NepTUNE: Synthesizer

Final Presentation

Group: 16
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Team

Anthony De Rosa

Electrical Engineering

Robert Rosario

Electrical Engineering

Jordan Khan

Computer Engineering

Dina Suleiman

Electrical Engineering

Alexander Barrass

Electrical Engineering


Project NepTune
UCF Senior Design – Group 16 – Fall '25
NepTune


ARTURIA

What Is a Synthesizer?

- An Electronic instrument that creates sound from scratch, rather than modifying or sampling an existing one
- **Oscillators** generate basic electronic waveforms
- Waveforms are stacked, then sculpted by a series of modules
- **Filters** change the tone, making it brighter or duller.
- **Amplifiers** control the volume.
- **Envelope Generators** shape how the volume changes when a key is pressed and released.
- The musician uses knobs and switches to control these modules, designing a unique sound in real time.

Motivation and Background

Problem:

- As technology has developed, musical synthesizers have become more powerful with many features.
- To save costs, essential controls are often hidden in complex digital menus.
- While this is great for professional instruments, the learning curve is very steep.
- The vast number of controls and features may discourage beginners who may be curious about the art.

Motivation and Background

Solution:

- "NepTune" will serve to fill this gap and offer an inviting platform for curious beginners.
- "Knob-per-Function" allows specified knobs and buttons for each function.
- Clear display of controls for user understanding.
- Purpose – built ICs for maximum performance in a small, easy-to-use packages.

Goals

Basic Goals

- 2 oscillators per voice
- Voltage Controlled Filters (VCF)
- Voltage Controlled Amplifiers (VCA)
- Envelope Generators
- Portability

Advanced Goals:

- 2 Voices
- Presets
- Low Frequency Oscillator (LFO)

Objectives

1. Build and test hardware to ensure power supply and signal stability through path.

2. Expand hardware capabilities to achieve stretch goals

3. Develop software connections to transmit user controls and input.

4. Expand software integration to allow more customization

5. Manufacture housing for boards in a single package ready for demonstration.

Engineering Specifications

Parameters	Values	Marketing Requirement	Description
Max Dimensions	18'' x 12''	1	L x W. System must be smaller than these dimensions.
Weight	< 8 lbs.	1	Weight of system.
Cost	< $500	2	The total cost of the synth to the end user.
Time Delay	< 7ms	4, 5	Response time of system from user input.
SNR	> 40dB	4	The signal to noise ratio (SNR) should be within an acceptable range for entry-level hobbyists.
THD	< 2%	4	The ratio of total undesired harmonics to the fundamental harmonic should be in an acceptable range.
Filter Roll-off	>12dB/octave	3, 4	Rate of roll off for configurable filters with key-tracking
Number of Octaves	8	3	Audible range of notes

Engineering Specifications

Parameters	Values	Marketing Requirement	Description
Dynamic Range	~ 60dB	4	The ratio between the loudest sound and the noise floor should be in an acceptable range.
Frequency Response	30Hz – 7kHz	4	The range of frequencies the synthesizer can play.
Headphone output voltage	~2.5 V_{rms}	3, 4	Voltage output for headphone jack in root-mean-squared voltage (V_{rms})
Headphone Output Impedance	16-50 Ωs	3, 4	Output impedance for headphone jack.
Line-Level Output Impedance	100-600 Ωs	3, 4	Voltage output for line-level out in Vrms.
Line-level output voltage	1-2 Vrms	3, 4	Output impedance for line-level out.
Power Consumption	< 25W	1, 2	Synth uses 12V for components and Neptune wants to limit to 25W maximum draw.

Time Delay

Test Condition	Time Delay(mS)
1 Note Input Square Wave	3.70
1 Note Input Ramp-up wave	2.96
1 Note Input Triangle Wave	3.55
1 Note Input Sine Wave	3.72
1 Note Input Ramp-down Wave	2.93
4 Notes Input Square Wave	3.03
4 Notes Input Sine Wave	6.05
4 Notes Input Ramp-down Wave	4.82
4 Notes Input Ramp-up Wave	5.68
4 Notes Input Triangle Wave	6.30

Signal to Noise Ratio(SNR)

Test Condition	Noise(mV)	Signal(mV)	SNR(dB)
Single Oscillator- Sine wave, 1 Note	42.77	115.05	8.59
Single Oscillator- Square wave, 1 Note	43.54	109	7.97
Single Oscillator- Sawtooth wave, 1 Note	41.07	93.92	7.18
Single Oscillator- Sawtooth wave, 4 Note	48.01	269.17	14.97
Single Oscillator- Square wave, 4 Note	48.84	201.86	12.32
Single Oscillator- Triangle wave, 4 Note	40.71	203.01	13.95
Two Oscillators- Sawtooth wave, 4 Note	41.26	203.03	13.84
Two Oscillators- Ramp-up, 4 Note	36.64	262.59	17.11
Two Oscillators- Sawtooth, 4 Note	35.29	179.2	14.11
Two Oscillators- Sawtooth, Max Resonance 4 Note	35.99	411.37	21.16

Total Harmonic Distortion(THD)

Test Conditions: Sine Wave, Frequency Range: 30Hz- 15KHz

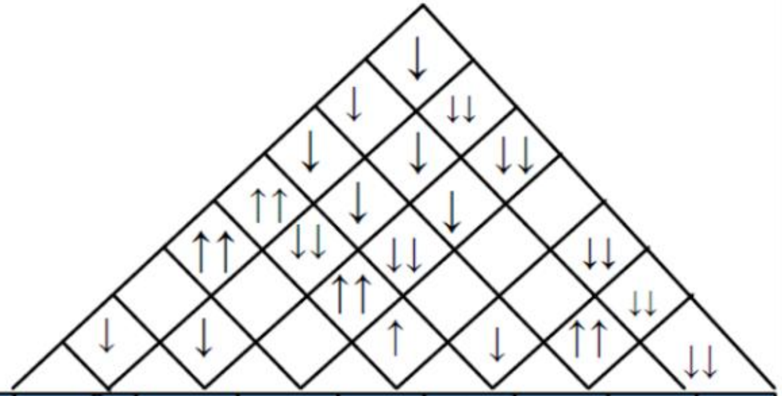
Fundamental Frequency	dbV	1st Harmonic Frequency	dbV	2nd Harmonic Frequency	dbV	3rd Harmonic Frequency		THD
28.17Hz	-19.98	56Hz	-79.1	84Hz	-80.74			14.2%
56Hz	-19.6	113Hz	-76.36					11.7%
113Hz	-19.5	225Hz	-77.08	323Hz	-66.74	443Hz	-81.72	24.2%
224.9Hz	-19.56	449Hz	-76.78	646Hz	-106			11.6%
450 Hz	-20.5	900Hz	-78.84					11.3%
900 Hz	-20.08	1.8KHz	-78.18					11.2%
1.8KHz	-24.58	3.60KHz	-86.8					11.4%
3.6KHz	-33.6	7.21KHz	-89.6					27.5%
7.2KHz	-25.44	14.46KHz	-97.58					6.8%
14.9KHz	-37.1	32.3KHz	-40.1					700.7%

House of Quality

Important Tradeoffs:

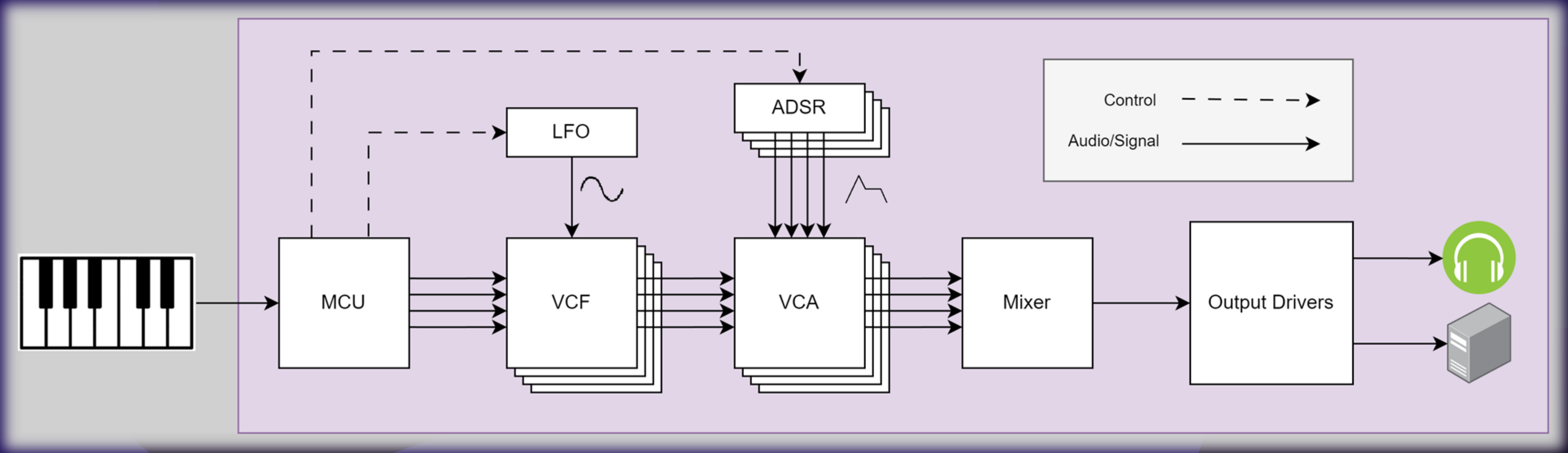
- Affordability vs. Features
- Power vs. Performance
- Weight vs. Portability

Legend	
↑↑	Strongly Positive Correlation
↓↓	Strongly Negative Correlation
↑	Positive Correlation
↓	Negative Correlation
+	Maximize
-	Minimize
X	No Correlation

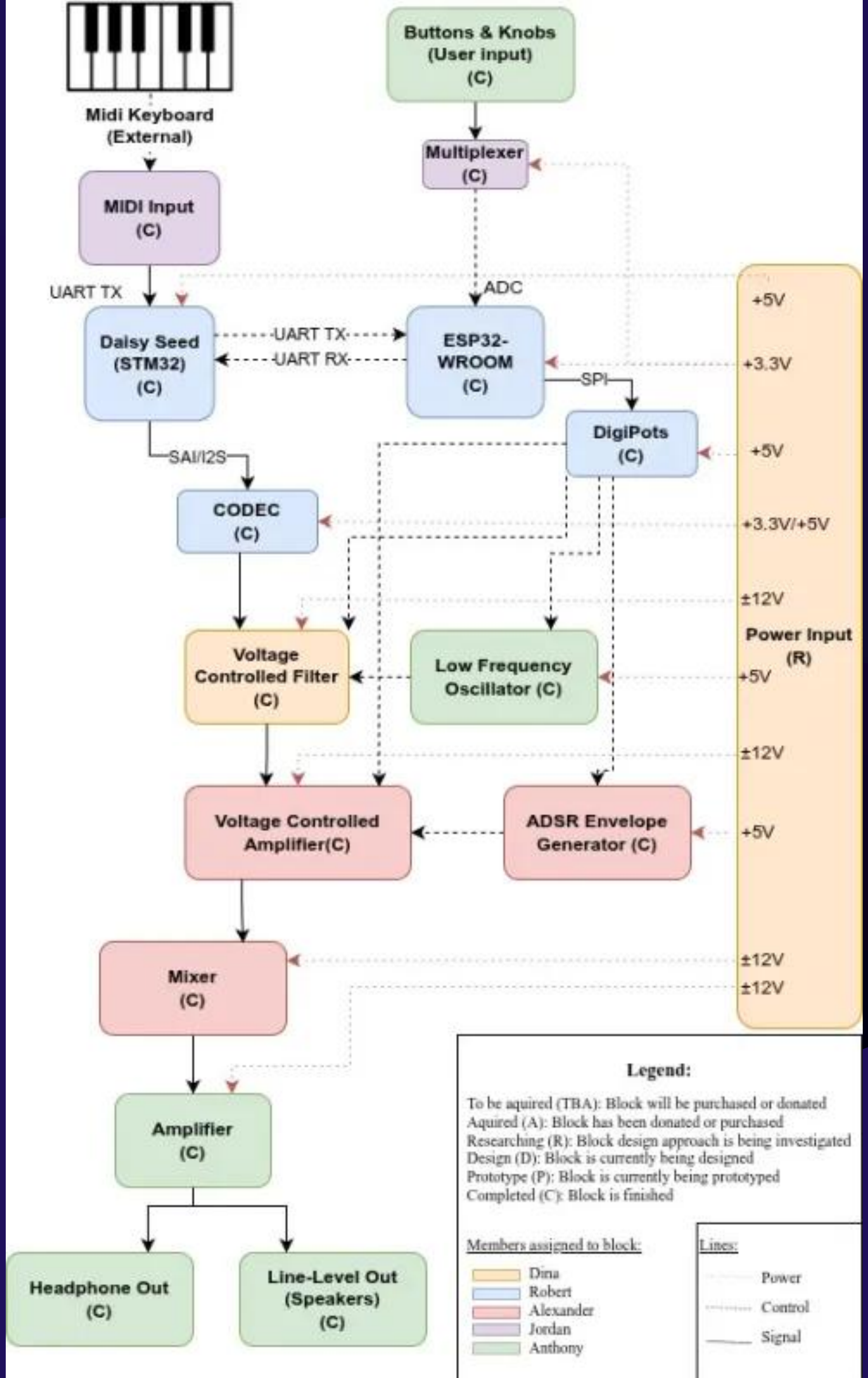


Marketing Requirements	Engineering Requirements		Output Impedance (Line-Level-Out)	Power Consumption	Number of Octaves	Time Delay	Filter Roll-off	Dimensions	Weight	Cost
			+	-	+	-	+	+	+	-
	Portability	+	↓	↓↓	x	x	x	↑↑	↓↓	x
	Affordability	+	↑	x	↓	x	x	↓	x	↓↓
	Features	+	x	↓↓	↑↑	x	↑	↓	↓	↓↓
	Sound Quality	+	↑↑	x	↑↑	↓	↑↑	x	x	↓
	Ergonomics	+	↓	x	↓	x	x	↓	↑↑	x
	Maintability	+	x	x	x	x	x	x	↑	↓↓
	Target Requirements		100-600 ohms	12V, Current TBD	2<V<6	<7 msec	12dB/Octave	18" x 12" inch	<10 Lbs	<200$

