A Digital Twin for Theremin's Terpsitone from 1970s

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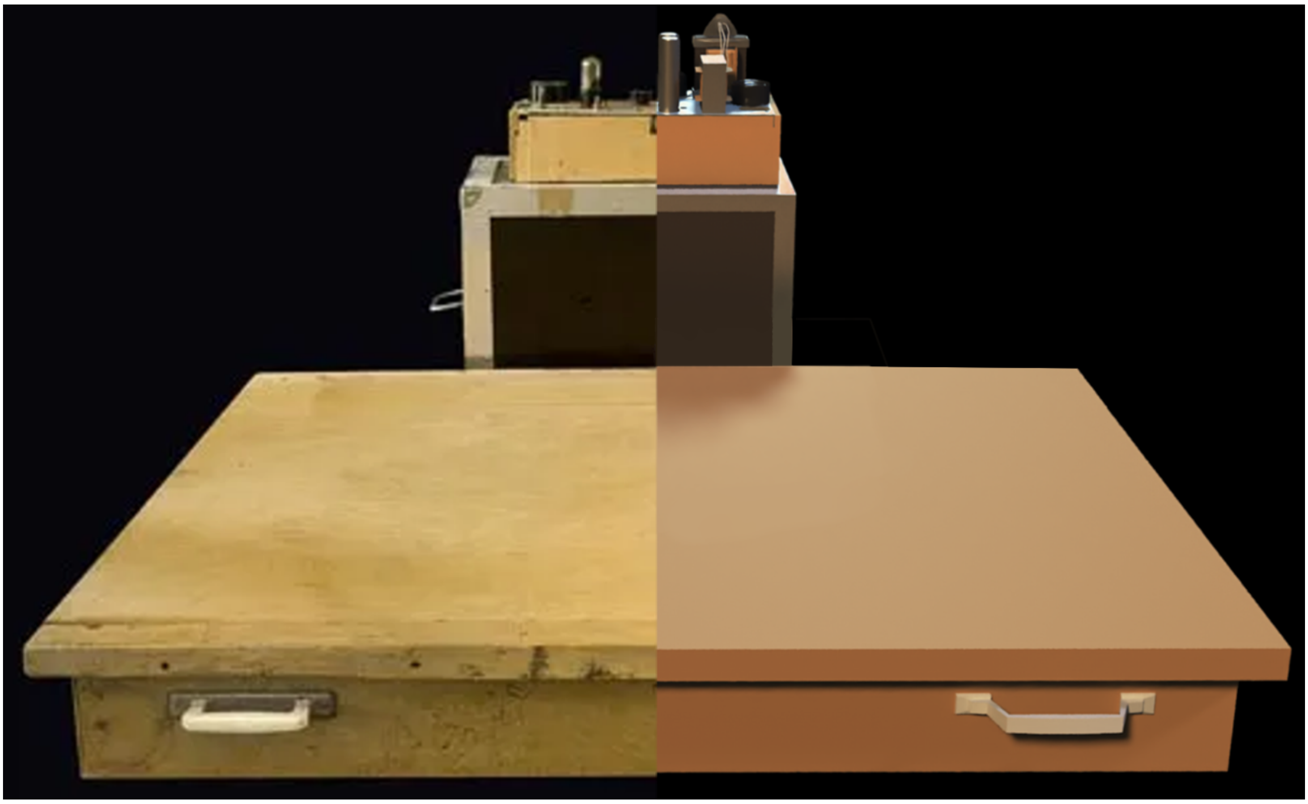

Figure 1: A collage of the real Terpsitone on the left and a full-size 3D model of it on the right.

Abstract

In this paper, we present a currnet work on creation of the first interactive digital twin of the Terpsitone - a rare electronic musical instrument designed by Leon Theremin to be played via full-body movements. This full-scale Virtual Reality (VR) replica serves two main purposes: preserving cultural heritage within an interactive volumetric context and making this unique instrument accessible for modern artistic and educational practices. This text discusses the general concept of preservation through Digital Twinning, attempts to provide a historically accurate introduction to the instrument based on primary sources, and details the technical implementation of the twin. We conclude with an outline for future work.

Keywords

Terpsitone, Theremin Leon, VRMI, procedural audio, digital twin, performative, historical electronic music instrument, VR, interactive, model.

