

The Analogue Computer as a Voltage-Controlled Synthesiser

Victor Lazzarini and Joseph Timoney

Maynooth University,
Maynooth, Co. Kildare,
Ireland

{victor.lazzarini,joseph.timoney}@mu.ie

Abstract. This paper re-appraises the role of analogue computers within electronic and computer music and provides some pointers to future areas of research. It begins by introducing the idea of analogue computing and placing in the context of sound and music applications. This is followed by a brief examination of the classic constituents of an analogue computer, contrasting these with the typical modular voltage-controlled synthesiser. Two examples are presented, leading to a discussion on some parallels between these two technologies. This is followed by an examination of the current state-of-the-art in analogue computation and its prospects for applications in computer and electronic music.

Keywords: analogue computing, voltage control, sound synthesis, filters, oscillators, amplifiers, FPAA, VLSI analogue circuits

1 Introduction

Computer Music, for the most of its history, has been concerned with the use of what we can generally class as the *digital stored-program computer*, although this (correct) terminology has by now fallen in disuse, due to the ubiquitous nature of these devices. In this paper, we will instead look at a different type of computer and its potential to sound and music design, and its relationship to the music instrument technology of voltage control. The principles we will explore fall into the category of *analogue computing*, which approaches both the actions involved in computation, the modelling and the problem design from a different perspective.

The principles that constitute analogue computing can be seen from two perspectives that are somewhat independent from each other. On one hand, the hardware that implements it allows for the solution of problems containing continuous variables, whereas digital circuitry implies a discretisation of these (even in models that assume underlying continuous quantities). In the case of music, the possibility of time and amplitude-continuous computation is significant, considering the amount of work that has been dedicated to solving discretisation issues in areas such as virtual analogue models [16].

From a different perspective, analogue computing approaches problems in a way that largely dispenses the algorithmic approach of digital computer programming in favour of hardware reconfiguration, setting up the computation not so much as a sequence of steps, but as an interconnection of components [20]. This also implies that the hardware model set up in this way is an *analogue* of the problem at hand. Additionally, while analogue computers may be able to compute problems related to the steady state of a system, they are more frequently used to providing solutions relating to transient behaviour [13]. Such problems are significant to sound and music applications, where the dynamic properties of a system are fundamental.

Analogue computing has had a long history, which began with mechanical devices that were used as aids to calculation of specific problems (navigation, gunnery, accounting, etc.), and became a major scientific field of research with the advent of practical electronic devices. These could be combined more flexibly to realise various types of modelling. From a music perspective, these developments influenced the technology of voltage control, and the modular aspect of electronic analogue computers appears to be significant in providing the principles underpinning early synthesisers [11].

In this paper, we will examine the relationships that exist between these devices. We will start by exploring the principles of analogue computation with electronic computers. This will be followed by an introduction to modular voltage-controlled synthesisers from the perspective of analogue computing. Then we will examine the possibilities of general-purpose electronic computers as musical instruments, followed by an examination of the current state of the art in the area and the perspectives for new research in sound and music (analogue) computing.

2 Electronic Computers

Analogue computers, as discussed in the introduction to this paper, operate under different principles to their digital stored-program counterparts. Generally, they are set up to provide solutions to a problem that is laid out in terms of a mathematical equation or set of equations, providing an answer to these, given a certain input. In this case, the type of problems that are applied to them can be of different characteristics, provided that they can be described in an algebraic form. Programming the computer is then a matter of setting an analogue to the original problem [20] by means of various computing elements. Therefore, the capabilities of a given analogue computer are determined by the types of computing blocks it can offer, and how they can be connected in a program.

2.1 Computing elements

Analogue computers are made of various types of components that often operate as *black boxes*, providing an output given a set of inputs and conditions, within a certain level of tolerance. The inputs and outputs of such boxes are electric signals whose voltages play the part of the variables that are manipulated in a

program. Programs will then be made up of patching connections between these different blocks, setting up the initial conditions that configure the problem and then running the computer, from which the answer or answers can be read by appropriate output devices.

While the components of an analogue computer can be quite varied in nature, there are some key blocks that are present universally in these devices, to provide basic computing operations.