System Overview



Hardware Diagram



Technology Comparison: Integrated Circuits Vs Discrete Components

- Had to choose between designing circuitry from discrete analog components (transistors, resistors, capacitors) or integrated circuits
- Ultimately settled on integrated circuits
- Design feasibility was the most important factor

	Discrete Components	**Integrated Circuits (ICs)**
Design feasibility	Poor	Good
Noise sensitivity	Poor	Good
Temperature stability	Moderate	Moderate
Component availability	Good	Moderate

Microcontroller Unit

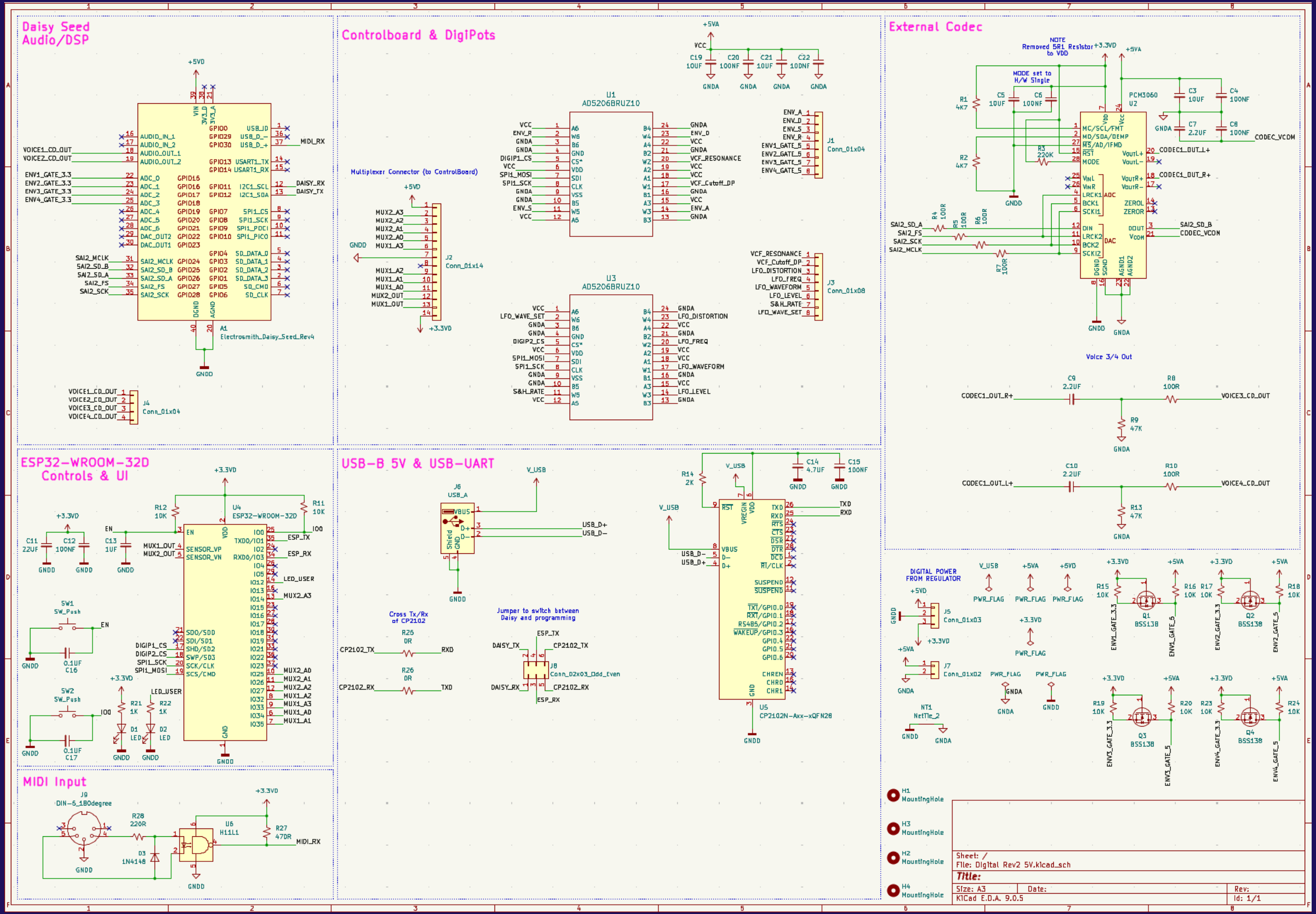
	MIMXRT1062	STM32H743	STM32H750	ESP32
Software Support	Moderate	Good	Good	Excellent
Library Support	Difficult	Moderate	Good	Difficult
Package Size	BGA-196	LQFP176	LQFP176	Custom
GPIO Specifications	3.3V Only	5V Tolerant	5V Tolerant	3.3V Only
Analog Peripherals	No DAC	Internal DAC	Internal DAC	Internal DAC/ADC
Flash Support	None	1MB	128KB	4MB
Performance	600MHz	480MHz	480MHz	240MHz
Cost	$10	$18	$10	$4

- While initially the STM32H750 was desired, after encountering insurmountable difficulty integrating it, the team pivoted to use the ESP32 as a master for controls.
- STM32H7 – Based Development board (Daisy Seed) is still used for audio signal generation due to its powerful libraries and audio-focused peripherals.

Hardware Design: Schematics

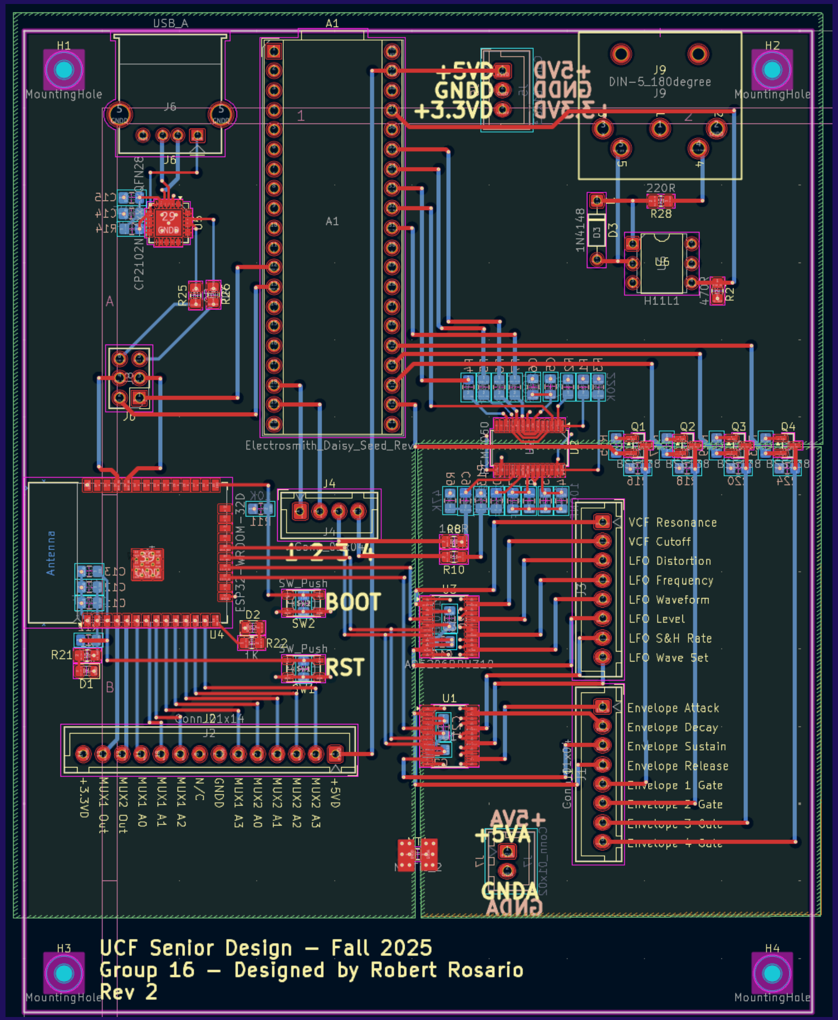
Digital Schematic

- Daisy Seed dev kit
- ESP32-WROOM-32D
- PCM3060 Codec
- MIDI input
- USB input
- CP2102 USB to UART
- AD5206 DigiPots
- Logic Level Shifters