1 Introduction

Originally emerging from engineering contexts [9, 10], the concept of "digital twin" - a virtual replica to a physical entity - has gained a profound utility in diverse fields ranging from medicine to cultural heritage preservation [11]. Within the specific domain of electronic music history, preserving an instrument requires more than just visual replication; it necessitates capturing the interactive aspects, for which we can use a term **"Interactive Kinematic Concept" (IKC)**. This term allows us to discuss the unique performative movements and physical logic inherent to an instrument class in it's connection to the sound, stepping beyond context-specific terminologies like "ergogenetic memory" [18] or "idiomatic playing style" [12], or simply "a musical gesture" (which may keep some association with a tradition of researching acoustic instruments) [24, 25]. While full physical restoration and replication remains the ideal, Virtual Reality (VR) offers a robust secondary avenue for archiving both the artifact and its specific IKC. To achieve this, our project employs an experimental methodology based on "forking," or generating multiple configuration branches, to optimize the interplay between three core components: a standardized 3D model (using formats like .obj or .fbx), a sound engine derived from original schematics and or audio samples, and the interactive linkage between them. This linkage ideally relies on documentation of the IKC, such as motion capture or indexed audiovisual records. The use of multiple "forks" enhances the probability of successfully preserving rare artifacts by allowing various digital iterations to share the same source data. Situated within the broader landscape of Virtual Reality Musical Instruments (VRMIs) [1, 30], this work uses procedural audio [26], defined here as real-time signal processing mapped to dynamic interactions within an immersive 3D environment [7, 16], the specific technique of which is detailed below.

1.1 Historical electronic music instruments (HEMIs)

As we discuss the preservation of historical artifacts - let us propose a description of "Historical Electronic Music Instruments" (HEMIs), which might be convenient for this research:

- They were invented and built before the emergence of a commercial industry of electronic music instruments (EMIs), lead by national corporations.
- They were usually developed by private individuals.
- They implement experimental and/or exploratory concepts.
- They bare cultural significance due to pioneering engineering or conceptual approach, or other reasons.
- They lack standardization of some types, including spatial and volumetric one, being much more diverse in shape and form then modern rack-mount or table-top devices.

Naturally the interaction with such HEMIs was different from the utilitarian IKC of today. This last parameter provokes spatial curiosity in potential performer. We may call this attribute **"a spatial intrigue"**. We believe that Virtual Reality can be a convenient way to preserve some important aspects of HEMIs.

1.2 What is Terpsitone?

It is a monophonic electronic music instrument, consisting of a horizontal plane, which is used as a small stage for a performer to stand on it. There is usually at least one additional block, which contains main circuitry, such as tone-generator and power supply [4, 20, 22, 23, 28, 29, 31, 35]. The intention of the instrument is to use full-body choreography to control sound. The name obviously refers to the ancient Greek Muse of dance and choral song - Terpsichora (or Terpsichore). The earliest primary source available to us, describing the instrument - is an anonymous article on page 154 of Sunday issue of the New York Times from March 27, 1932 [37]. It calles the instrument "a Musical Dance Stage". The first source, mentioning the name "Terpsitone" - is an article by C.P.Mason fully dedicated to the instrument, and marked as "for the first time in any radio publication" - in number 6 of Radio-Craft Magazine for 1936 [20]. **The main IKC of a Terpsitone is this:** The pitch of sound is controlled by the performer's position in vertical axis. We state this as the main IKC, because everything else was a subject for variations. Leon Theremin himself built several versions of Terpsitone. In recent years the instrument has regained interest among media, sound, and contemporary dance artists, who develop their own interpretations of it. This allows us to say that Terpsitone is not a name for one specific instrument, but is a name of a class of instruments, - because there might be many different variations of Terpsitone. They may differ in technical realizations, but keep the main IKC intact.

1.3 Why replicate Terpsitone?

Terpsitone is a HEMI. And besides being culturally significant as the first full-body performative audio-visual tool built by non-other than Leon Theremin himself - it is also spatially intriguing, like no other HEMI. It requires a very specific type of interaction, which at the same time can be replicated in VR to a significant extent.

2 Terpsitone's history

One of the main sources on the history of this instrument is a fundamental research of Soviet music technology by Andrey Smirnov, where we find a chapter about Terpsitone [31]. It mentions three main versions: the first one, built in 1930 and publicly presented in 1932 in New York; the second one - developed in Moscow in 1966; the third - built for Lydia Kavina in the end of 1970s. Later the text notes, that several version of the instrument were made in the 30s with additional functions. The visual analysis of primary sources shows, that there were two Terpsitones built in 30s in distinctively different designs. The further analysis of text sources confirms, that there were more than two Terpsitones in New York in 30s. That is why we suggest, that Leon Theremin has built at least four (or maybe more) instruments in this series.

