction**: We learned how to design and model the synthesizer's physical structure, creating a functional and visually cohesive layout for all modules. This included ergonomic placement of controls and durable housing design.
- **System Integration:** Combining analog and digital elements into a single modular synthesizer improved our understanding of hybrid systems and real-time signal interaction between different circuit types.

Future Plans

Looking ahead, there are several potential developments and improvements for this project:

- **Expanded Module Library:** Future iterations could include additional modules such as ring modulators, additional LFOs, or sample & hold circuits, increasing the synthesizer's sonic capabilities.
- **Enhanced Digital Integration:** Improvements in ESP32 firmware and Raspberry Pi software could allow for more advanced control over modules, including MIDI input, preset storage, and automated modulation sequences.
- **Touch Keyboard Implementation:** Replacing the mechanical keyboard with a touch-sensitive keyboard would enhance playability, provide more precise control, and allow for more compact and flexible layouts.
- **Compact and Ergonomic Design:** Further optimization of the physical layout and 3D enclosure design could make the synthesizer more compact and user-friendly for live performance or desktop use.
- **Commercial and Educational Use:** With refinements in design and functionality, this hybrid synthesizer could serve as a low-cost, versatile instrument for musicians, educators, and sound designers, offering hands-on experience with both analog and digital synthesis.

References

Espressif Systems. (2019). *ESP32 technical reference manual (version 4.2)*. Retrieved from https://www.espressif.com/sites/default/files/documentation/esp32_technical_reference_manual_en.pdf

Espressif Systems. (2021). *ESP32 datasheet*. Retrieved from https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

Python Software Foundation. (2023). *Python documentation*. Retrieved from https://docs.python.org/3/

Raspberry Pi Documentation
https://www.raspberrypi.com/documentation/

Moritz Klein playlists
https://www.youtube.com/@MoritzKlein0/playlists

Multisim User Guide - National Instruments
https://download.ni.com/support/manuals/374483a.pdf

EasyEDA Std User Guide
https://docs.easyeda.com/en/

Thank You

We would like to extend our heartfelt gratitude to all those who contributed to the successful completion of this project.

First and foremost, we would like to thank the head of our project, **Zviad Sulaberidze**, for his invaluable guidance and for providing essential materials and advice throughout the development process. His support was instrumental in overcoming many technical challenges during the project.

We would also like to express our gratitude to our coursemates, the **ECE21 students**, for their continuous assistance and encouragement. Their collaboration and willingness to provide feedback significantly aided our progress.

Special thanks go to our lecturer, **Guga Vardiashvili**, for creating a motivating and supportive learning environment. His engaging teaching style and insightful advice made the project both challenging and enjoyable.

Finally, we sincerely appreciate everyone who contributed in any way to this project. Your help and encouragement were crucial in bringing this analog-digital modular synthesizer to completion.

Attachments

Github link, where are all information, codes, picture of 3D models of our project:
https://github.com/lpkha21/Analog-Digital-synth