Hardware Design: PCB

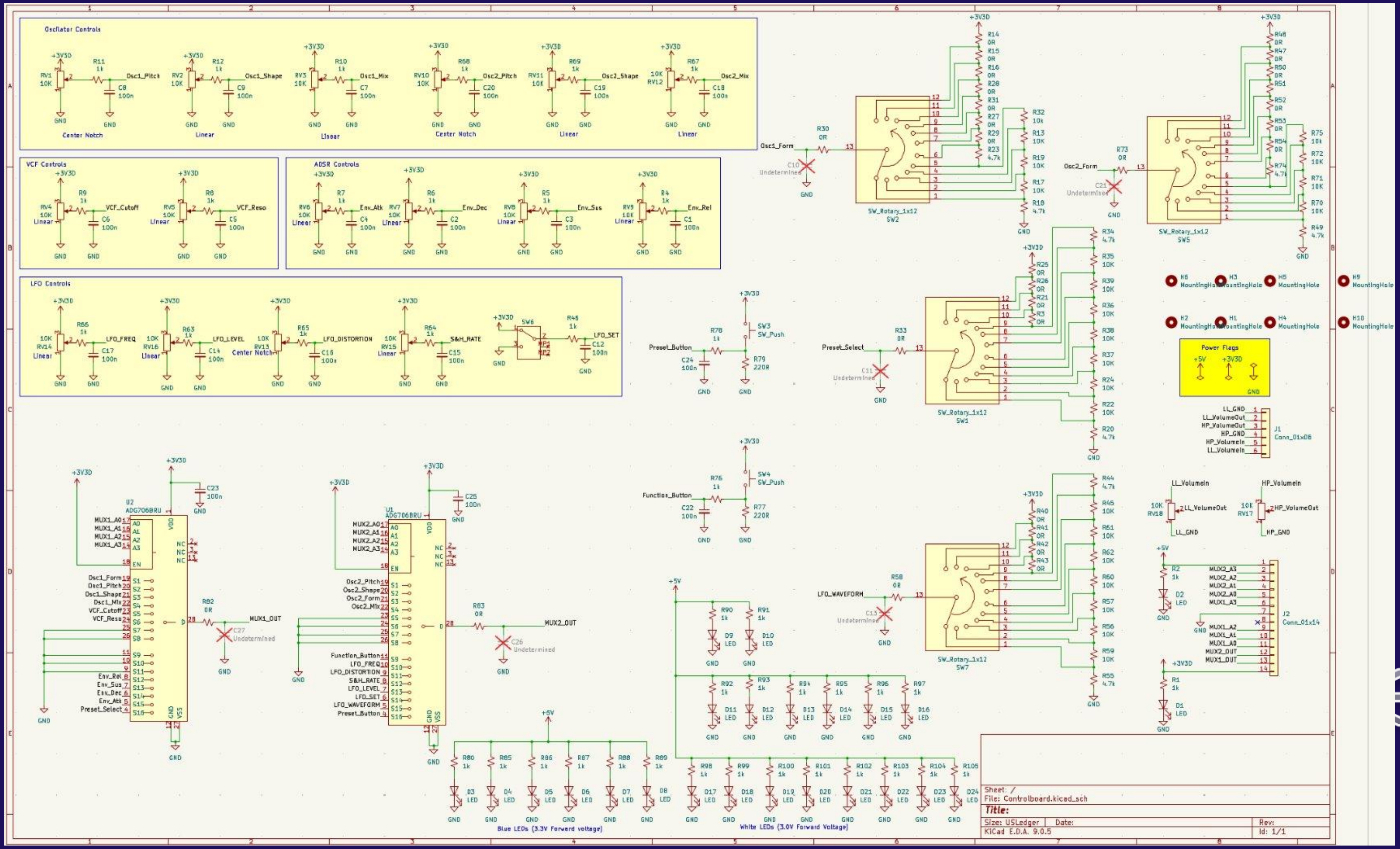
Digital Board



Hardware Design: Schematics

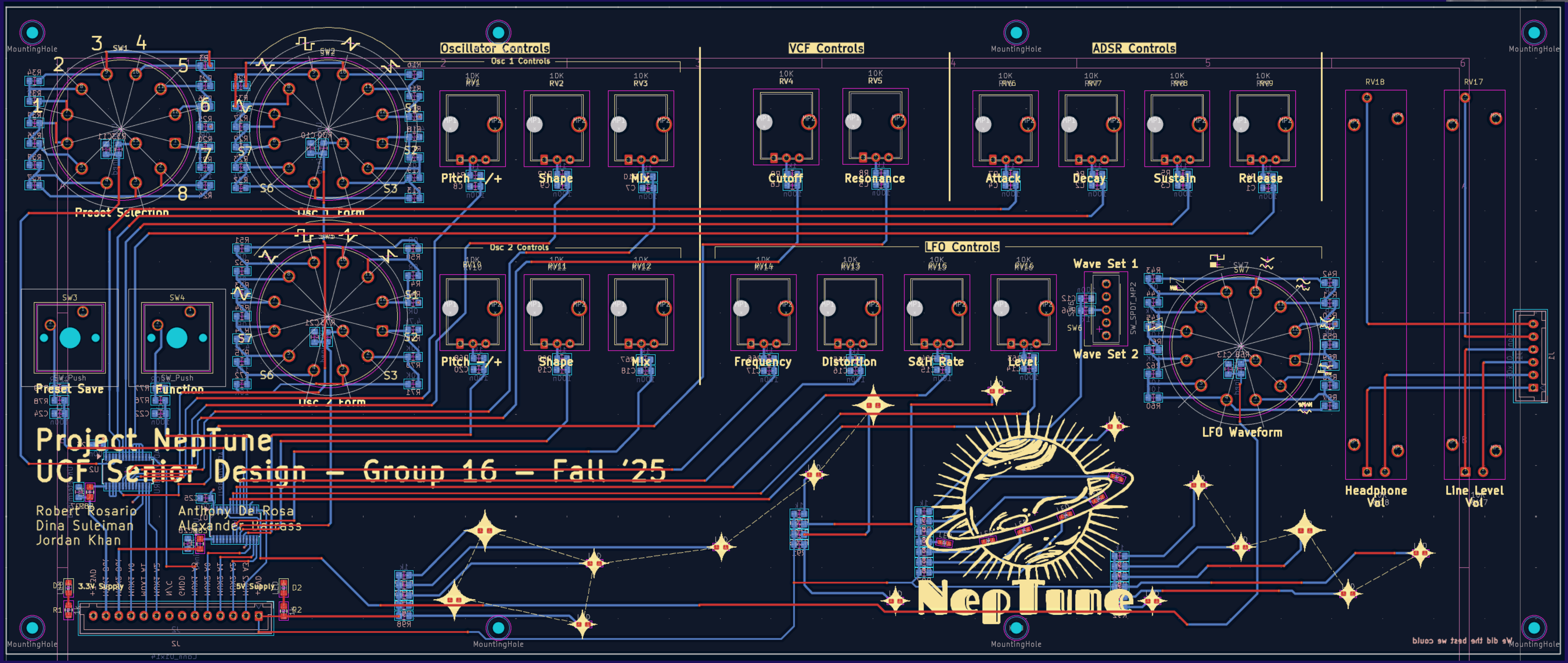
Control board

- Potentiometers
- Rotary Switches
- Toggle Switches
- 16:1 Multiplexers



Hardware Design: PCB

Control Board

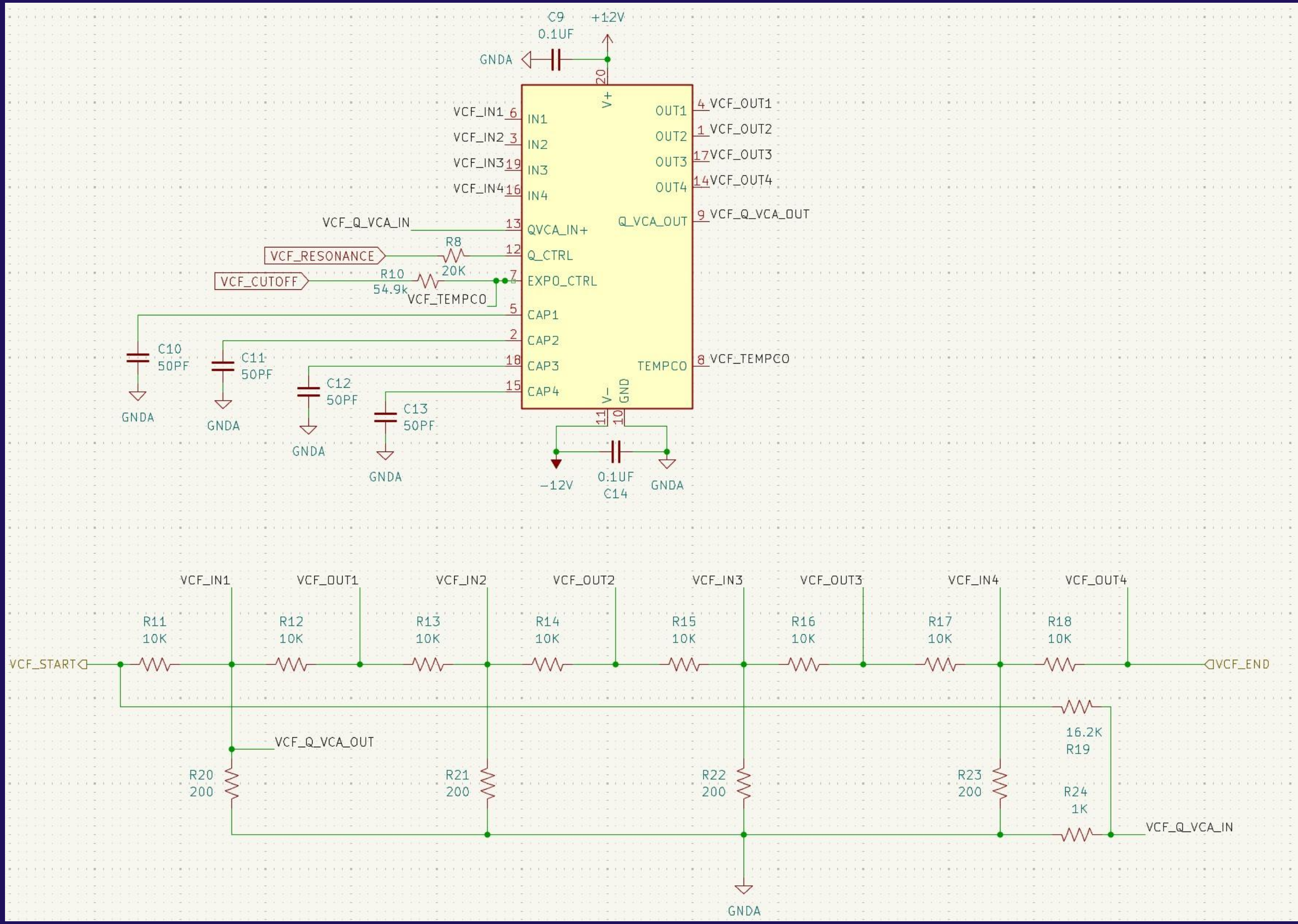


Voltage Controlled Filter (VCF)

	V3320	SSI2140	MF10-N	AS3320
Control Method	Linear- Current control	Voltage Control	Clock-signal Control	Voltage Control
Temp Stability	±200ppm/C	±50ppm/C	N/A digital	±200ppm/C
Supply Range	±4V to ±16V	±5V to 12V	±5V	±9V
Package	SOP-18 (SMT)	SOIC-16 (SMT)	DIP-14, SOIC-14	PDIP-18 QFN-24
Poles	State-variable 4-poles	State-variable 4-poles	Switched capacitor 2	State-variable 2-poles
Cost Range	5$	4$	4$	8$

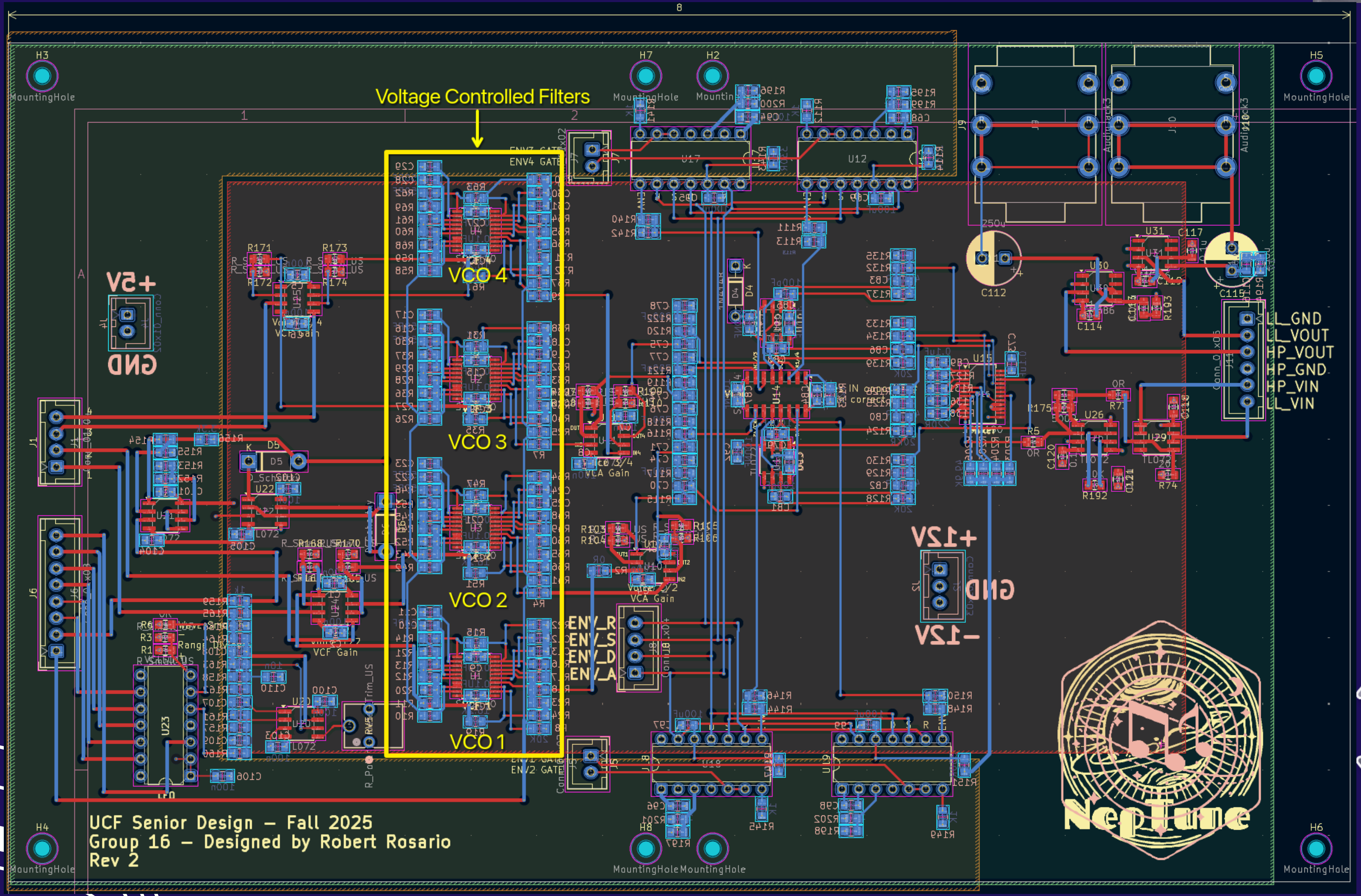
Hardware Design: Schematics

Voltage Controlled Filter (VCF)



Hardware Design: PCB

Voltage Controlled Filter



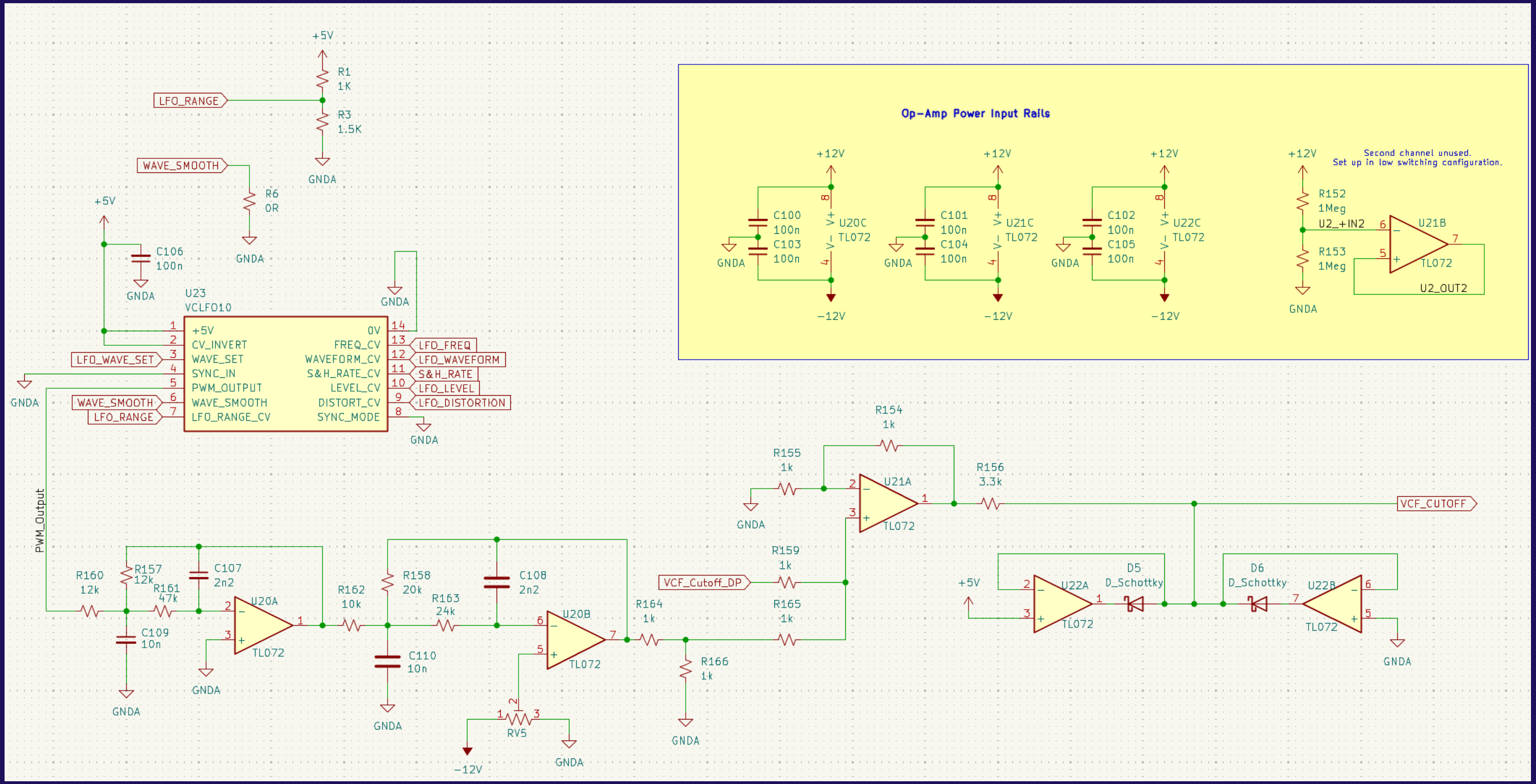
Low Frequency Oscillator (LFO)

	AD9833	TAPLFO3D	VCLFO10
Available Software Support	N/A	Yes	Yes
Package Size	10-pin MSOP	14-pin DIP	14-pin DIP
Low Frequency Output	0 Hz to 12 MHz	0.025Hz to >50Hz	0.05Hz to 102.4Hz
Desired Waveforms	Sine, Triangle, Square	Sine, Triangle, Square, Sawtooth, +12 more	Sine, Triangle, Square, Sawtooth, +12 more
Output Signal Type	Analog	PWM	PWM
Target Application	Sensing	Tap-tempo	LFO in musical synthesis
Cost	$15	$6	$6

VCLFO10 was selected for its specialized design, which combines the best aspects of both the AD9833 and the TAPLFO3D