Arithmetics We can divide the arithmetic operations into three fundamental categories, that are addressed by specific types of electronic circuits: (a) multiplication by a scalar; (b) addition/sum; (c) multiplication of signals. In the case of (a) and (b), a fundamental component is the *operational amplifier* [18]. This component allows a gain to be applied to the signal, and facilitates both multiplication and addition to be implemented. Of course, if only attenuation is required, then a signal can be passively modified by a variable resistance (fig. 1), but in all other cases, the op amp is required.

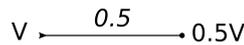


Fig. 1. Attenuation example

Gain scaling is implemented simply by setting the multiplier constant k in the op amp, which is the ratio of the resistances R_f/R_i that are employed in the circuit (fig. 2)

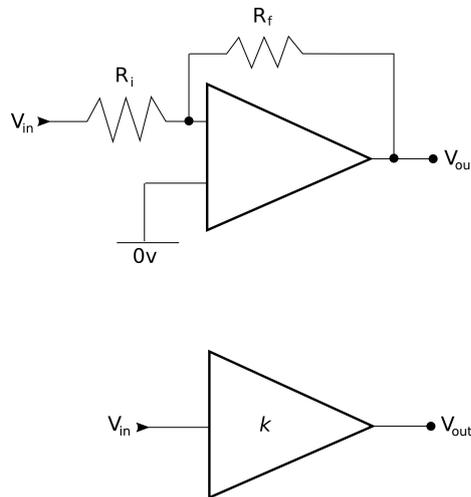


Fig. 2. Op amp circuit schematics and gain scaling symbol

$$V_{out}(t) = -kV_{in}(t) \quad (1)$$

Note that the op amp will normally have the effect of inverting the sign of the voltages applied to its input, due to the fact that only its inverting input is used.

Summing two voltages also require an op amp (fig. 3), and the input signals are scaled by the ratios of the individual input resistances and the feedback path resistance, $k = R_f/R_n$. Note that adding units such as these can be set up for more than two inputs.

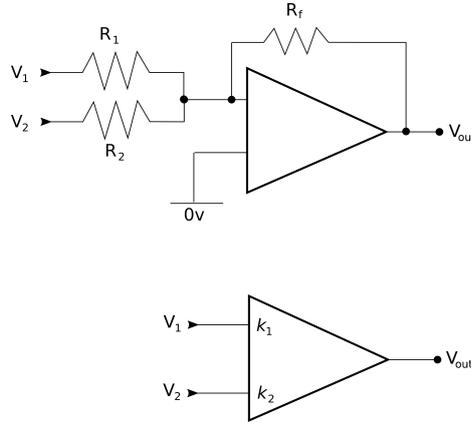


Fig. 3. Summing amp circuit with two inputs and symbol

$$V_{out}(t) = - \sum_0^n k_n V_n(t) \quad (2)$$

Multiplication of two signals is generally taken as a separate category as it requires more complex circuitry. In this case, the output is equivalent to the instantaneous value of the multiplication of its inputs, scaled by a constant.

Integration Another key component of an analogue computer is the integrator. The means of integrating an input signal is provided by a capacitor, and the circuit (fig. 4) also includes an op amp to complement it. As we can see, the capacitor replaces the feedback resistor in a simple scalar multiplier. The output is also scaled by $k = 1/R_i C$ where C is the capacitance in the op amp feedback path. The voltage across the capacitor can also be set as an initial condition V_0 .

$$V_{out}(t) = -k \int_0^t V_{in}(t) + V_0 \quad (3)$$

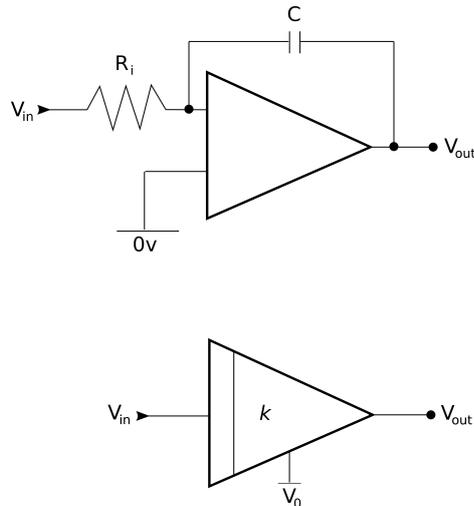


Fig. 4. Integrator circuit and symbol

It is also a simple matter to include multiple input signals to an integrator, using a combination of the circuits of figs. 2 and 3. In this case, the different inputs are scaled and added together before the integration is performed.

