

The Historical Development and Contemporary Applications of Subtractive Synthesis

Xiangyu Xin

*Beijing Chaoyang Tongwen Foreign Language School, Beijing, China
xiangyu1371@gmail.com*

Abstract. Subtractive synthesis is one of the most influential sound synthesis techniques in the history of electronic music. It was originally developed for analog voltage-controlled synthesizers. Since its occurrence in the 1960s, it has served as the cornerstone of numerous analog and digital synthesizers, playing a vital role in music composition, sound design, as well as audio technology. Subtractive synthesis was aimed to generate harmonically rich waveforms and shaping their timbre via filtering and amplitude alteration. This review examines the historical evolution of subtractive synthesis, tracing its development back from early modular analog systems to integrated synthesizers, further to digital implementations and contemporary virtual instruments based on software. This review illustrates that the oscillator-filter-amplifier architecture emerged during the 1960s and 1970s became a durable model for electronic instrument design because of the combined technical flexibility with a straightforward method of shaping timbre. It concludes that subtractive synthesis remains relevant because its architecture continues to connect historical instrument design with current software production, modular practice, hybrid systems, and emerging machine-learning-assisted synthesis.

Keywords: subtractive synthesis, analog synthesizer, sound synthesis, virtual analog synthesis, electronic music

1. Introduction

Electronic synthesizers have shifted the sound design procedure. In conventional acoustic instruments, they are the material of instruments, structure, and method of play that determine the timber; While in electronic synthesizers, sounds are capable of being decomposed to several controllable parameters, including frequency, waveshape, amplitude and envelope. Specifically, subtractive synthesizer is one of the most influential synthesizers. It is usually based on waves with ample harmonics such as saw, square, or pulse waves, then cut down or amplify specific frequency using filters, finally manipulate the variation of sound as time changes with amplifier and envelope. A typical subtractive synthesis signal path consists of an oscillator, a filter, and an amplifier, while low-frequency oscillators, envelope generators, and other control sources modify parameters such as pitch, filter cutoff frequency, and amplitude [1].

The emergence of voltage-controlling module in 1960s allowed multiple sounds to be controlled by a unique voltage-control driver. In his 1965 paper, Moog discussed the use of voltage-controlled

oscillators, amplifiers, and filters in electronic music and described the circuits employed in these modules [2]. The importance of this technique not only is generating new sounds, but also fosters a repeatable, combinable, and live-controllable instrument system. Manning notes that the early commercial Moog and Buchla systems emerged at approximately the same time in the mid-1960s, but embodied different design approaches: Moog increasingly adopted keyboard control and more standardized signal paths, whereas Buchla emphasized experimental control methods and non-traditional performance [3].

Advances in portable keyboard design, polyphony, patch memory, microprocessor control, and Musical Instrument Digital Interface (MIDI) connectivity made subtractive synthesizers more compact, programmable, and easier to integrate with other equipment. As a result, these instruments moved beyond research laboratories into live performance, recording studios, and eventually home-based music production. After entering the digital era, it has been transformed into virtual analog software, digital hardware, and a hybridization of digital oscillator with analog filter rather than being entirely replaced.

Accordingly, a central question has been raised in this review: why has the oscillator-filter-amplifier architecture thrived from the era of analog circuit to digital hardware and software platform? To answer this question, this review first examines how this architecture evolved from modular system into standardized instruments. After that, analysis of the technical challenge involved in the digital implementation of this architecture and consideration about how this structure poses impact on the production of timbres of electronic music are proposed.

The core argument of this review is that not only is the sustainability of subtractive synthesizers attributable to the amorphous sense of "analog warmth," but it is also driven by a suite of stable and portable controlling method: oscillators provide the wavetable, filters shape and cultivate harmonics, envelopes manage the time, and modulations generate variation. This is able to be implemented by transistor circuit, as well as by a hybridization of digital signal processing and plugins. It, furthermore, allows users to build a relatively unequivocal relationship between acoustic result and technical parameters.