2.1 "The Musical Dance Stage" 1930-1932

Leon Theremin arrived to New York City on December 22, 1927 [23]. He lived and worked in the USA until 1938. He became a head of a company Teletouch inc., licensed his most famous invention to the Radio Corporation of America (RCA) in 1929 [2]. And among many other wonderful adventures, which are beyond the scope of this paper - established his studio and workshop on West 54 Street in Manhattan [31]. He started performing publicly with his first concert at 8.30pm on Tuesday evening January 31st 1928 at the Steinway Hall of Metropolitan Opera House [32]. The first version of Terpsitone, although referred in sources as "Musical Dance Stage" [37] or "the Theremin ether-wave dance stage" [3, 36] was built in around year 1930 in New York City [31] (see Fig. 2). It was shown publicly at another Theremin's recital. This time at Carnegie Hall on April 1st 1932 at 8.30pm [3, 35]. The report from the concert published the next day states: "the first demonstration of the Theremin ether-wave dance stage" [36]. We find peculiar quotes about the demonstrations done by Clara Rockmore, at that time referred to with her maiden name Clara Reisenberg: "Strangest of his new creations is a platform on which a dancer plays a tune by the movements of her body. Waving the arms governs the pitch, and stooping or rising, the volume" [35]. This is a description of IKC for that particular instrument, and it perhaps was given by the observer, who was not aware of the technicalities of the instrument. That is the volume control was most probably done through stepping forward or backward on the platform, changing the proximity to a second antenna, most probably mounted in the speaker stand behind the performer.

2.2 Second Terpsitone c.1936

As mentioned earlier, the source, referring to the instrument by the name "Terpsitone" is dated year 1936 [20]. In that article we

Figure 2: Clara Rockmore (Reisenberg) pictured demonstrating the first "Terpsitone" (the Musical Dance Stage) in Carnegie Hall (New York) on the evening of April 1st 1932. We can see the stage panel for the performer to stand on (the floor antenna to control pitch) and a structure behind, which holds the custom-built speaker, and most probably hides the second antenna (volume control). In some secondary sources this picture is attributed wrongly [4] or not in-full [31]. The correct primary source is [35].

find several photographs and schematics (see Fig. 3, 4, 5, 6). As it is obvious from the visual comparison of the photos from 1932 (Fig. 2) and 1936 (Fig. 3) - the instruments look different. The earlier one was mobile and was probably intentionally designed for stage shows. The one we discuss in this section - was a stationary setup for the studio. Without additional deeper investigation it is hard to say objectively if they were both designed at the same time or if actually one predates the other. But because the primary source, showing the photos of the studio Terpsitone, was dated later - we convene in calling it "the second" at least in this text. In his letter to F.K.Prieberg about his period in NYC, Theremin writes: "Performative instrument for music and dance, called Terpsitone <…> has been demonstrated in concerts as monophonic only. At the same time I worked with multiple performers in my studio to play more complicated polyphonic pieces, for example I.S.Bach's fugues." (quote by [31], transalted from Russian). Taking into account that Terpsitone's construction was kept consistent in decades - it is unlikely that Theremin was talking about a special polyphonic version of the instrument. This gives a hint, that in addition to the instruments, pictured in press in 1932 and 1936 - there were indeed more Terpsitones present in Theremin's dance studio in Manhattan. Looking into the technical diagrams of The Second Terpsitone, we see important details. For example, two oscillators represent the heterodyning principle of generating the sound frequency in a musical range (same way as in Thereminvox) (Fig. 5) - proving the known fact, that Terpsitone is effectively a rearrangement of Thereminvox's modules. There is a visual note indicator (also Fig. (Fig. 4)). Mason's article describes the "partly-mechanical method" of these reactive lights: they were switched by a set of vibrating reeds, which were tuned to the correpsonding frequencies. It is an early example of basic spectrograph.

We reprint the original caption in Figure 5 - and it gives a sort of confusing explanation on the role of the vibrator. As we see - the performer's movements had no effect on the volume of the tone in this Terpsitone, but only on pitch. One interpretation of the vibrator's action, is that it just added a low frequency amplitude modulation to the tone, to make it more musical. Another - that it served as a "scaler" - bypassing the amplitudes of the tones, corresponding with a particular scale only. Both ways would make the instrument more controllable and sound more musical indeed. If the second interpretation is correct - we see a very early historical example of a kind of "assisted musicality", when the designer of the instrument adds automations to the technical system to simplify the performer's work. This was later explored in developments like Max Mathews's Radio Baton (in Conductor Mode) [21] and many Accessible Digital Musical Instruments (ADMIs) in NIME area [8]. Finally in Figure 6 a phonograph for accompaniment is clearly shown, perhaps illustrating two facts: Theremin thought of the Terpsitone as of a solo instrument; and he was probably more interested in melodic music of a mainstream western tradition, than in avanguard experiments happening at that time. The latter is ofcourse supported by the notorious Thereminvox's repertoire inherited by present days.