Functions It is also fundamental for analogue computers to be able to provide means of generating a variety of functions. Among these we will find the usual single-variable functions trigonometric, exponential, triangle, rectangular, ramp, etc. Some computers would also have more sophisticated means of generating user-defined functions [20]. It is worth noting that function generators is a general class of modules that also include the multiplication, summation, and integration blocks described above [13].

Other Modules Various other modules exist in various analogue computing devices [20]. Logic blocks such as comparators allow voltages to be compared for binary decisions (such as opening and closing signal connections) and step-function implementations. Limiters are special-purpose comparators that can keep signals within a given range. Time delays provide a means of shifting the phase of functions and can be implemented in discrete capacitor circuits called bucket brigade devices [19] Output of analogue computations involve some means of measuring the voltage of a program, which can be done by various means such as strip-chart and xy recorders, oscilloscopes, voltmeters, and similar components. A sound and music computing relevant output block would consist of an audio pre-amplifier that allows line-level connections to a mixer and power amplifier. This is of course, the main output component of a voltage-controlled synthesiser.

3 Modular Synthesisers

Modular electronic sound synthesis, especially the variety involving voltage control technologies, has been a cornerstone of electronic music since the post-war era [21]. In examining the devices that have been and are currently used for this purpose, we can see very clear parallels with the technology of analogue computers. In fact, analogue synthesisers in general have been identified as special purpose computers [20]. As in that type of technology, modules play an important part as the components of programs, which in the case of the typical modular design are made up of patch-cord connections between them.

3.1 Modules

Voltage-controlled synthesizer modules are generally built at a higher level of operation if compared to analogue computing blocks. This means that access to fundamental aspects of computation are less common. For example, function generators in the form of oscillators realise compound operations, which in the case of an analogue computer would be provided in smaller building blocks of a time function generator, plus multipliers and adders. However, some basic elements are given: ring modulators implement two-input multiplication, mixers are summing modules, and offset/scaling modules can provide addition and multiplication of signals and scalars. The typical modules of a synthesiser include voltage controlled filters (VCFs), oscillators (VCOs), and amplifiers (VCAs).

In general, modular synthesisers provide a rich set of components, many of which can be seen as different types of function generators: for attack-decay-sustain-release curves, noise sources, and sequencers, which provide user-defined functions. However, the synthesiser set of components is provided with significant specialisation, and in general lacks access to the fundamental building blocks of computation. Tracing an analogy to the music languages used for programming digital computers, modular synthesizers provide high-level unit generators [6], but not the means of coding (or in this case, setting up) the unit generators themselves (the modules in the analogue domain).

4 Examples and Discussion

In order to expand the discussion of analogue computing for sound and music, it is interesting to consider some examples to illustrate simple operations. While we would put these problems from a general-purpose computing perspective, we would also like to consider them with respect to typical sound synthesis applications.

4.1 Linear Functions

The simplest example of the application of analogue computation is to set up the solution to a linear problem, such as

$$f(t) = ax(t) + b \tag{4}$$

which may be applied, for instance, to glide the pitch of a tone from one frequency to another. The program for this is shown in figure 5, smoothly sliding by a user-defined interval. In this case, each increment of 1V in the input starting from a voltage V_0 , will provide a jump of k semitones, when used as a 1V/oct exponential frequency signal.

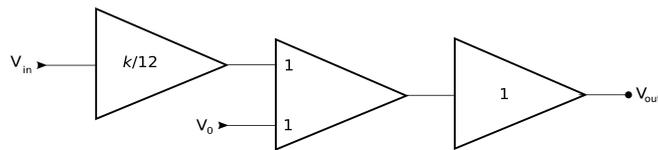


Fig. 5. Linear equation program

This, of course, can easily be set up in a modular synthesiser by the use of an amplifier and an offset, which are blocks that are readily available. At this level of simplicity, the synthesiser can match the analogue computer almost on a one-to-one component basis.

