

Embedded Virtual Analog Modelling with Recurrent Neural Networks

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Virtual Analog Modelling

Creating a digital emulation of a classic analog audio effects.

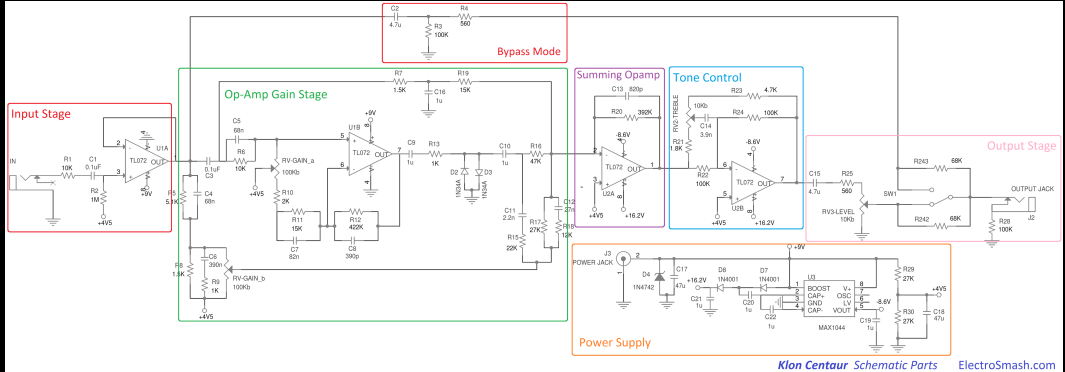
- Provide access to effects that are old or rare.
- Lower cost.
- Convenience.
- Improved understanding.

Klon Centaur

Guitar pedal made by Bill Finnegan (MIT) from 1994-2000



Klon Centaur Circuit Schematic



Klon Centaur Schematic Parts ElectroSmash.com

Traditional Circuit Modelling

Nodal Analysis¹

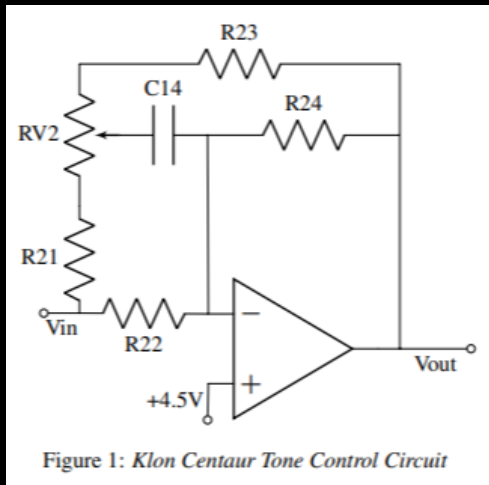


Figure 1: Klon Centaur Tone Control Circuit

¹Smith, *Physical Audio Signal Processing*; Maby, *Solid State Electronics*.