2. Historical and technological development

2.1. From voltage-controlled modules to standardized instruments

Conventionally, electronic music studios have already been able to construct sounds with oscillator, filter, noise, and tape. These devices, nevertheless, typically are with various size, ports, and ways of control. Pitch, cutoff frequency, and amplitude were ported into a common controlling system, allowing different modules could be driven by keys, envelopes, Low Frequency Oscillators (LFO), and sequencer. Moog's voltage-controlled oscillator provided multiple waveform outputs, while his amplifier and filter designs allowed musical parameters to be varied by external control signals [2]. The importance of this variation is not derived from a single circuit, but from a music composing system formed by multiple circuits.

Such modular architecture separates audio signals from controlling signals: audio signals pass through oscillator, filter, and amplifier, resulting in an aural product; controlling signals then regulates the variation of these modules by time. An envelope could control amplifier, making the sound louder or quieter; as well, it is filter that could be controlled, the sound turning from brighter to dimmer and more implicit. LFO is able to control pitch, filter, as well as pulse width, generating vibrato, periodical frequency swipe, and the variation of timbre. Modular synthesis thus made the design of relationships between signals an integral part of the compositional process.

At the same time, open-formed wire connection results in a higher learning and operating cost. It is complicated to save patches, and periodical revision of pitch and gain is needed. Historical research has shown that the architecture of original synthesizers is not decided only by engineers. Drawing on interviews and archival material, Pinch and Trocco show that the Moog synthesizer developed through interactions among engineers, musicians, salespeople, and emerging markets [4]. Pinch later characterizes early synthesizer innovation as a distributed process involving people, machines, materials, and newly constructed forms of use [5]. This means that the "instrument standard" is a common result of choice by technological feasibility and musical practice.

Moog and Buchla represent two inspiring directions. Manning records that commercial Moog and Buchla systems appeared almost simultaneously in 1966, while their control philosophies and musical contexts differed [3]. Gradually, Moog integrated keyboard, traditional pitch controlling module, and clear signal paths; Buchla, yet, more emphasized on touchable interface, sequencer, and unconventional controls. This distinction indicates that different musical concepts could be served by a unique voltage-controlling method: one prefers mixing synthesizers into current performing system; another prefers redefining the way how sounds are composed.

The emergence of portable synthesizers with fixed architectures further transformed the condition of use. Instruments, such as the Minimoog, have integrated oscillators, mixers, low-pass filters, envelope generators, and amplifiers into a single chassis, minimizing free-form patching at the same time. Although such fixed signal path sacrificed part of the openness in structure, portability, stability, and live efficiency have been significantly boosted. The knob has fostered an unequivocal correspondence with the pitch, waveform, cutoff frequency, resonance, and time of Attack Decay Sustain Release (ADSR) in envelope, providing producers the feasibility of shaping a timbre in a straightforward way while performing. Therefore, the fixed architecture did not simply reduce functionality; it, rather, codified the knowledge embedded in modular synthesis into a learnable grammar for instrument.

From a review perspective, Manning's technological history is useful for establishing chronology and system structure, whereas Pinch and Trocco's sociotechnical account explain how particular configurations acquired musical and commercial significance [3, 4]. They are complementary: the former answered "how new forms of sound synthesis became reality", the latter responded to the question "why a particular technological possibility were widely adopted, further reaching the goal of standardization". Were the development of synthesizers to be considered solely from the respect of technological progress, it might be regarded as a natural, as well as linear, process of product evolution; On the contrary, were the social and cultural elements to be highly emphasized, the substantive changes in innovations of synthesis capabilities, such as the voltage control technique and transistor-based circuitry, may be underestimated.