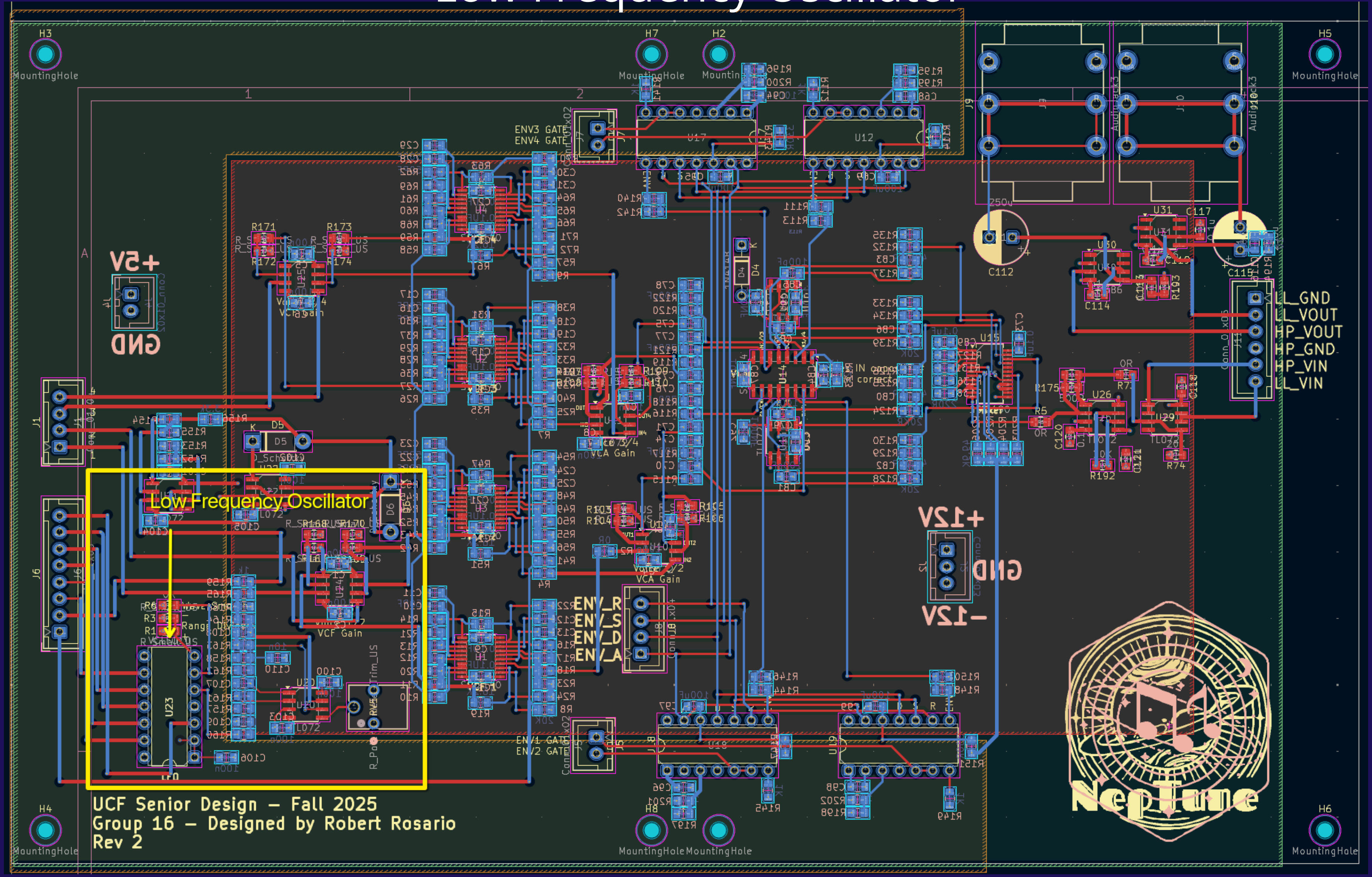
Hardware Design: Schematics

Low Frequency Oscillator (LFO)

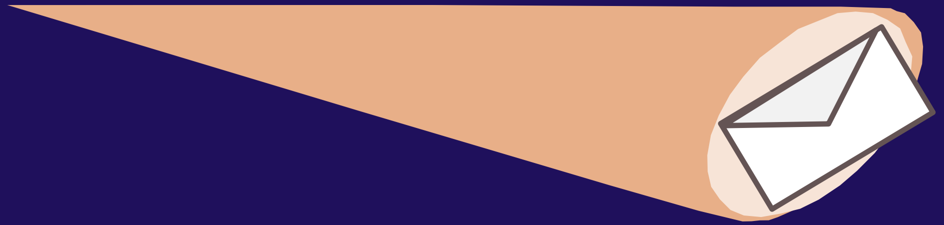


Hardware Design: PCB

Low Frequency Oscillator



Envelope Generator [ADSR]



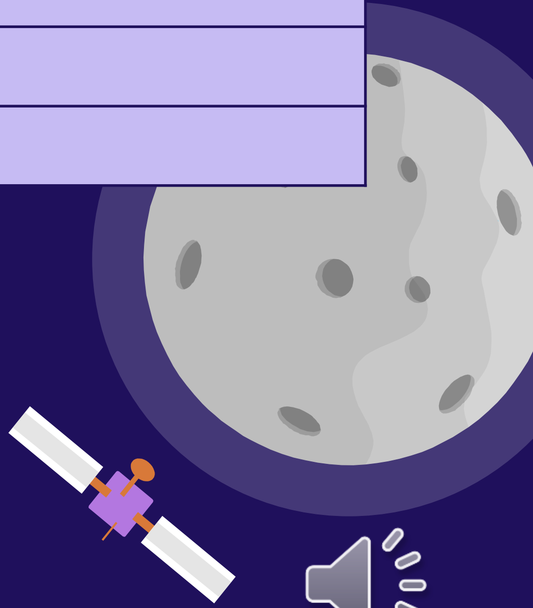
	AS3310	AS3360	ENVGEN8
Channels	1	1	1
Analog/Digital	Analog	Analog	Digital*
Timing Range	1ms – 10s	1ms – 5s	1ms - 10s
Linear/Exponential	Configurable	Exponential	Configurable
Power Range (V)	12 - 15	12 - 15	3.3 - 5
Difficulty of integration	Medium	Difficult	Easy
Cost (per voice)	$6	$6.40	$5.25

ENVGEN8 was selected for its ease of integration and the low supply power. The digital aspect to its performance also allowed us to reprogram its output which helped avoid additional components.

Voltage Controlled Amplifier (VCA)

	THAT2180	AS3360	SSI2164
Noise (µV RMS)	1.3	2.0	0.8
Response	Linear	Exponential	Configurable
Bandwidth	10MHz	500kHz	1MHz
Distortion	0.003%	0.03%	0.003%
Power Range (V)	12 - 15	5 - 15	12 - 15
Cost (per voice)	$10	$4	$3.75

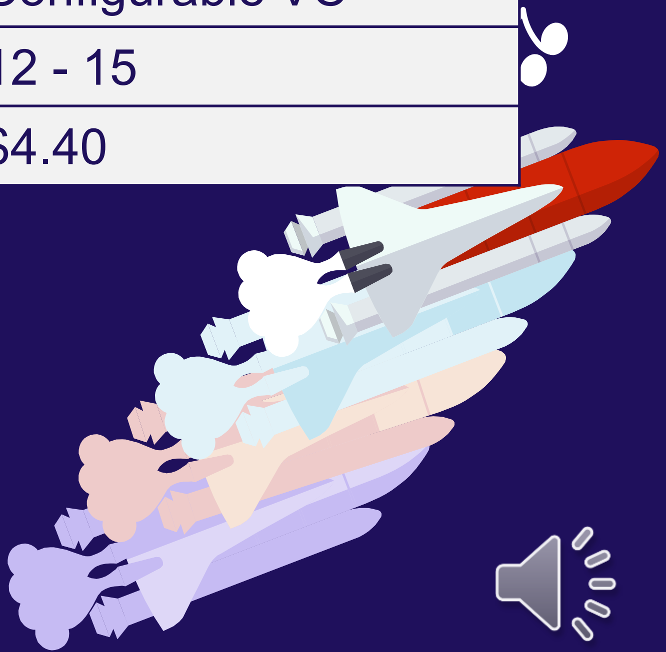
SSI2164 was selected for having the lowest noise rating along with having clearly documented integration with other Sound Semiconductor components.



Audio Mixer

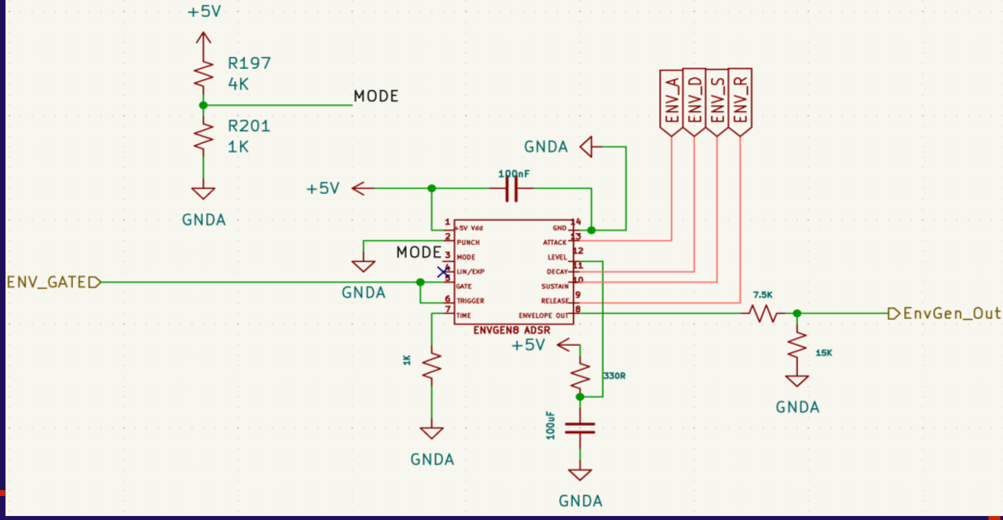
	SSI2190	SSI2130	CoolAudio V2164
Noise (dBu)	-100	-106	-94
Classification	Linear Mixer	Stereo Mixer	Quad VCA
Channels	6	2	4
Gain Control	Fixed (None)	Exponential VC	Configurable VC
Power Range (V)	12 - 15	12 - 15	12 - 15
Cost (per voice)	$5.36	$5.40	$4.40

The mixer selected was the SSI2190 for hosting the largest number of available channels and because it perfectly satisfied our needs for noise reduction.