4.2 Differential Equations

A more common application of analogue computers has to do with the solution of differential equations. Consider the following example,

$$y(t) = ax(t) - b \frac{dy(t)}{dt} \tag{5}$$

which is a simple first-order differential equation. This can be translated into an analogue computer program as shown in fig. 6. The significance of this is that such a differential equation also implements a simple infinite impulse response low-pass filter. With this approach, could implement filters of different designs, more complex of course, but using the common blocks of an analogue computer.

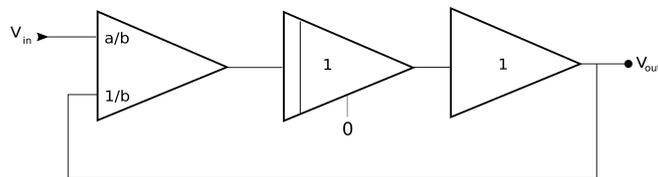


Fig. 6. Difference equation program

Hutchins [4] pointed out that the fundamental voltage-controlled building block used here (fig. 6), the integrator, is applicable to the well-known state variable filter (SVF) design. He noted that the fact that the SVF is formed from elemental blocks of two integrators and a summer in a loop has been known from analogue computer programs, where it was used in physical simulations of second-order responses by producing voltages corresponding to the magnitudes of the *state variables* of the system.

This first-principles approach is contrasted now with the filter modules implementing different topologies, with various particular characteristics, that are found in voltage controlled synthesisers. The significant difference is that these are fixed to a given design, and do not allow access or manipulation of its circuit connections. This demonstrates an example where there is no one-to-one match between an analogue computer and a synthesiser.

4.3 The General-purpose Analogue Computer as a Musical Instrument

Given the examples discussed above, it might be surprising to see that not a lot has been made in terms of utilising general-purpose analogue computers in musical applications. The composer Hans Kulk appears to be a solitary figure working in this field [5]. This may be attributed to various factors: cost, as in the heyday of analogue computers, it was very expensive to access these; complexity, programming analogue computers required significant technical expertise, which was not mitigated by music-directed approaches, as for instance provided by music programming languages in the case of digital computers.

The existence of the modular synthesiser, in fact, can be seen as the analogue counterpart to the digital computer music programming environments. However, as noted above, they were not developed to provide lower-level access to computation, which is the case of digital computer programming (as in, for instance, Csound [7]). Finally, also we should consider that the obsolescence of the general-purpose analogue computer, in parallel with the ubiquitousness of the digital computer, also played a part in the process. However, some new prospects in the analogue computing domain may allow us to re-appraise these devices as possible vehicles for music making. The main consideration is that there is no fundamental impediment to this; on the contrary, there seems to be fertile ground for work in this respect.

5 Prospects for Electronic and Computer Music

While analogue computers may appear to some to have passed their heyday and be generally obsolete today, that does not seem to be the case if we look at some cutting-edge research in the field. The direction of travel seems to involve the development of very large scale integration (VLSI) components that implement a collection of computing elements. These can then be made available for programming in flexible ways and used as dedicated processors within a larger

host system [2]. The technology of Field Programmable Analogue Arrays [8,9,10] has also opened some interesting possibilities in the particular case of analogue signal processing.

It is within this context that a number of prospects for musical signal processing may arise. The interest in re-creating analogue environments using digital simulations that sparked virtual analogue model research may have exhausted its potential for further refinements, and work that is actually directed to the *real* thing is an attractive proposition. Music production is one of the few areas of technology where analogue signal generation and processing techniques continue to be used, and in fact, have enjoyed a significant resurgence

5.1 Field Programmable Analogue Arrays

Recent developments in analogue signal processing technology included the development of Application-specific Integrated Circuits (ASICs), used in the implementation of synthesiser modules such as filters and oscillators. However, as the name implies, ASICs target specific purposes and re-designing them is very expensive. What would be more suitable is to have an analogue equivalent of the digital Field Programmable Gate Array (FPGA). Fortunately, the concept of Field Programmable analogue Arrays (FPAAs) was introduced with the promise that it facilitated analogue components to be connected together in an arbitrary fashion, allowing for rapid testing and measurement of many different circuit designs.