Furthermore, the standardization engendered a long-term path dependence. A fixed signal chain allowed panels from different brands to share a similar conceptual framework: learnt operation of oscillator, filter, envelope, and modulation could be transferred to another instrument or software. At the same time, this architecture naturalized several design choices, such as the prioritization of keyboard, low-pass filter, and note-triggered envelope. These familiar modules are still widely being used as an entrance though new waveforms and modulation method are added later. Consequently, while standardization lowered the barriers of learning, users' conception of alternative approaches to sound organization may also have been constrained.

2.2. Polyphony, memory, and MIDI

Portable monophonic synthesizers are suitable for the generation of melody, bass, and effects (FX), but not for chord. The proper distribution of oscillator, filter, amplifier, and envelope to multiple voices should be considered in the design of polyphony, addressing tuning, voice triggering, and cost-related issues at the same time. In the late 1970s, microprocessor started to be combined with analog sound channel, integrating polyphony, parameter management, and program recall into a unified instrument system. Dave Smith's AES historical account identifies the Prophet-5 as an early fully programmable polyphonic synthesizer whose design incorporated microprocessor control [6]. This variation indicated that digital management is compatible with analog sound: The processor is responsible for the scan and storage of parameter and keyboard, while the analog circuit manage the genuine signal path.

The preset storage also enhanced the repeatability of live performance and recording. Programmable instruments are able to save and instantly retrieve parameter states. In this way, timbre had transformed from a one-off setting to a labelable, categorizable, exchangeable, and salable object. Presets also pose effects on how musicians acknowledge instruments: sound designer and corporations categorize complicated parameter group into an expectable function with labels such as Bass, Lead, Pad, String, or FX.

Such convenience also shifted the power of creation. Presets allowed beginners to instantly acquire applicable sounds, but transferred some decision on timbre from users to manufacturers and sound designers. Therefore, the key issue is not whether presets are "lack of originality", but whether the interface helps users understand and modify parameters: unequivocal parameter relationship supports studying, while structures hidden by menu or macro make presets to be a closed system.

Device communication further expanded reproduction. In 1981, Smith and Wood proposed the Universal Synthesizer Interface as a preliminary industry-wide method for interconnecting synthesizers, sequencers, and home computers [7]. The later formed MIDI control, but not the sound itself, allows producers to separately edit the performance, timbre selection, and record of sound. MIDI integrated synthesizers into a network comprising by sequencer, drum machines, and effects processors, making their value not only dependent on their sonic capabilities, but also dependent on system compatibility.

2.3. Digital implementation and virtual analog synthesis

Digital synthesizing and samples expanded the range of timbre, but did not eliminate the controlling logic of subtractive synthesizers. Digital system, still, are able to generate waves full with harmonics, then shaping the sound using filter. Huovilainen and Välimäki define digital subtractive, or virtual analog, synthesis as the computational imitation of the sound-generation principles associated with analog synthesizers of the 1960s and 1970s [8]. Therefore, "virtual analog" is not synonymous with all digital synthesizers, but refers specifically to digital system designed to preserve or emulate the architecture of classic subtractive synthesis.

Digital implementation first had to address oscillator aliasing: there are discrete values existing in ideal saw and square waves that its harmonics, extending indefinitely in frequency, could not be represented by a finite sampling rate. Because classical sawtooth and square waves are not bandlimited, direct sample-by-sample generation causes components above the Nyquist frequency to fold into the audible spectrum as aliasing [8, 9]. Aliasing will import frequencies that are not existing in original signal and shifts with the variation of pitch and modulation.

Antialiasing oscillator should balance between sound quality, calculation cost, and the flexibility of modulation. Välimäki and Huovilainen review bandlimited methods that synthesize only valid harmonics and quasi-bandlimited methods that correct waveform discontinuities or their derivatives [9]. Consequently, Digital oscillators should be also evaluated under demanding conditions such as high pitches, frequency sweeps, oscillator synchronization, and pulse-width modulation.

3. Musical influence and contemporary relevance

3.1. Timbre, performance, and genre formation

Subtractive synthesis became the shared timbre in electronic music, allowing the cut-off frequency, resonance, envelope, and modulation could be associated with several acoustic determination such as "light", "dim", or "sharp."