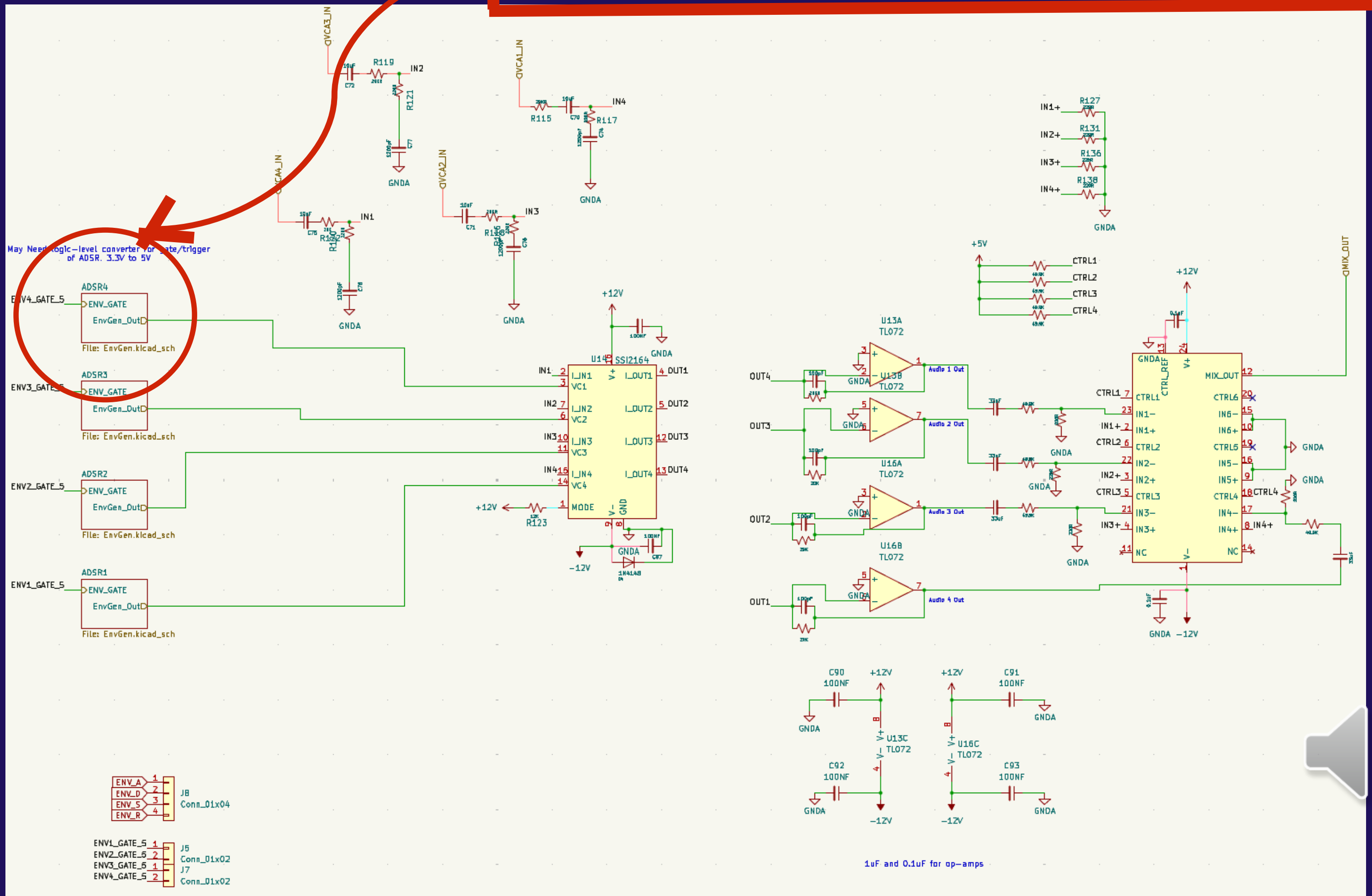


Hardware Design: Schematics

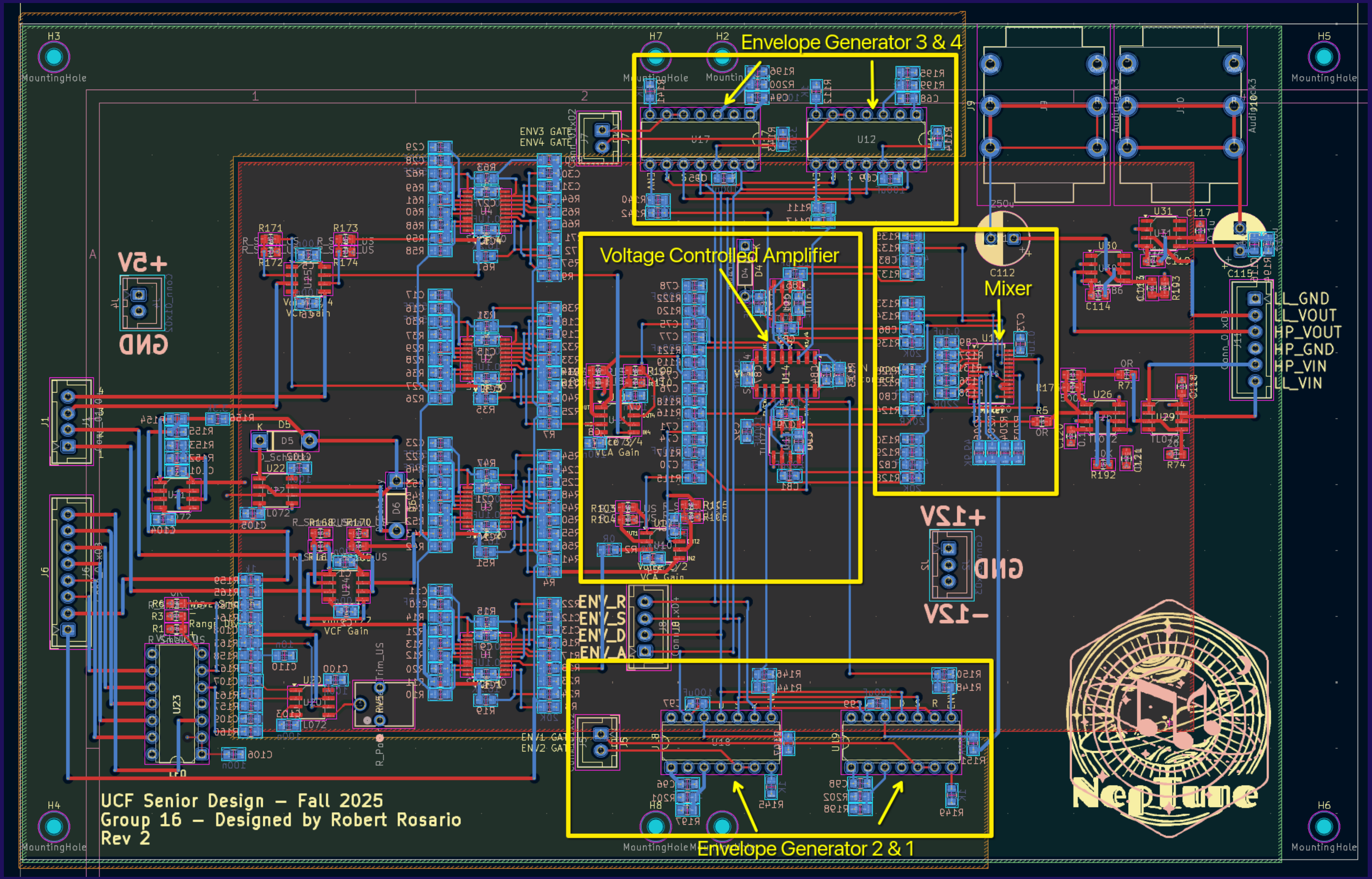
Envelope Generator (ADSR)



Voltage Controlled Amplifier (VCA) with Mixer



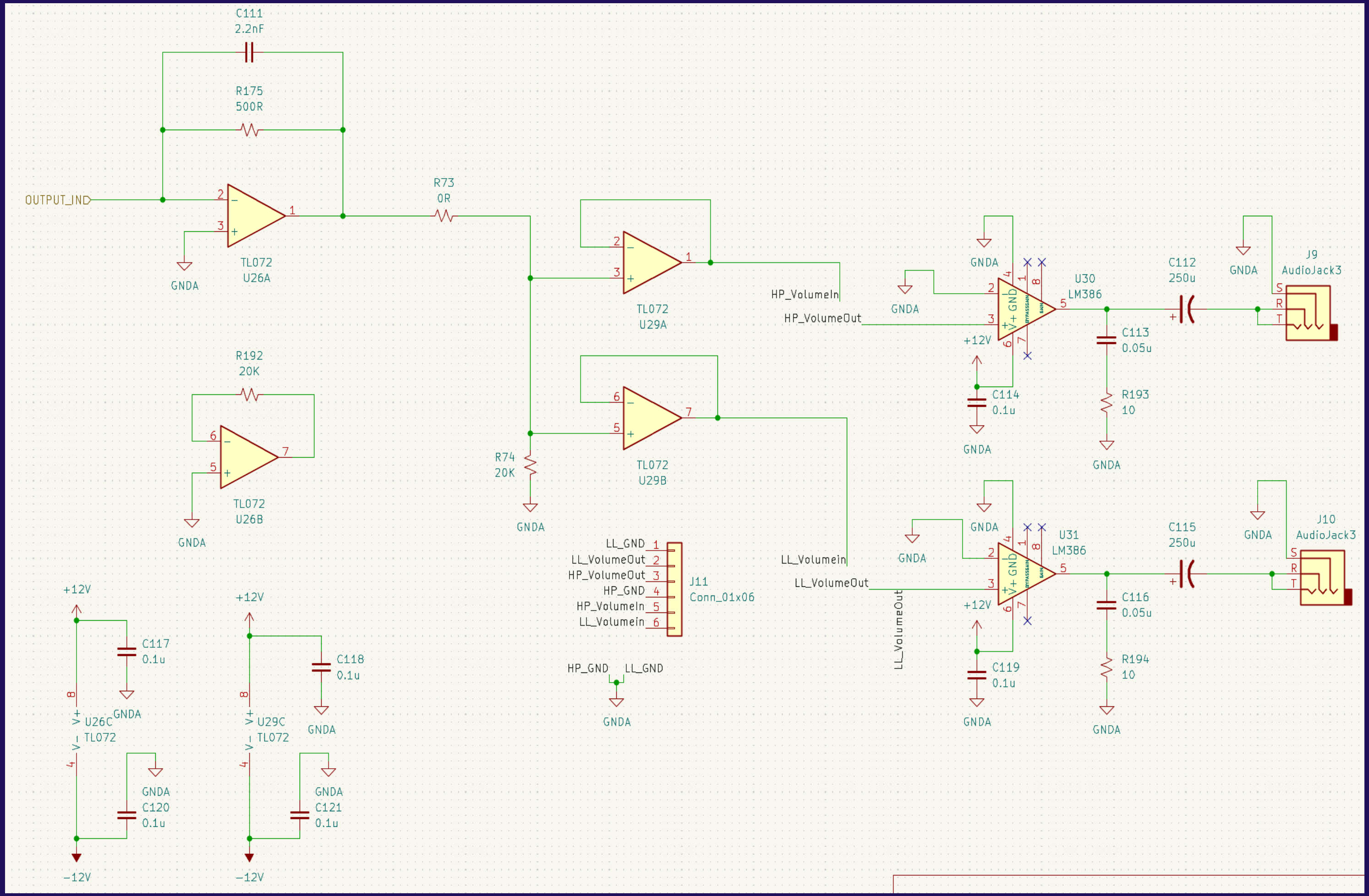
Hardware Design: PCB



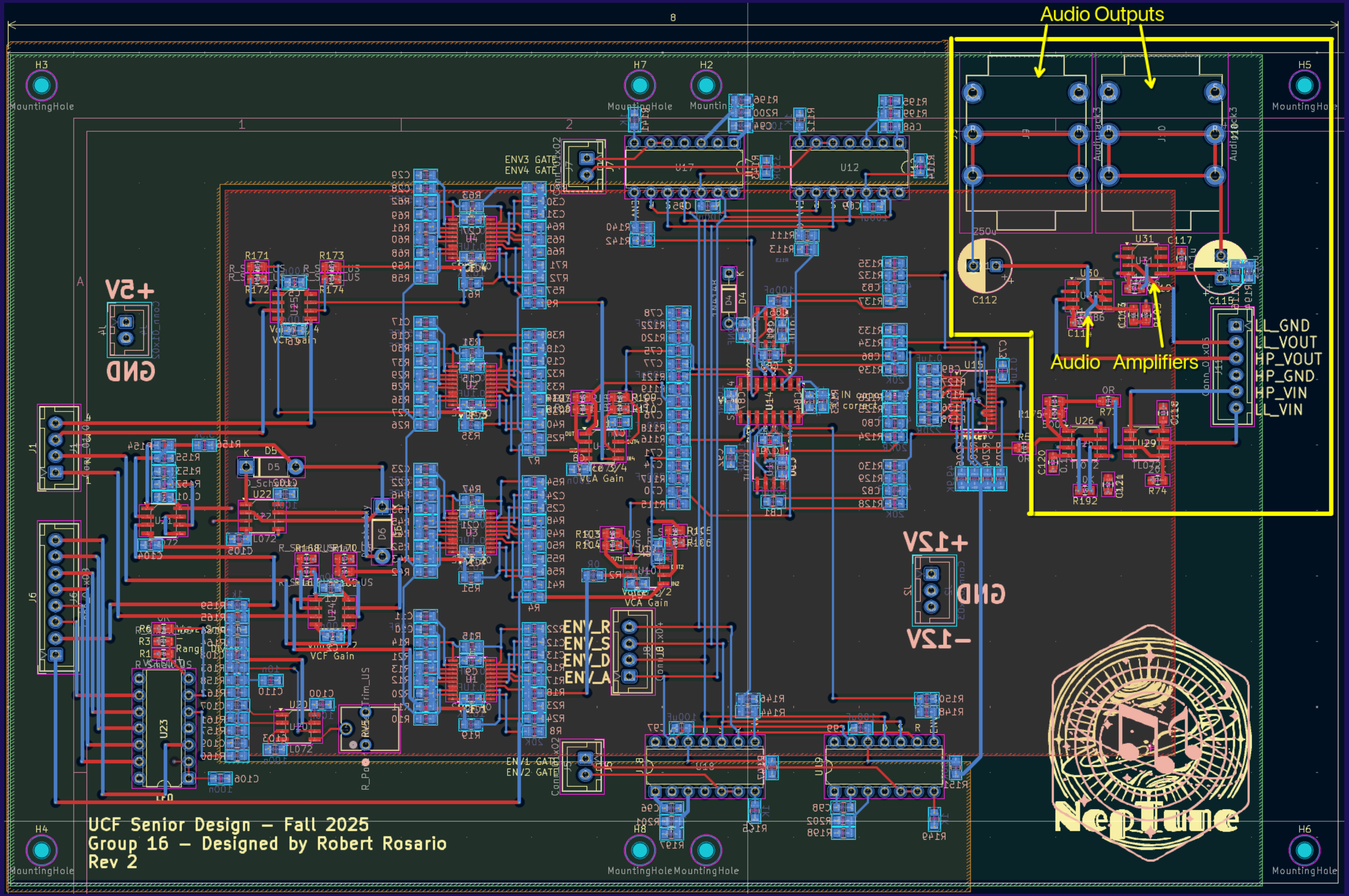
Hardware Design: Schematics

LM386

- Dedicated Audio Amplifier
- Wide supply Voltage range 4V – 12V
- Voltage Gain of 20
- Low distortion: 0.2%
- Available in SOIC package



Hardware Design: PCB



Power Requirements

Part	Description	Digital (D) or Analog (A) Power	Input Voltage (per IC)	Input Current (per IC)
ADG706	MUX	D	+3.3V	10mA
AD5206	DigiPOT	D	+3.3V	4mA
PCM3060	CODEC	A & D	+5V(A) & +3.3V(D)	10mA
ENVGEN 8D	ADSR Env. Gen.	A	+5V	5mA
VCLFO 10	LFO	A	+5V	5mA
TL074 (Not acquired)	Op-amp	A	+/-12V	10mA (for TL084)
Daisy Seed	Embedded platform for audio applications	D	+5V	200mA
ESP-32	Microcontroller	D	+3.3V	40mA
SSI2190	Mixer	A	+/-12V	11.4mA
SSI2164	VCA	A	+/-12V	6mA
SSI2140	VCF	A	+/-12V	11 mA