A similar but less sophisticated technology is the PSoC (programmable system-on-chip) by Cypress Semiconductor. These chips include a CPU core and mixed-signal arrays of configurable integrated analogue and digital peripherals. The FPAA was introduced in 1991 by Lee and Gulak [8]. The idea was further enhanced by the same authors in 1992 [9] and 1995 [10] where op-amps, capacitors, and resistors could be connected to form a biquad filter, for example. In 1995, a similar idea, the electronically-programmable analogue circuit (EPAC) was presented in [17].

Within the FPAA explored in [14] it was organised into three functional blocks: (1) the computational analogue block (CAB), which is a physical grouping of analogue circuits that act as computational elements, (2) the switch matrix (SM), which defines the interconnection of CAB components, and (3) the programmer which allows each device to be turned completely on, turned completely off, or operated somewhere in-between. This flexibility means that switch elements can be used for computation as well as routing. This is especially beneficial in audio applications, since transistors set to a constant bias are often necessary.

Only in recent years have FPAAs become powerful enough to be considered for facilitating complex analogue sound synthesis, in the implementation of common modules. Two papers investigated whether FPAAs were capable of creating entire synthesis systems. One paper illustrated how the low-pass VCF developed and popularised by Robert Moog [12] could be implemented using an FPAA [14]. For this implementation it was found that the FPAA could support 12 VCFs,

assuming perfect utilisation of all the available resources by the CAB, but it may also be possible to include another 8-10 filters under alternative constraints. A second paper looked at the FPAA configuration for a VCO and VCA, and two common control modules, the low-frequency oscillators and the envelope generator, which would allow for the development of a complete synthesiser [15]. The paper identified a number of challenges, which included whether the VCO implementation would be controllable over a wide pitch range and remain stable with temperature changes. In general, FPAAs appear to be one of the most promising analogue technologies for sound and music computing.

5.2 Programmability

Programming a modular synthesiser with patch-cords is a significant undertaking, and the traditional analogue computers presented much bigger challenges in that respect. Clearly, if we are to be able to implement signal-processing operations from first principles, the question of programmability takes is a key concern. In modern VLSI-based systems such as the one described in [2] and in the case of FPAAs, some means of setting up connections between components is provided (and storing/retrieving these), which can be at various levels.

We could trace a parallel with digital computers, where the code may be represented by an assembly-type language for a given hardware, or in a high-level language such as C. In an analogue computer, we could manually translate equations (such as for instance eq. 5) into the actual hardware connections (e.g. fig. 6), or potentially use an algebraic compiler to synthesise the necessary circuits (such as the one discussed in [1]). We can hypothesise that such a high-level language could be developed targeting the requirements of analogue signal processing for music computing applications.

5.3 Hybrid Digital-Analogue Systems

Another emerging characteristic of modern analogue computing appears to be the development of hybrid digital-analogue systems. One such arrangement is described in [3], where a combination of digital and analogue circuits are used to construct a programmable device. This type of arrangement is mirrored in modern polyphonic analogue synthesisers, where audio signals are kept in the analogue domain, and control signals originate from digital representations and are transformed into voltage control via a number of digital-to-analogue converters. This allows some level of interconnectivity via so-called modulation matrices that mimic the modular approach, albeit in a smaller scale.

6 Conclusions

This paper attempted to demonstrate the usefulness of an analogue computing approach to electronic and computer music research. It provided a general introduction to the area, alongside tracing a parallel to modular voltage-controlled

synthesisers. Examples were given that had direct relevance to analogue audio signal processing, demonstrating some immediate applications in research and music production.

A survey of the state-of-the-art in analogue computing provided us with some first candidates as technologies that might be ready for use. In fact, in one case some interesting results had already been presented. Challenges remain, however, given that the target outputs of analogue computing for music applications have some key constraints of quality, including low signal-to-noise ratios and pitch/voltage stability. Assessing this should play an important part in any future research.