Such language also shifts the performance: traditional keyboards typically pass pitch and velocity, while interfaces on synthesizers allow performer to control the structure of sound at the same time. Different filter, envelope, and mapping form different controlling preference. Pinch and Trocco demonstrate that the meanings and uses of early synthesizers emerged through interaction between designers and users rather than being determined by inventors alone [4]. Therefore, the instrument is formed by both circuit, interface, and actual use.

Specific device also may involve in the formation of a music genre. Davis's study of device-specific "acid pattern" notation shows that the Roland TB-303's sequencer and control structure affected how acid-house patterns were programmed, documented, shared, analyzed, and recreated [10]. This case did not demonstrate that a device independently "created" a particular genre; rather, it illustrates that how constraints, such as sequence length, accent, glide, and knob modulation, can be transformed into a stylistic convention via use, sharing, and repetition.

Consequently, synthesizers influenced music through sound traits, control actions, storage, and the method of sharing.

3.2. Presets and production workflows

Preset, MIDI, and software automation let sound design to be a revisable procedure. Producers may first record the performance, then change the patch or adjust the filter, envelope, and FX. Sound, performance, and record therefore became multiple editable stage, boosting the efficiency.

Contemporary software synthesizers often provide more parameters and modulation options compare to conventional hardware instruments. Although these functions expanded the possibilities of sound design, they, at the same time, raise the operational difficulty and decrease the system interpretability. Hence, the increment in the number of parameters does not necessarily improve the usability. Masuda and Saito observe that the relationship between synthesizer parameters and perceptual qualities is often difficult to understand, leading many producers to depend on presets created by sound designers [11]. The more flexible a system becomes, the more difficult it may be for users to achieve their goal.

4. Discussion and future directions

4.1. Integrated findings

According to present articles, subtractive synthesizer has encountered three times of reconfiguration: voltage control organized discrete devices into a modifiable module; fixed architecture, polyphony,

storage, and MIDI transformed module knowledge into stable instruments and procedure; digital signal procession and software then decoupled this architecture from specific physical circuit. These variations are not a single-way substitution, they, rather, are a reallocation of efficiency, repeatability, and operation.

The continuous existence of subtractive synthesis is because of its low difficulty of implementation, ability to generate continuous variations, clear correlation of parameters, and the accumulated shared vocabulary and set of practices. Its strength lies not in its ability to synthesize all possible sound, but in providing learnable, transformable, and extensible framework of sound organization.

4.2. Machine learning and research opportunities

Machine learning proposed a reversion question to subtractive synthesis: deriving editable parameters from a target sound. Barkan et al. use convolutional neural networks to estimate synthesizer parameter configurations from spectrograms or raw audio and evaluate the method on a subtractive synthesizer with frequency modulation [12].

Another path is provided by DDS. Engel et al. introduce differentiable digital signal processing as a framework that integrates established signal-processing elements with deep learning and gradient-based optimization [13]. Masuda and Saito implement a differentiable subtractive-synthesis model and report that spectral-loss optimization improves sound matching, including training with real-world sounds that lack ground-truth parameter labels [11]. Traditional synthesis modules can serve as a structural prior, preserving some of the interpretability and user control.

Apart from that, three directions of research should be promoted conducting analog-digital blind listening tests with rigorously matched parameters and openly available sources; examine the influence to study and exploration by interface design, visualization, and tactical control; broadening the historical and practice-based sample, promoting the shift of research from histories centered on canonical brands to a more comprehensive technological cultural history.

5. Conclusion

The develop of subtractive synthesis is not a linear history of analog circuit being replaced by digital algorithms. It, rather, is a nonstop reformation process of sound structure, controlling interface, and music practice. Voltage control established the base of module; fixed architecture, polyphony and storage enhanced performance and the stability of use; MIDI connected instruments with produce network; virtual analog synthesis reproduces classic analog behaviors in digital domain; software, modular, and hybrid system continue to reshape the boundaries of interaction and creation.