Power Supply Unit

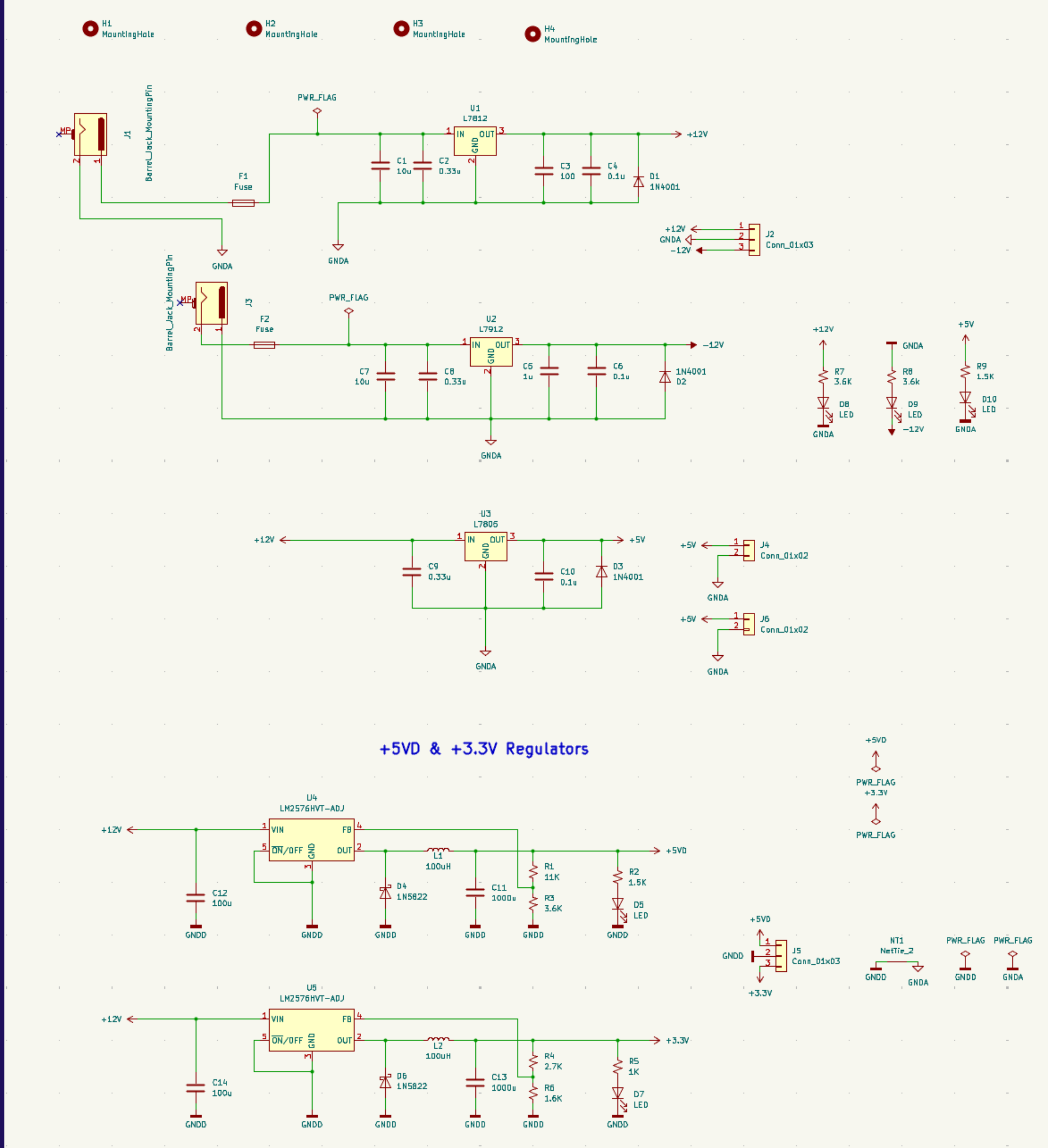
	LT3045	TPS7A47	LM317	L78XC	LM2576-A
Noise Generation level	Ultralow	Ultralow	Low	Low	High
Output Voltage	Adjustable 0-15V	Adjustable 1.4 - 20.5V	Adjustable 1.25 - 37V	Fixed 12V & 5V	Fixed 3.3V
Current Generated at Voltage dop	500mA @ 260mV	1A @ 307mV	1.5A	1A @ 2V	0.5A to 3A
Cost	$10.45	$6.28	$0.41	$0.48	$8.51

Hardware Design: Schematics

Power schematic with:

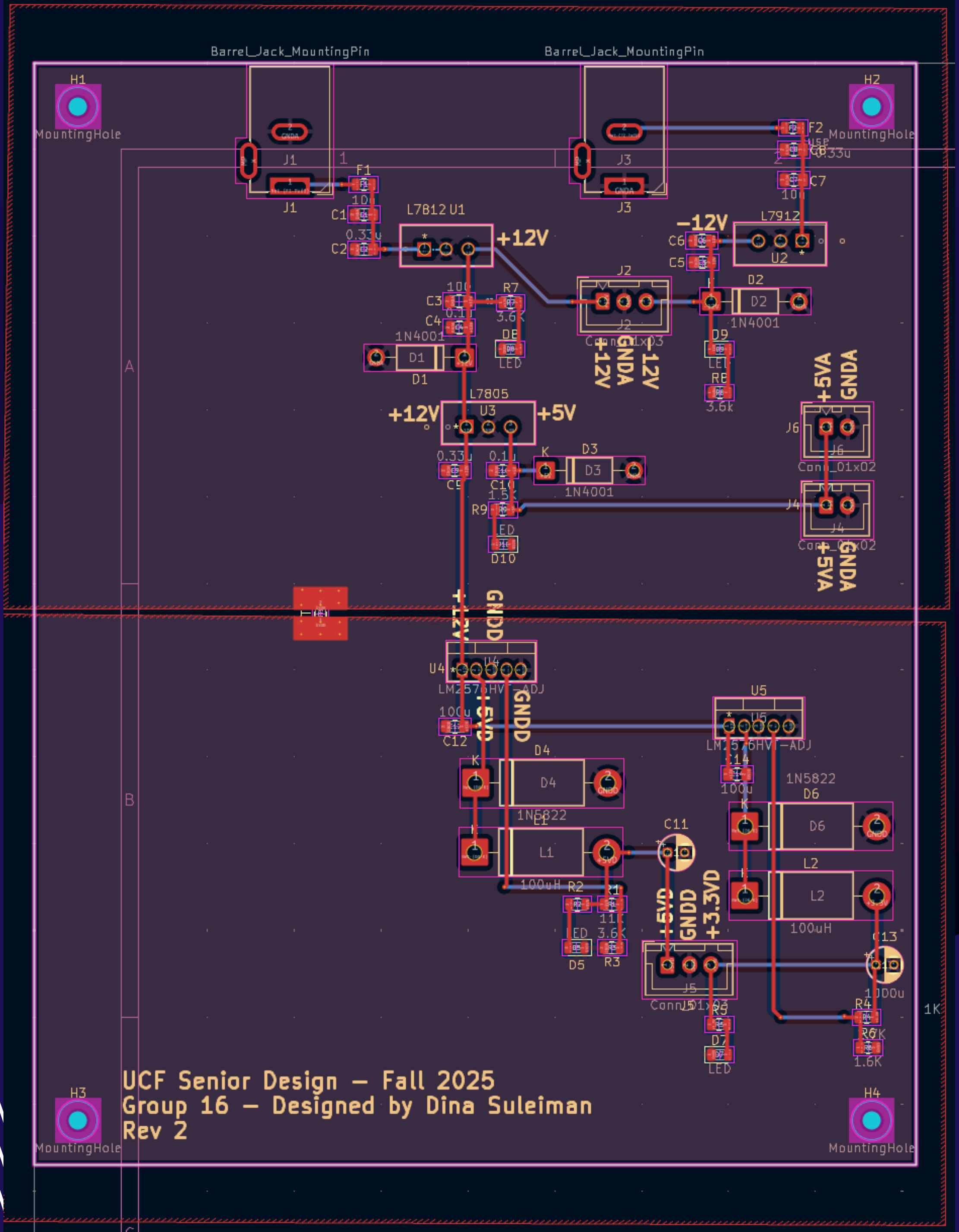
- LM7812
- LM7912
- LM7805
- LM2576

- Mention wrong 7912 symbol in kicad...

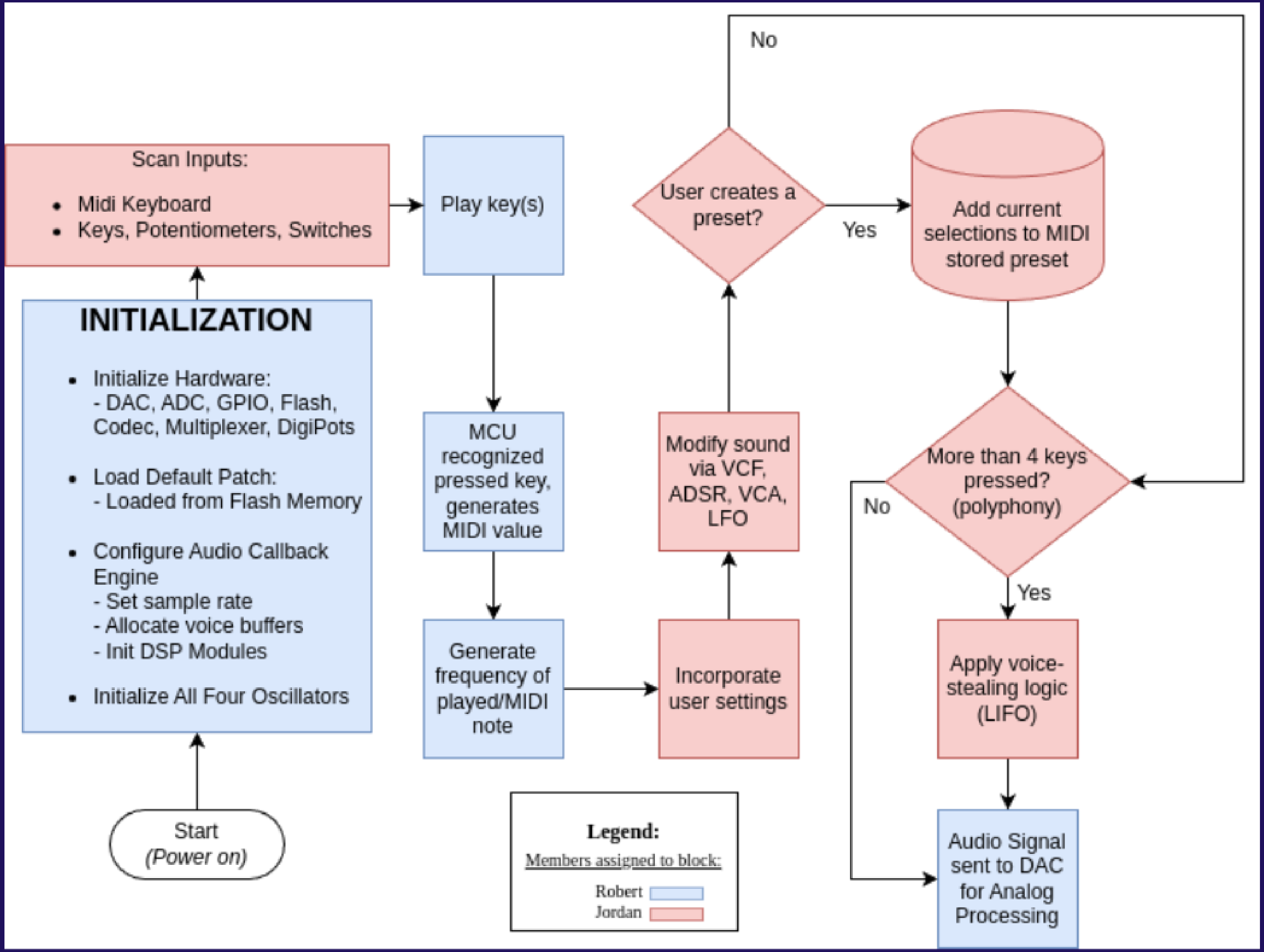


Hardware Design: PCB

Power Board

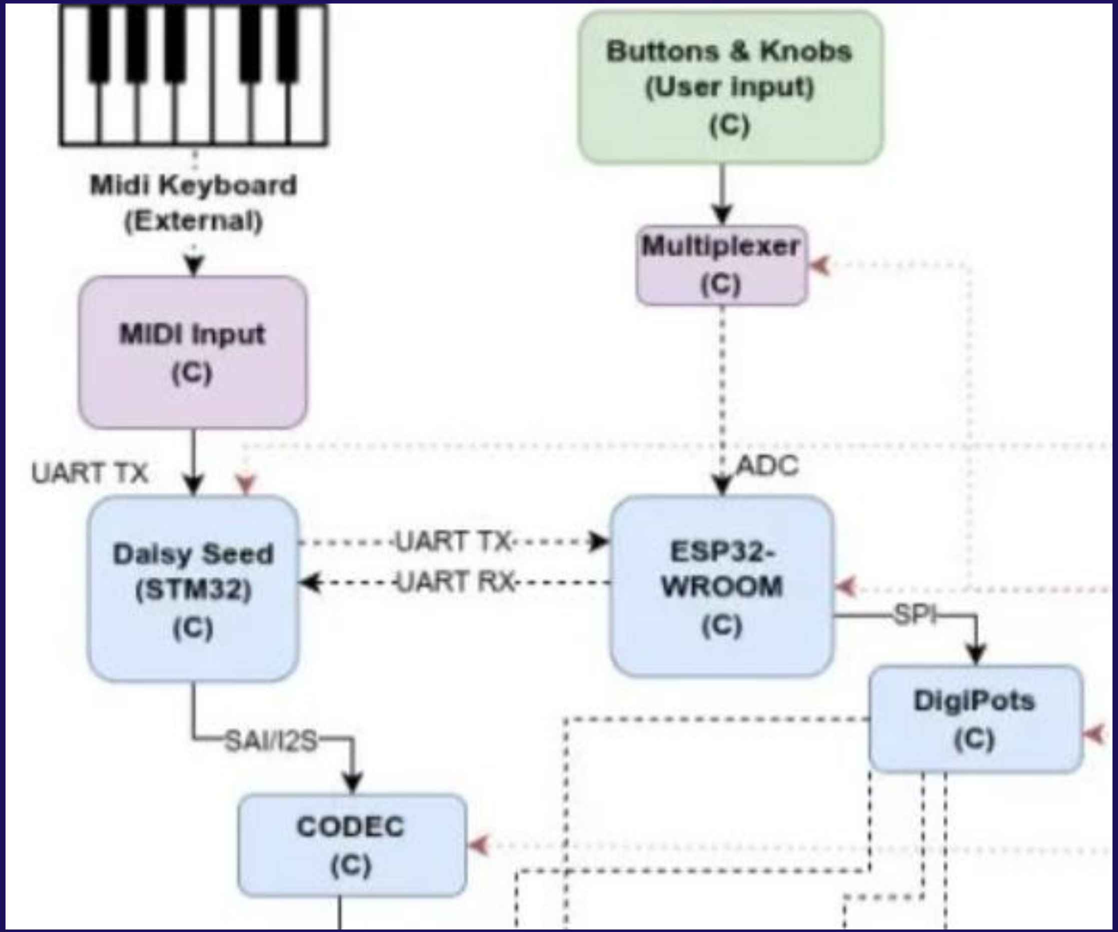


Software Design: Overall Flowchart



Communication Protocols

- UART
  - ESP WROOM-32/DaisySeed (STM32H7)
  - MIDI Keyboard Controller
- SPI
  - 2x AD5206 Digipots (Comm. with ESP32)
  - 2x ADG706 Multiplexors (Comm. with ESP32)
- SAI/I2C
  - 2x PCM3060 Codecs (Comm. with STM32)