Nodal Analysis

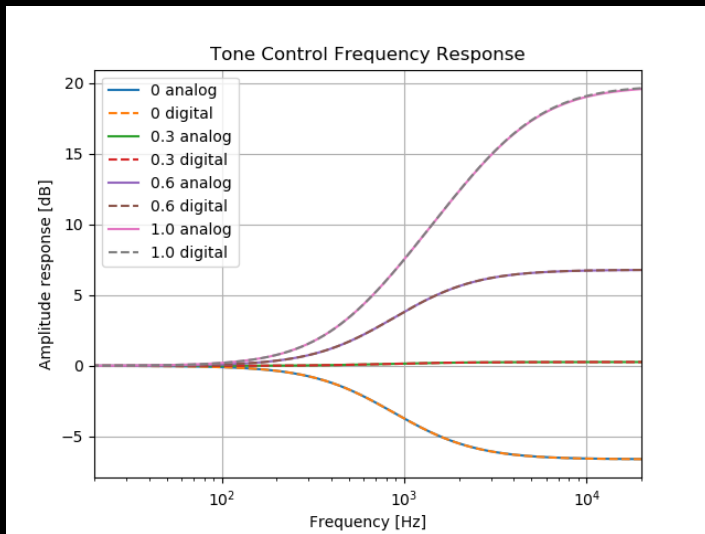
Laplace domain transfer function

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{C_{14} \left(\frac{1}{R_{22}} + \frac{1}{R_{21} + R_{v2b}} \right) s + \frac{1}{R_{22}} \left(\frac{1}{R_{21} + R_{v2b}} + \frac{1}{R_{23} + R_{v2a}} \right)}{C_{14} \left(\frac{1}{R_{23} + R_{v2a}} + \frac{1}{R_{24}} \right) s + \frac{-1}{R_{24}} \left(\frac{1}{R_{21} + R_{v2b}} + \frac{1}{R_{23} + R_{v2a}} \right)} \quad (1)$$

Bilinear transform (or other conformal map)

$$s \leftarrow \frac{2}{T} \frac{1 - z^{-1}}{1 + z^{-1}} \quad (2)$$

Nodal Analysis



Wave Digital Filters (WDFs)²

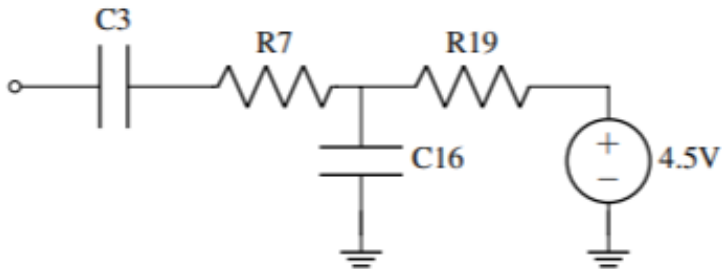
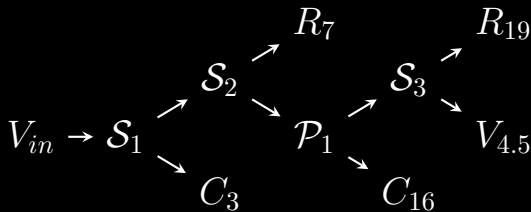


Figure 3: *Klon Centaur Feed-Forward Network 1 Circuit*

²Fettweis, "Wave digital filters: Theory and practice"; Werner, "Virtual Analog Modeling of Audio Circuitry Using Wave Digital Filters".

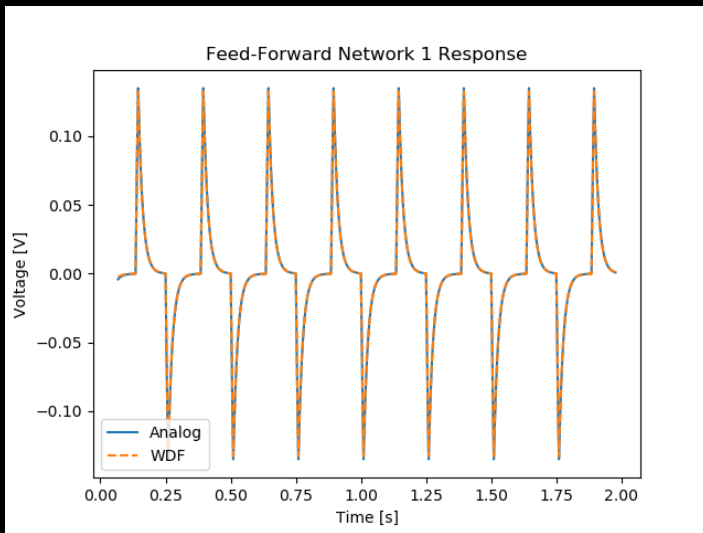
Wave Digital Filters (WDFs)

- Use wave variables instead of voltage/current.
- Port resistance free parameter.
- Discretize each circuit element separately.