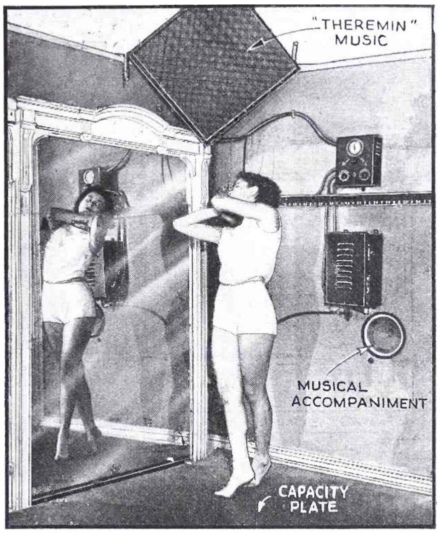

Figure 3: The Terpsitone from 1936, mounted in Theremin's studio in Manhattan. Name of the dancer is unknown. The original markings point to: the main speaker for the tone of the instrument above the dancer; speaker, which plays the musical accompaniments; and the floor antenna - the capacitive plate. Picture is attributed to "Halbran photos". Primary source: [20].

In his interviews and the letter (mentioned above) Theremin accounts that there were many students coming to his studio in Manhattan to practice with Terpsitone [23, 31]. One of the students was a young black woman dancer Lavinia Williams, who later became Leon Theremin's wife. The destiny of the Terpsitones, developed in 30s is currently unknown. It is a historical fact, that Leon Theremin left the USA abruptly in 1938, leaving everything behind. The reasons vary in sources and are beyond the scope of this particular research. Deeper invetigation is needed towards the traces of his estate of that time.

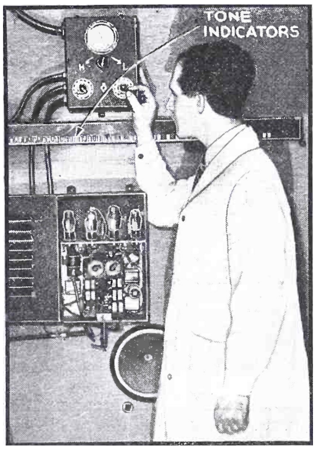

Figure 4: Professor Theremin himself adjusts the volume of the Terpsitone, because it was not under control of the performer at all. Panel with partly-mechanical tone indicators is marked. And the synthesizer block of the instrument is open and proudly demonstrates victorian valves, which constitute two heterodyning oscillators. Taken from [20].

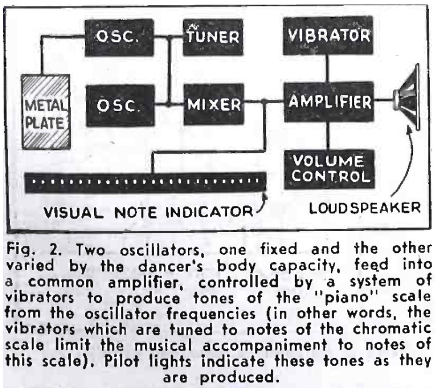

Figure 5: The principle diagram of the Second Terpsitone. We reprint the original caption, which is important for understanding the role of the vibrator module, which may predate modern research in "assisted musicality". Taken from [20].

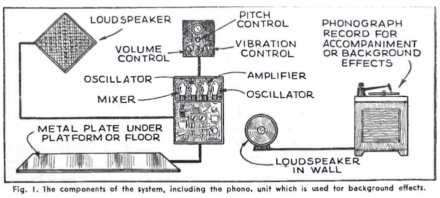

Figure 6: Illustration of the main physical modules of the The Terspitone from 1936. It non-ambiquosly includes a phonograph for a background accompaniment, so that Theremin's students could practice solo. Taken from [20].

2.3 Third Terpsitone 1966-1967

After Theremin's dramatic dissapearance from the USA in 1938, he spent decades under KGB supervision in the USSR: first as a prisoner in concentration camps, and later as a prisoner-academic in "sharashkas" (the secret governmental research institutions which served to military complex of the Soviet Union). It was only after his retirement from KGB in October 1964 when he was freed from the system and was able to return to his experiments in music technology. On April 26, 1967 through an article by Harold Schonberg in the New York Times, the western world discovered, that Leon Theremin was still alive [29]. We encounter the echo of the Third Terspitone in that exact text:

> "Now I will show you something special," (Theremin said). He ushered the visitor into a room in which a small dance floor had been constructed. Mr. Theremin stood on the floor, raised his arms, made motions, and started to play the *Massenet Élégie* on nothing at all. The room was filled with sound, and it was positively spooky. No wires, no gadgets, nothing visible. Merely electromagnetic sorcery.