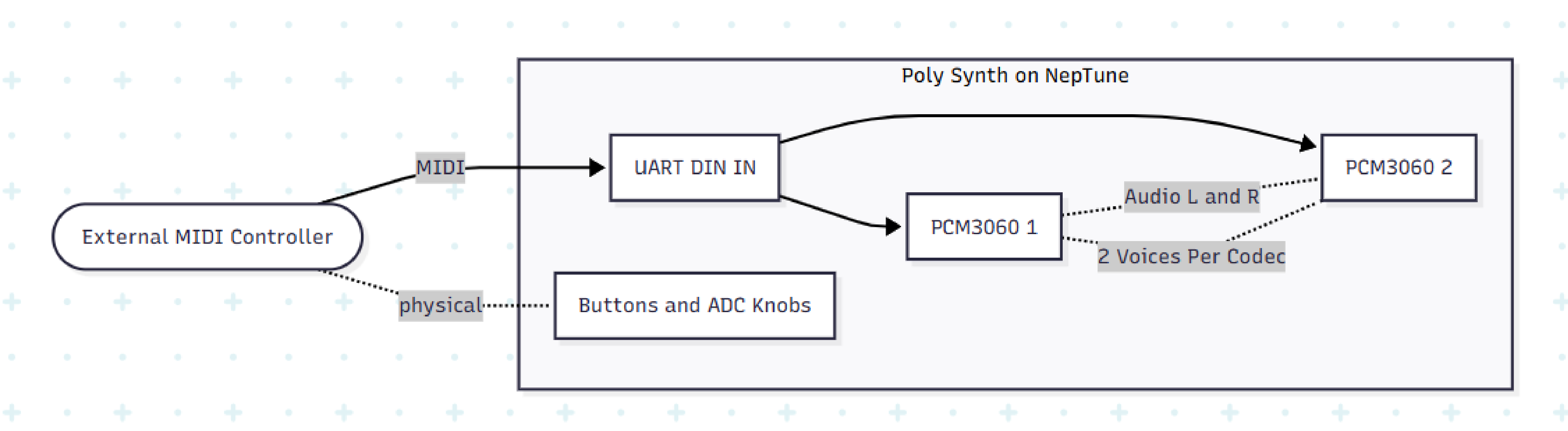
Pros and Cons of Various Libraries

	LibDaisy & DaisySP	Teensy Audio Library	Bela C++ API with libpd
Audio and DSP Capabilities	A rich and curated set of modules; floating-point precision and optimized for STM32	Moderate but accessible DSP toolkit; fixed-point arithmetic; static audio graphs and ease of use	Derives its audio capabilities from Pure Data; DSP highly flexible and comprehensive in coverage
Runtime Flexibility and Workflow	Conventional embedded development cycle; deep control over the firmware and timing	Semi-flexible workflow; convenient for visual learners and suitable for fast prototyping	Excels in runtime flexibility; live coding-like experience; makes the test/debug cycle fast and fluid
Integration and Portability	Written in portable C++; reused in desktop or plugin projects; can be written in Arduino (DaisyDuino)	Tightly coupled to PJRC hardware and Arduino-style C++; limiting reuse outside that ecosystem	Pd patches and libpd engine are highly portable across platforms; stands out in system integration
STM32 Compatibility	High STM32 compatibility; can theoretically be adapted to other STM32 boards	Targeting ARM Cortex-M processors; does not support STM32 natively	Running on a BeagleBone Black with a Linux OS; not compatible with STM32 at all

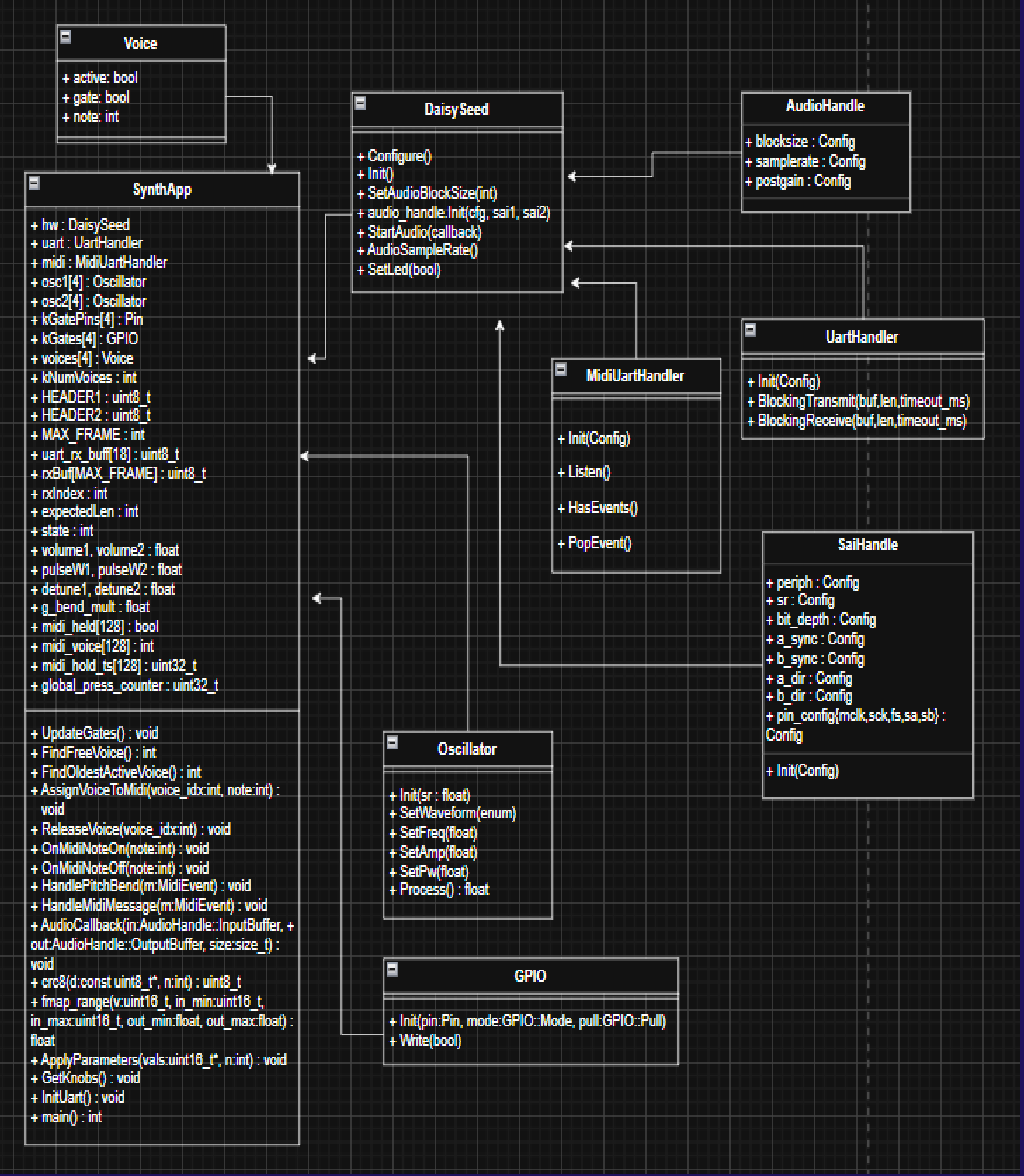
Pros and Cons of Languages Used by Teensy, Daisy Seed, and Bela

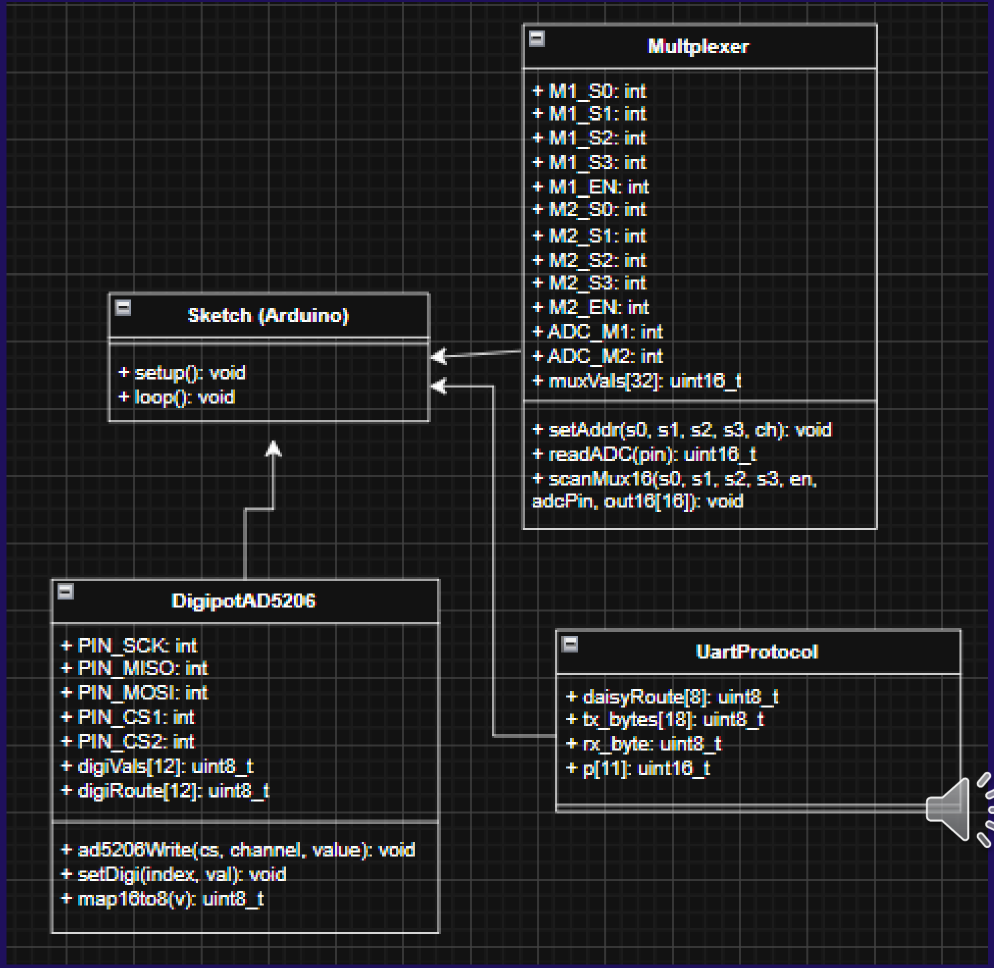
	C++	Arduino C++	Pure Data (Pd)
Programming Paradigm and Abstraction	Can implement any algorithm given enough coding effort	Can implement any algorithm given enough coding effort with simpler project structure	Graphical dataflow paradigm instead of text; less programmatic flexibility
Learning Curve and Accessibility	Hardest to learn, requiring formal programming study	Built on C++ but packaged in a beginner-friendly IDE and API	Most accessible for non-programmers in the audio domain
Performance and Resource Usage	Generally, yields high performance and low overhead	Reasonably fast but bounded by MCU hardware constraints	Uses more CPU and memory to support dynamic patching
Toolchain and Development Workflow	Involve a code-edit-compile-deploy cycle; powerful but can be complex	Simpler than a raw C++ toolchain at the cost of advanced features	Workflow is fundamentally different; less suited to structured software engineering