Another aspect that was raised was to do with programmability. We see that key developments in the area are necessarily linked to the potential of music programming systems. Having analogue computing-dedicated music tools, similar to what exists for standard digital computers, will play an important part of making the technology available to a wider range of users (musicians, artists). This possibly points out to another fertile field of computer music research.

References

1. Achour, S., Sarpeshkar, R., and Rinard, M. Configuration synthesis for programmable analogue devices with Arco. In *Proceedings of PLDI 16* (Santa Barbara, CA, 2016), pp. 177–193.
2. Cowan, G., Melville, R., and Tsividis, Y. A VLSI analogue computer / digital computer accelerator. *Journal of Solid-State Circuits* 41, 1 (2006), 42–53.
3. Guo, N., Huang, Y., Mai, T., Patil, S., Cao, C., Seok, M., Sethumadhavan, S., and Tsividis, Y. Energy-efficient hybrid analog/digital approximate computation in continuous time. *Journal of Solid-State Circuits* 51, 7 (2016), 1514–1524.
4. Hutchins, B. Revisiting some vcf ideas – and a few new ideas. *Electronotes* 23, 215 (2013), 1–23.
5. Kulk, H. Proposal for extending analogue modular electronic music synthesizers with function modules from the analogue computation repertoire. In *Symposium Think Analogue! Humboldt University* (Berlin, 2012).
6. Lazzarini, V. The development of computer music programming systems. *Journal of New Music Research*, 42 (2013), 97–110.
7. Lazzarini, V., fitch, J., Yi, S., Heintz, J., Brandtsegg, Ø., and McCurdy, I. *Csound: A Sound and Music Computing System*. Springer Verlag, 2016.
8. Lee, E. K. F., and Gulak, P. G. A cmos field-programmable analog array. *IEEE Journal of Solid-State Circuits* 26, 12 (Dec 1991), 1860–1867.
9. Lee, E. K. F., and Gulak, P. G. Field programmable analog array based on mosfet transconductors. *Electronics Letters* 28, 1 (Jan 1992), 28–29.
10. Lee, E. K. F., and Gulak, P. G. A transistor-based field-programmable analog array. In *Proceedings ISSCC '95 - International Solid-State Circuits Conference* (Feb 1995), pp. 198–199.
11. Moog, R. Voltage controlled electronic music modules. *AES Preprint 346* (1967), 1–19.
12. Moog, R. Electronic high-pass and low-pass filters employing the base to emitter diode resistance of bipolar transistors, 1969. US Patent 3475623A.

13. Navarro, S. *analogue Computer Fundamentals*. Wadsworth Publ. Co., Belmont, CA, 1962.
14. Nease, S. H., Lanterman, A. D., and Hasler, J. O. A transistor ladder voltage-controlled filter implemented on a field programmable analog array. *J. Audio Eng. Soc* 62, 9 (2014), 611–618.
15. Nease, S. H., Lanterman, A. D., and Hasler, J. O. Applications of current-starved inverters to music synthesis on field programmable analogue arrays. *J. Audio Eng. Soc* 66, 1/2 (2018), 71–79.
16. Pakarinen, J., Valimaki, V., Fontana, F., Lazzarini, V., and Abel, J. Recent advances in real-time musical effects, synthesis, and virtual analogue models. *Eurasip Journal On Advances In Signal Processing* 2011:940784 (2011), 1–15.
17. Pierzchala, E., Perkowski, M. A., Van Halen, P., and Schaumann, R. Current-mode amplifier/integrator for a field-programmable analog array. In *Proceedings ISSCC '95 - International Solid-State Circuits Conference* (Feb 1995), pp. 196–197.
18. Ragazzini, J., Randall, R., and Russell, F. Analysis of problems in dynamics by electronic circuits. *Proceedings of the IRE* 35 (1948), 444–452.
19. Sangster, F., and Teer, K. Bucket-brigade electronics - new possibilities for delay, time-axis conversion, and scanning. *IEEE Journal of Solid State Circuits* 4, 3 (1969), 131–136.
20. Ulmann, B. *Analog Computing*. Oldenbourg, Munich, 2013.
21. Wells, T. *The Technique of Electronic Music*. Schirmer Books, New York, 1981.