More technical information and some images are available in the report of Acoustic Laboratory of Moscow State Conservatory from 1968 [5], where Theremin took a position and constructed that instrument some years before. As well is in the patent application, presumably from 1966 [33].

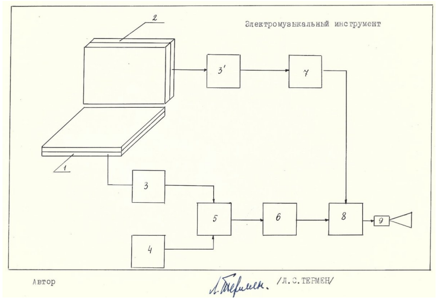

Figure 7: The structural schematic of the third Terpsitone from the patent application, presumably done in 1966. It is titled "Electro-musical instrument". Theremin's russian signature is seen in the bottom. The modules described in the source are: 1 - metal stage with isolated cover; 2 - similar plane on the back; 3 - variable frequency generators; 4 - stable frequency generator; 5 - mixer; 6 - low frequency filters block; 7 - frequency demodulator; 8 - timbre block with an amplifier; 9 - acoustic system. Reprint from primary source: [33]. Also available in [31].

The structural schema of the instrument (Fig. 7) shows the same modules, as the earlier Terpsitones had, except here we can see the background panel, which controls the volume in the same technical way, as it is controlled in Thereminvox - through frequency demodulation applied on amplitude envelope. In this case the performer can move forward or backward to control the loudness. It is safe to state, that this type of volume control most probably has been used in some of the Terpsitones in 30s. Though, as we will see further - Theremin kept explorng various ways of mapping the amplitude in Terpsitones. We can not clearly confirm that the back panel is present on the only photographic picture of this Terpsitone from 60s, available in the Lab Report (Fig. 8). In the report itself the Terpsitone is called "the instrument for the synthesis of melody and plastic movement" and later "monophonic setup in type of "terpsitone"" (translated from Russian). The main modules include: electronic tone block, dance stage, dynamic speaker. The device for interactive control of volume, similar to the backpanel in the patent, is described as

Figure 8: The Terpsitone from 1966-1968. We can see the segment of the floor panel (pitch control) on the bottom and the synthesizer module (tone block) mounted on the wall in a fashion of the studio Terpsitone from 1936. We can not confirm if the black panel on the left is a second antenna for the volume control. This most probably was the "small dance floor", described by Schonberg in New York Times. Primary source: [5].

"the schematics of additional devices". Although this might be a matter of adjustment to beurocratic requirements of some sort. The peculiar part of the report also mentions another additional block, which was used to stabilize tone, during the movements of the performer with a type of electric analog memory system. This time we clearly see a prospect of "assisted musicality", mentioned in a section above. In general, the Terpsitone of 1966-1967 most likely served as an experimental setup for the further development of the ideas behind the instrument, rather than as a regular performative space for dancers, as it had been in New York decades earlier. This instrument reportedly was lost, along with many other Theremin's inventions of that period, when he was expelled from the Acoustics Lab, which according to his interviews, happened mainly because Schonberg's New York Times publication ended up on a table of Conservatory's administration. We can confirm that the name of the bureaucrat, who destroyed the laboratory and fired Theremin was K.N. Nuzhin (vice-rector for administrative affairs at the Conservatory in the 1960s) [15, 22, 23, 31].

2.4 The last Theremin's Terpsitone 1978-1979

Leon Theremin left Moscow State Conservatory's Acoustics Lab for good in 1972 [31]. And after some time found a place to continue his experiments at the Physics department of Moscow State University. Those years (1972-73) is when Lydia Kavina has her earliest memories about the great inventor, who was a cousin of her grandfather Mikhail Nesturkh, and has been very close with her family [13, 14]. Theremin built his last Terpsitone as a gift for Lydia in years 1978-1979, when she was just 11 years old [28]. Although there has been no public performances with the instruments in those decades - it reportedly was used for demostrations of the Terpsitone's principles, as well as for practical explorations [28]. For the convenience, and because this is the last original Terpsitone in existence, built by Leon Theremin, we will be referring to it as "the Terpsitone" further in this text. On the rare photo from that period (see Fig. 9) we can see Lydia (presumably age 12) dancing on a massive wooden panel (floor antenna). It was designed for Theremin by Lydia's father - Evgeniy Kavin [15]. To the right from the panel beneath the stylish wall clock - is the box of the tone block for the instrument. The smaller rectangular part leaning on the wall - is a small detouchable speaker. The composition concludes with a darker corner, where Leon Theremin himself sits and perhaps gives directions for the demonstration.