Simple Audio Flowchart

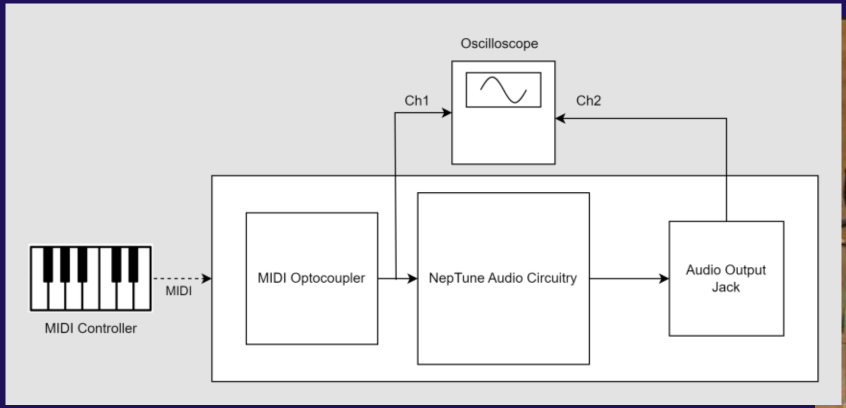


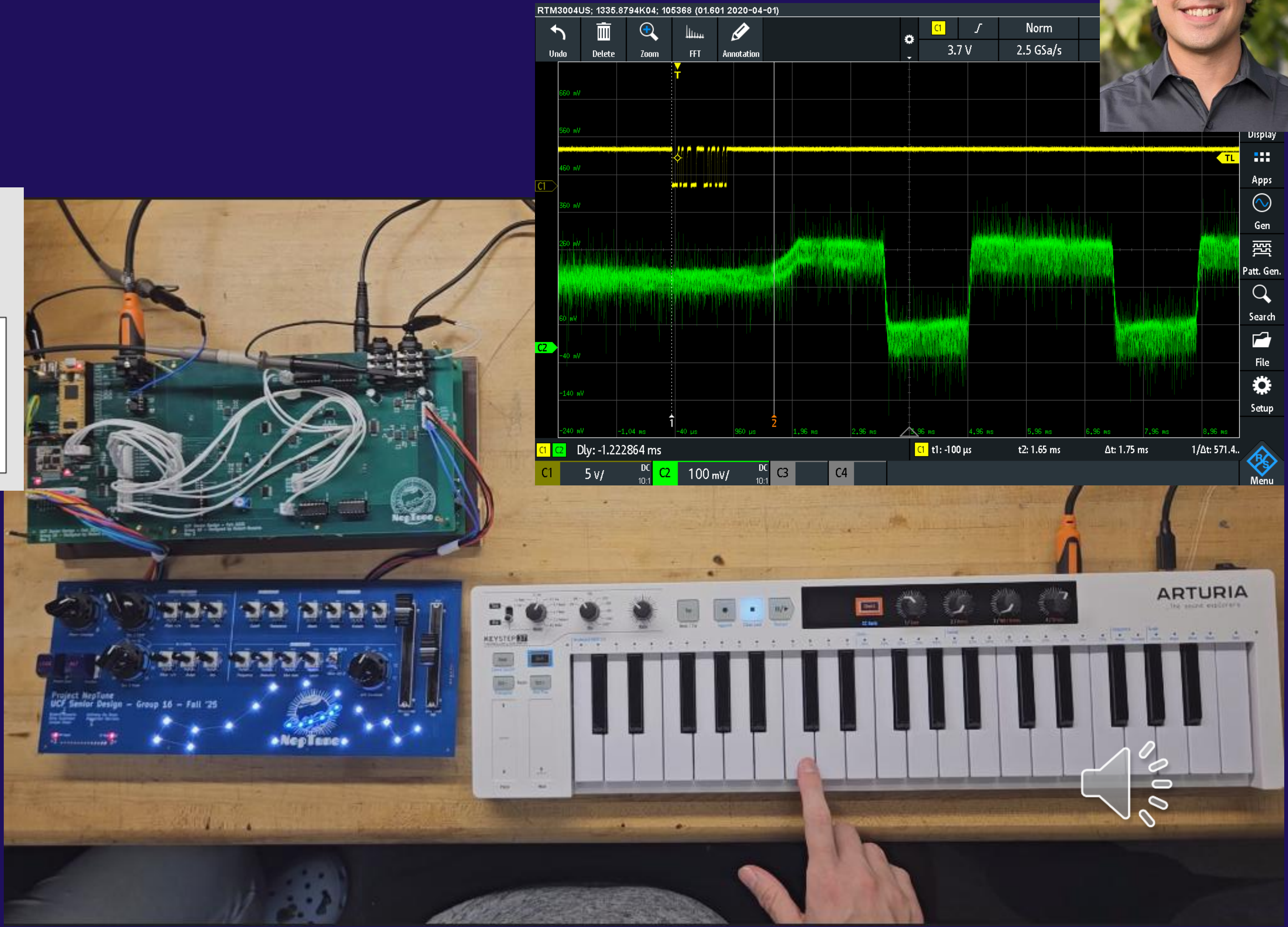
Class Diagram – Key types and relations





Testing: Time Response



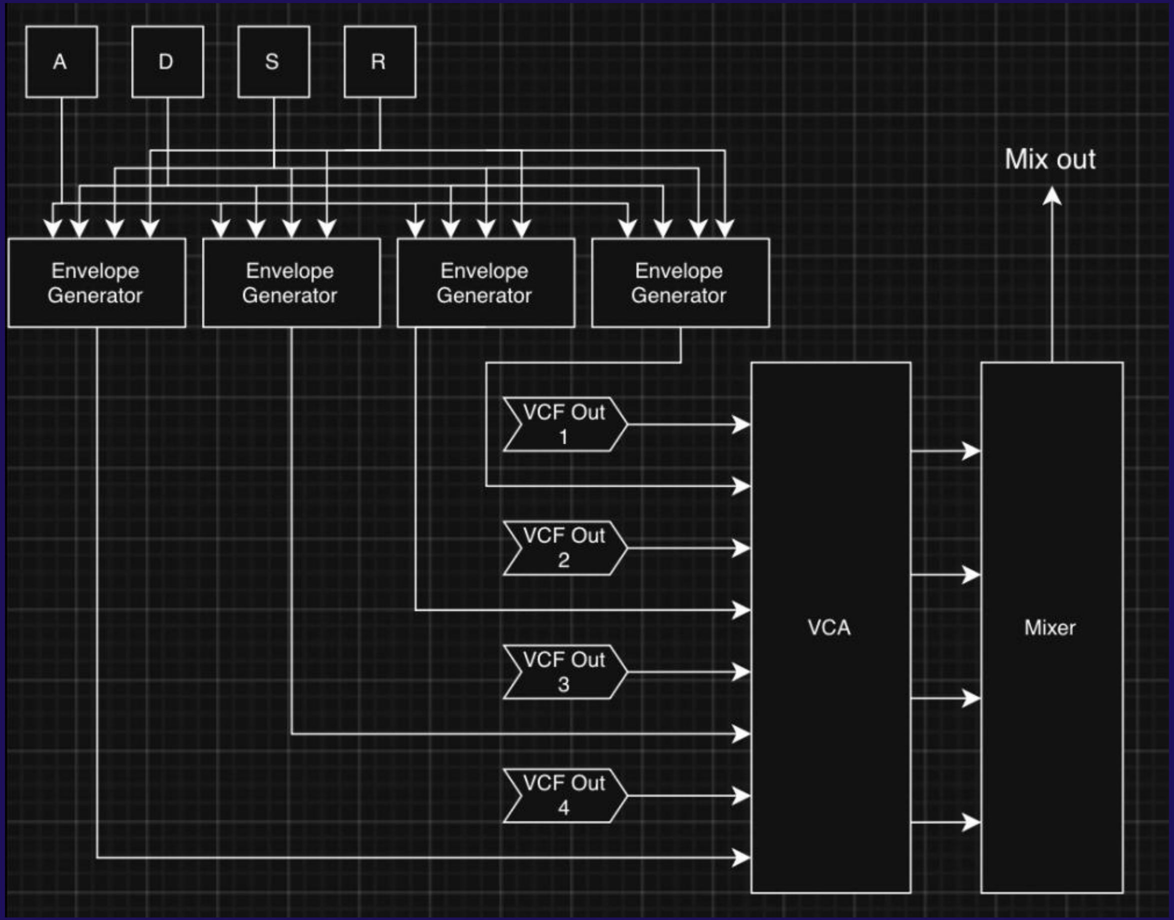


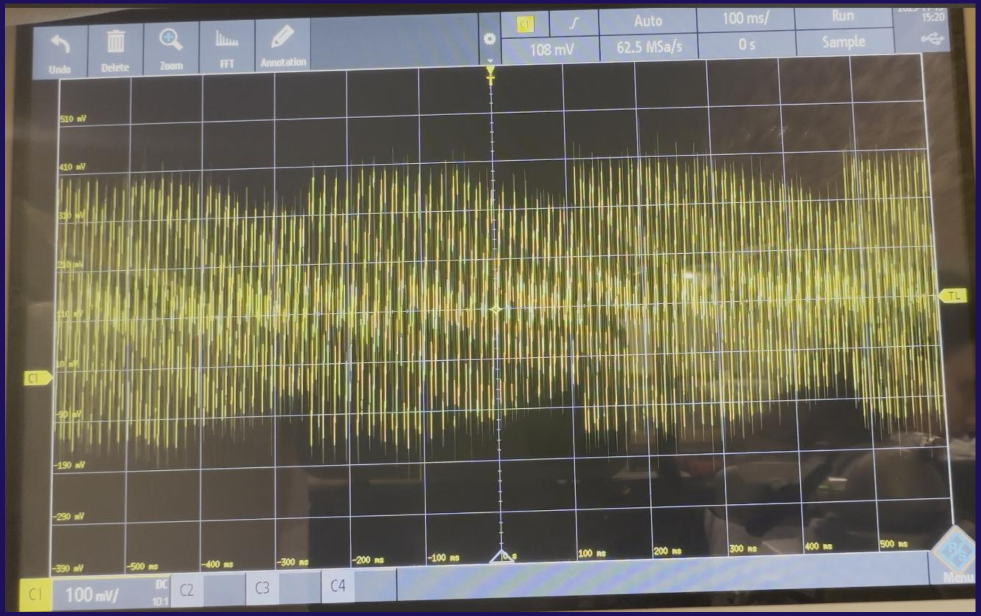
Oscilloscope:

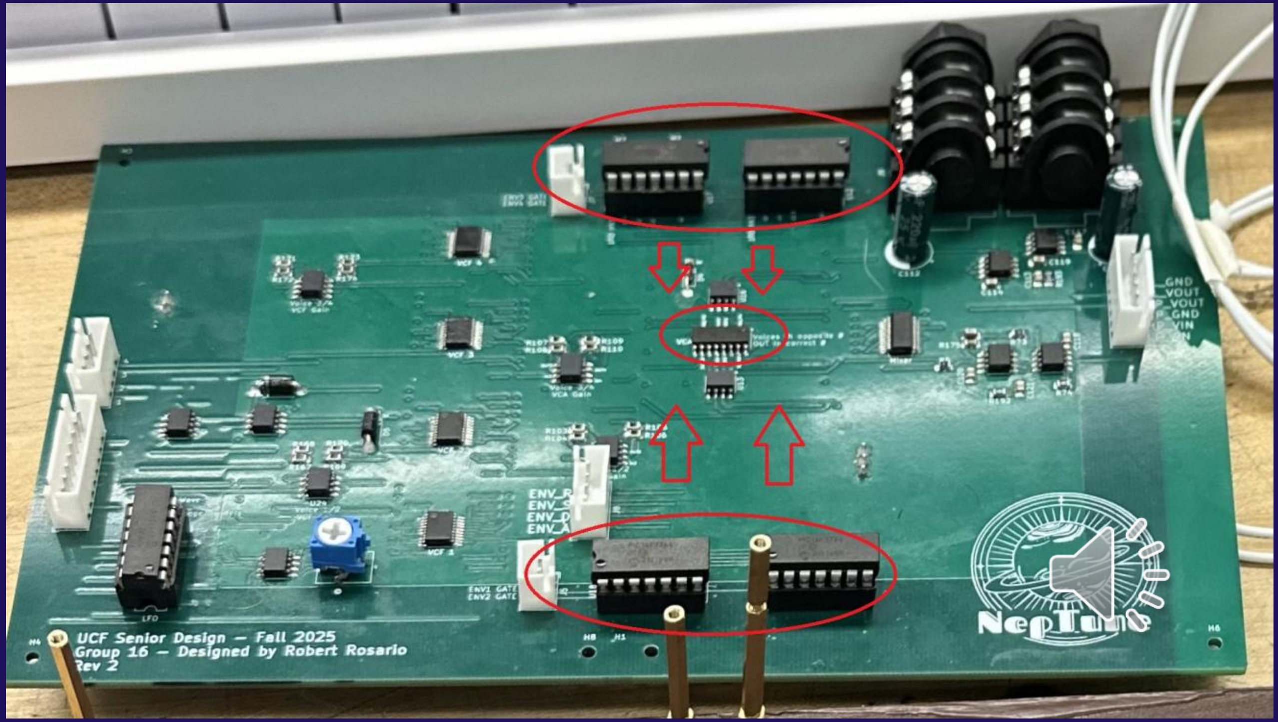
- Channel 1: MIDI optocoupler
- Channel 2: Audio Jack

Time Delay Average = 4.27ms

Prototyping and Testing:
Envelope Generator & VCA







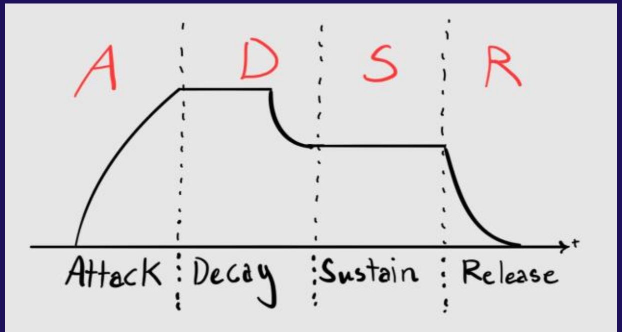
Prototyping and Testing:
Envelope Generator & VCA

Ch.1 ADSR
Ch.2 VCA out

VCA output is combination of VCF output and envelope shape.

Video shows [A,D,S,R] being manipulated in real time.

Output of VCA measured ~1.5V which is within the range of operation for the mixer.



Difficulties during design

- We had difficulty getting communication working for the STM32 which required us to pivot and use the Daisy Seed Development board and the ESP32.

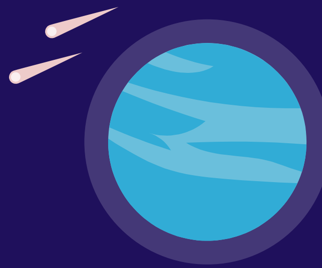
- Novel challenges we faced were the separation of digital and analog grounds, low noise design, inter-circuit board connections.

- Difficulties with testing the board all at the same time as many components were housed on the same PCB and required us to take turns testing in time.

- Envelope Generator IC had to be reprogrammed to accommodate for design choices.

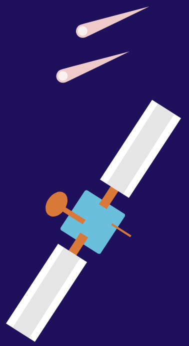
Administrative content: Work Distribution

Deliverables	Primary	Secondary
Filters	Dina	Anthony
LFO	Anthony	Dina
Amplifiers	Alex	
ADSRs	Alex	Robert
Mixer	Alex	Anthony
Power	Dina	
Audio Output	Anthony	Dina
Microcontroller	Robert	Jordan
Software	Jordan	Robert
DAC	Robert	Jordan
USB MIDI	Jordan	
Controlboard	Anthony	Robert
Motherboard	Robert	
Website	Anthony	Dina



Administrative Content: Budget

Item	Description	Budget allocation
Daisy Seed	Daisy Seed development boards by Electrosmith. This will be used to accelerate prototyping.	$65
Buttons, Pots, & Switches	Buttons and potentiometers the user needs to interact with the synthesizer.	$70
Parts	Miscellaneous components such resistors, capacitors, and inductors.	$635
PCBs	All PCBs required for this build.	$240
ST Links	Required for programming the STM32.	$20
Screen	Screen and related hardware.	$35
Other	Miscellaneous and unexpected costs.	$110
TOTAL:		$1175



Future Progress plan

Work into making the chassis water resistant.

Expansion of voices to handle up to 6 voices at a time.

Safety and standard integration techniques

Optimizing software to generate better performance and reponse.

Feature expansion to encapsulate more of what is possible for synthesizers.

Finishing integration of AC rectifying power board to avoid double DC power jack.

Thank you!

Questions?