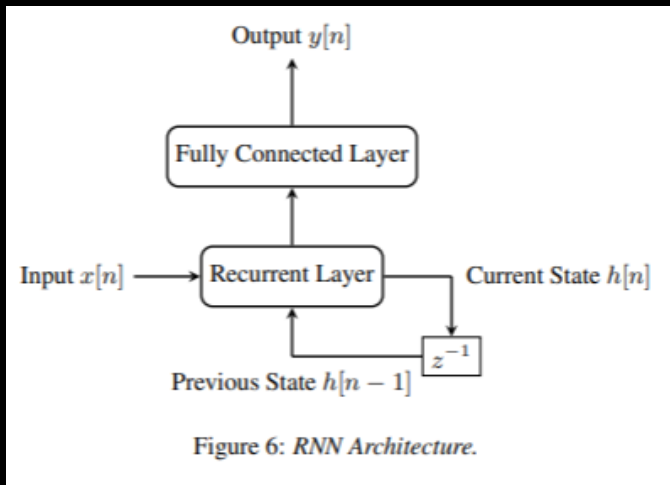
WDF tree for the Klon Centaur Feed-Forward Network 1 Circuit. \mathcal{S} and \mathcal{P} nodes refer to series and parallel adaptors respectively.

Wave Digital Filters (WDFs)



Neural Network Circuit Modelling

Recurrent Neural Network³



³Wright, Damskagg, and Valimaki, "Real-Time Black-Box Modelling with Recurrent Neural Networks".

Recurrent Neural Network

Recurrent layer: Gated Recurrent Unit

$$z[n] = \sigma(W_z x[n] + U_z h[n-1] + b_z) \quad (3)$$

$$r[n] = \sigma(W_r x[n] + U_r h[n-1] + b_r) \quad (4)$$

$$c[n] = \tanh(W_c x[n] + r[n] \circ U_c h[n-1] + b_c) \quad (5)$$

$$h[n] = z[n] \circ h[n-1] + (1 - z[n]) \circ c[n] \quad (6)$$

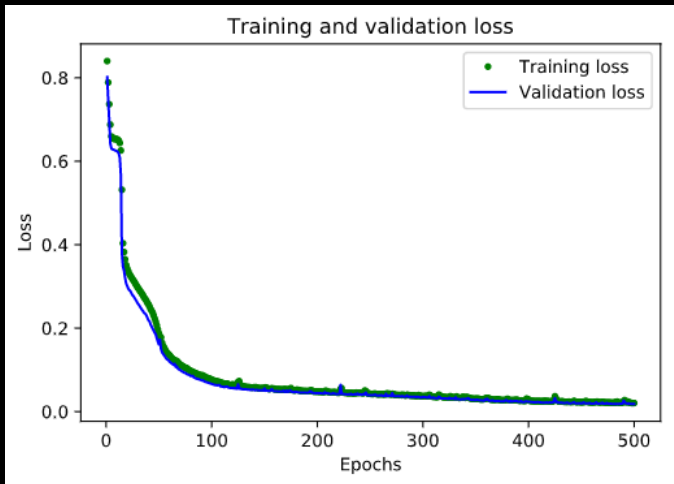
Recurrent Neural Network

Loss Function: Error-to-Signal Ratio

$$\mathcal{E}_{ESR} = \frac{\sum_{n=0}^{N-1} |y[n] - \hat{y}[n]|^2}{\sum_{n=0}^{N-1} |y[n]|^2} \quad (7)$$