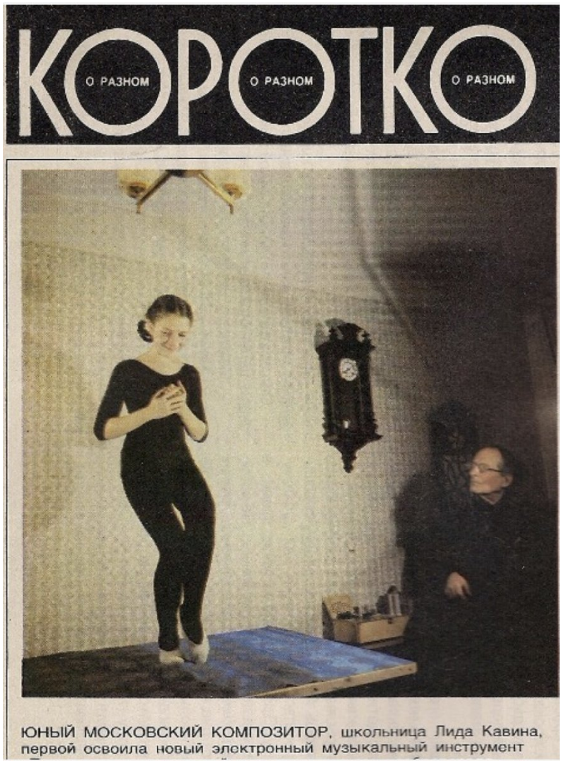

Figure 9: The dance on the Terpsitone. Magazine "Sovetskaya zhenschina" n.4, 1982. Caption: "The Young Moscow composer, Lydia Kavina plays a new electronic instrument…" (translated from Russian). Taken from [14]. According to Lydia's recollection - it is possible, that Theremin held a small controller in his right hand (visible), which he used to handle the amplitude changes, instead of a second antenna [15].

Leon Theremin passed away on November 4, 1993.

Up until that time and long after - The Terpsitone existed in Lydia Kavina's home [15]. In year 2005 it was transferred to the Theremin Center of Moscow State Conservatory - a non-profit arts organization, founded by the followers of Theremin under the leadership of Andrey Smirnov in 1992. One of the authors of this text recollects the first encounter with the Terpsitone in the Theremin Center in year 2005. The pictures, taken during that period are available (see Fig. 10).

After the closure of the Theremin Center in 2010 - the Terpsitone was stored privatly, and later in 2014 it moved to the newly established Moscow Sound Art Studio (a.k.a. `SA))_studio`), where it was stored until 2023. For a brief period the tone block has been transported to the Sound Laboratory of Rodchenko's Art School. In 2023 and 2024 both the panel and the tone block were transfered to the Center of Electroacoustic Music of the Moscow State Conservatory (CEAM), where they are stored currently. The smaller detouchable speaker module reportedly was lost.

Figure 10: The photos of the Terpsitone, taken by Lydia Kavina at the Theremin Center in 2004. Left: Julia Koroleva shows position on the antenna panel. Upper right: the panel alinged with the wall nearby the tone block and a speaker. Lower right: the tone block and the speaker module close-up. Despite the drastic visual difference between this antenna panel and the one in Fig.9 - we confirmed, that this was the same device. The photo from 1982 shows it, covered with decorative fabrics, which were lost with time [15]. Photos taken from [28].

3 The sound of Terpsitone

As we see by now, Terpsitone was a significant invention for Leon Theremin himself. In the interview to Olivia Mattis he says: "It's important to talk about this instrument, because it required a great deal of work" [22]. We see aswell, that he continuesly returned to it's development through all the major parts of his life. Was it the beauty of the body-to-sound synergy, or the power of unsolved engineering tasks - we can not be sure what kept Theremin's interest in this machine. We only know, that most probably there are no audio recordings in existence of any Terpsitones, except the last one. The earliest publicly available recording of the Terpsitone's sound along with the short video of an improvised demo was done in January 2013 at the installation of the instrument for the NODE Festival in Lausanne, Switzerland (see Fig. 11).