The continuous effect of subtractive synthesis was come from its portable control logic: it separates sound into material, spectrum, time, and modulation, allowing technical parameter to build an interpretable connection with acoustic variation; engaging in the shape the performance, trend of preset, procedure of recording, and genres of music.

The future subtractive synthesizers will continue to draw from wavetable, sample, digital effect, machine learning, and new interface, but its value was determined by whether the system could support interpretable sound design. Therefore, subtractive synthesis remains a foundational framework connecting audio engineering and musical practice.

References

- [1] Roads, C. (2023). *The computer music tutorial* (2nd ed.). The MIT Press.
- [2] Moog, R. A. (1965). Voltage controlled electronic music modules. *Journal of the Audio Engineering Society*, 13(3), 200–206.
- [3] Manning, P. (2004). *Electronic and computer music*. Oxford University Press.
<https://doi.org/10.1093/acprof:oso/9780195144840.001.0001>
- [4] Pinch, T. J., & Trocco, F. (2004). *Analog days: The invention and impact of the Moog synthesizer*. Harvard University Press. <https://doi.org/10.4159/9780674042162>
- [5] Pinch, T. (2015). Between technology and music: Distributed creativity and liminal spaces in the early history of electronic music synthesizers. In R. Garud, B. Simpson, A. Langley, & H. Tsoukas (Eds.), *The emergence of novelty in organizations* (pp. 129–156). Oxford University Press.
<https://doi.org/10.1093/acprof:oso/9780198728313.003.0006>
- [6] Smith, D. (2016). *Synthesizers: From analog to digital to software to analog* [Richard C. Heyser Memorial Lecture]. Audio Engineering Society 141st Convention. <https://aes.org/community/technical-council/richard-c-heyser-memorial-lecture-series/details-of-heyser-lectures/memorial-lecture-at-141st-dave-smith-synthesizers-from-analog-to-digital-to-software-to-analog/>
- [7] Smith, D., & Wood, C. (1981). The "USI," or universal synthesizer interface. *Audio Engineering Society 70th Convention*, Paper 1845. <https://secure.aes.org/forum/pubs/conventions/?elib=11909>
- [8] Huovilainen, A., & Välimäki, V. (2005). New approaches to digital subtractive synthesis. In *Proceedings of the International Computer Music Conference 2005* (pp. 399–402). <https://research.aalto.fi/en/publications/new-approaches-to-digital-subtractive-synthesis/>
- [9] Välimäki, V., & Huovilainen, A. (2007). Antialiasing oscillators in subtractive synthesis. *IEEE Signal Processing Magazine*, 24(2), 116–125. <https://doi.org/10.1109/MSP.2007.323276>
- [10] Davis, D. (2022). Acid patterns: How people are sharing a visual notation system for the Roland TB-303 to create and recreate acid house music. *Organised Sound*, 27(1), 7–19. <https://doi.org/10.1017/S1355771822000164>
- [11] Masuda, N., & Saito, D. (2021). Synthesizer sound matching with differentiable DSP. In *Proceedings of the 22nd International Society for Music Information Retrieval Conference* (pp. 428–434).
<https://archives.ismir.net/ismir2021/paper/000053.pdf>
- [12] Barkan, O., Tsiris, D., Katz, O., & Koenigstein, N. (2019). InverSynth: Deep estimation of synthesizer parameter configurations from audio signals. *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, 27(12), 2385–2396. <https://doi.org/10.1109/TASLP.2019.2944568>
- [13] Engel, J., Hantrakul, L., Gu, C., & Roberts, A. (2020). DDSP: Differentiable digital signal processing. In *Proceedings of the 8th International Conference on Learning Representations*. <https://research.google/pubs/ddsp-differentiable-digital-signal-processing/>