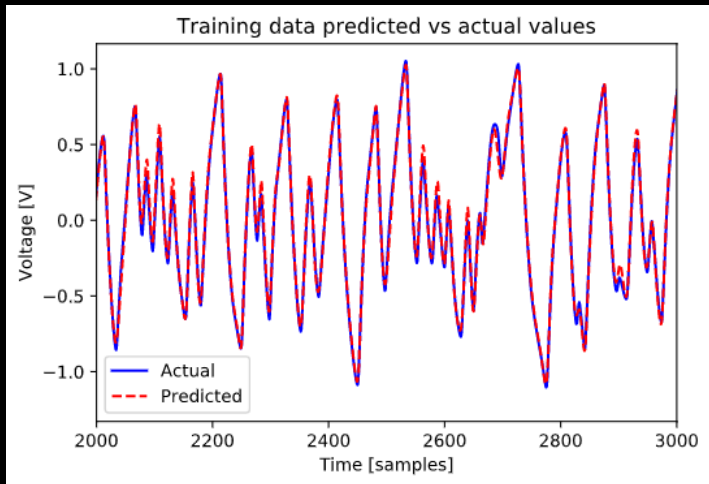
Recurrent Neural Network

Training: 500 epochs, ~ 8 hours



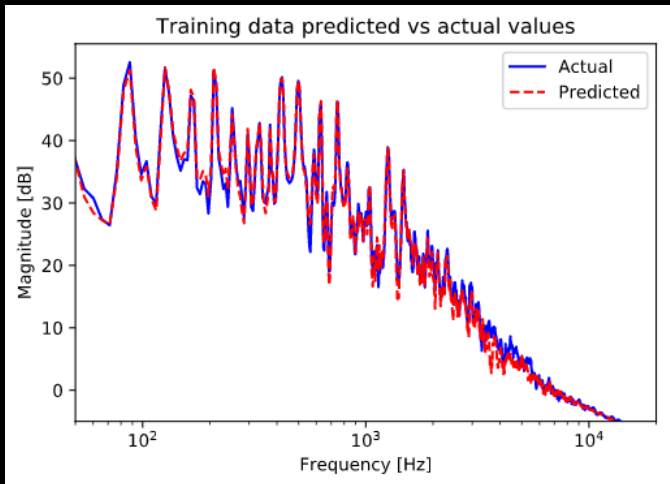
Recurrent Neural Network

Training results (time domain)



Recurrent Neural Network

Training results (frequency domain)



Real-Time Implementation

Implementation

Non-ML Implementation

- Use a combination nodal analysis, WDFs
- Control parameters for Treble, Gain, Level

ML Implementation

- RNN model for Gain Stage, nodal analysis elsewhere
- Fade between models for variable Gain control
- Custom GRU and Fully Connected implementations in C++

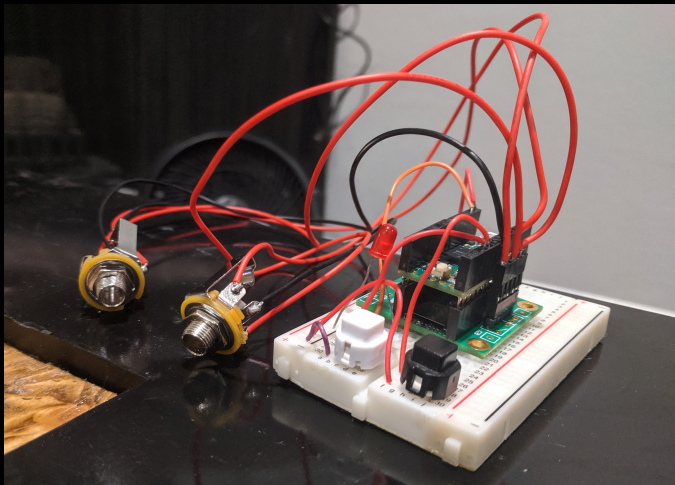
Implementation

Desktop Audio Plugin (JUICE/C++)



Implementation

Teensy 4.0, Teensy Audio Shield, Teensy Audio Library



Results: Performance

Compute time per second of audio.

Block Size	NonML Speed	ML Speed
8	0.0723437	0.0528792
16	0.0703079	0.0510437
32	0.0652856	0.0511147
64	0.0662835	0.0502434
128	0.0666593	0.0495194
256	0.0696844	0.0480298
512	0.0669037	0.0477946
1024	0.060816	0.0488841
2048	0.0695175	0.0488309
4096	0.0623839	0.0472191

Results: Summary

- Subjectively, non-ML and ML models sound very similar.
- ML model has slightly damped high frequency response, (not a big deal on guitar input; more noticeable on other audio).
- ML model is more efficient!

Live Performance!