This last Terpsitone has not been used widely for performative practices, as for the majority of modern artists and musicians it's possibilities seemed to be too limited, while the physicality of the device, made in 70s prompted logistical difficulties. For the last decades it served more as an inspiration and as an important totem for the generations of younger sonic explorers, who could touch something, made by hands of the legendary Leon Theremin. At the same time the elegant principles behind Terpsitone are easily retranslatable into modern digital domaines with use of various sensors, or computer vision. And that was the path most of the Terpsitone scholars have chosen. The artifact itself stayed silent for a decade until December 7, 2024, when the one and only public performance with the original Theremin's Terpsitone actually happened in Artemiev Space of CEAM 12.

In the two videos, mentioned above we can hear the real sound of the last Theremin's Terpsitone. It is a thick heterodyning oscillator timbre, naturally compressed at low-end and cleanly sinusoidal at high - very characteristic for classic Thereminvoxes.

Figure 11: A frame from the video available online. Thierry Frenkel plays a melody on the Terpsitone from 78-79. We can see that the floor panel is not the original one. Due to enormiously high weight and simplicity of construction - it proved to be impractical to tranpsort the antenna. The Terpsitone and the Sensor Garden installation by Andrey Smirnov. NODE Festival. Le rendez-vous des curiosités sonores. Lausanne, Switzerland. January 2013. Taken from [6].

Figure 12: Frames from the video documentation of the live performance with the Terpsitone happened Dec.7, 2024 in Artemyev Space of CEAM. Choreography, performance and staging by Vladimir Ermachenkov. Music, sound, engineering by Oleg Makarov. Upper left, right and lower left: motion phases of the choreography. Lower right: authors open a discussion with the audience. Source: CEAM archive.

4 Terpsitone's technicalities

According to one of the authors of the performance - Oleg Makarov - the Terpsitone did not require any significant restoration. Due to it's relative simplicity - the device worked after decades of being inactive [19]. Let's look in more detail into it's technical structure.

From the history observed above - we can see variations in number of modules of different Terpsitones. The one availble to us represents the core minimum - it currently has two parts: the antenna panel, which is used as the stage; and the tone block, which holds a power supply, the circuitry for the controllers and the synthesizer for the tone.

4.1 the Antenna Panel

This module is a rectangular box made of playwood, it has 4 metal handles on 3 of it's sides and 3 rotary wheels on the 4th side (Fig.13).

Figure 13: The full view of the Antenna Panel of the Terpsitone. Photos: G.Krasnokutskaya, A.Paz.

The top of the box is wider than the bottom and under it there is metal grid which serves as an electrode for the open capacitor type sensor, similar to Thereminvox's antenna. For the dimensions please see Figure 14.

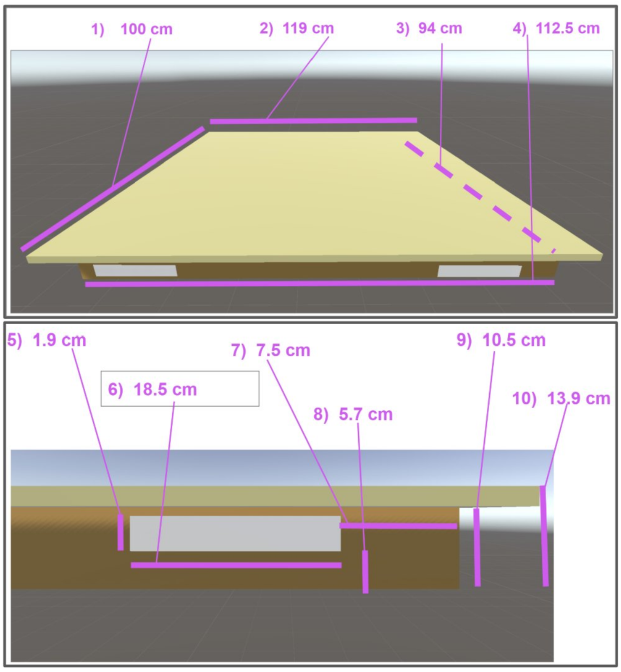

Figure 14: The dimensions of the panel in centimeters.

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4.2 the Tone Block

This module is a rectangular box made of playwood with a metal top, which holds a number of electronic elements, controllers and connectors (see Fig.15). The main dimensions are in Figure 16.

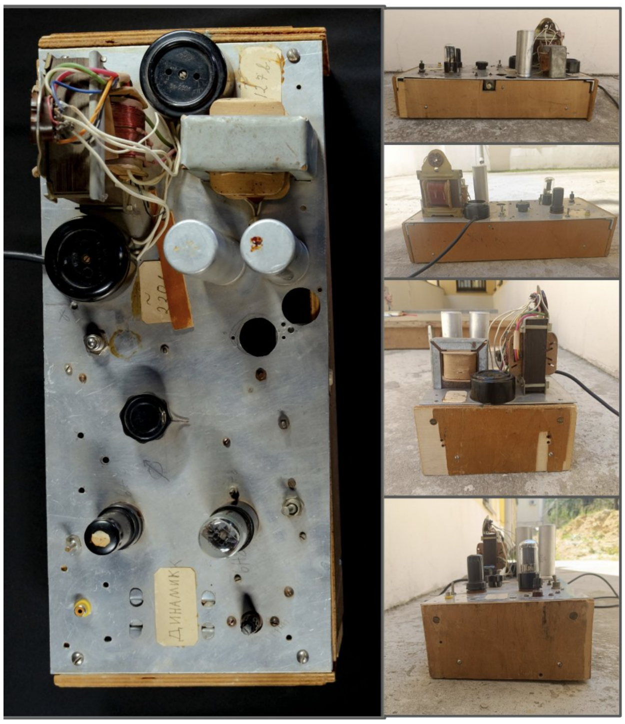

Figure 15: The Tone Block views. Photos: CEAM archive and G.Krasnokutskaya, A.Paz.

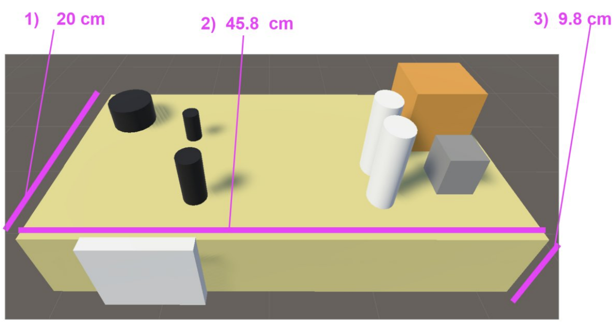

Figure 16: The dimensions of the Tone Block in centimeters.

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The frugal aesthetics of this box provokes admiration in any modern D.I.Y. enthusiast. Fluid, adaptive, expressive, almost naturalistic style of imporvised assembly, like a poetry sketched by a hand of a master. Some parts are hidden inside, others are casually left nesting right on top in open air, holes were added to the top and sides following the need to experiment or adjust. The Tone Block's design is a signature of time, when technical explorers in Soviet Union had to utilize anything they could find for free, as well it is a palette or a small piece of a sketch-book of one of the originators of do-it-yourself approach in electronic music. Besides just being beautiful, this box is a true historical artifact.

Structurally the Block contains two main parts: a power supply and the synthesizer. We provide the circuit diagram for the synthesizer (see Figure17). The schematic was restored from the sketch, retireved from the original device itself. Unfortunatelly it lacks some of the nominals. Additionally, we provide the Soviet nominals for the vacuum tubes as in the original. But the modern analogs are as follows: 6H8C (modern 6SN7GTB / 6SN7GT); 6A7 (modern 6SA7).

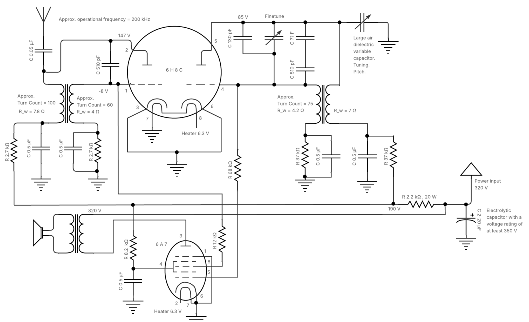

Figure 17: The most complete by this time circuit diagram for the synthesizer of the Tone Block. Please zoom in to see details. Not all the nominals were restored from the original. Source: the schematic was reverse-engineered by Andrey Smirnov by testing and measuring the original circuit in c.2011-2012. It existed as a hand-drawn sketch in private archive. It was digitized by the authors of this text and subsequently reviewed by additional experts. Published first time.

As stated before - the principle of control-synthesis here is similar to the classic Thereminvox. The core is two high frequency oscillators operating way above the hearing range and driven by the double-triode (6H8C). One has a fixed (adjustable) frequency, another - depends on the capacitance of the open component, to which the electrode (the Antenna Panel) is attached. The two oscillators are mixed, producing the third - lower frequency, which enters the hearing range. It depends on frequncies of both fixed and reactive oscillators. This is heterodyning explained in simple terms.

5 Making a Digital Twin

The production of a Digital Twin for a HEMI consists of three main parts: creating a full-size 3D model with a pre-determined level of detail; developing the procedural audio engine; mapping the interaction between the model and the engine.

5.1 Real-size 3D model

There are many ways to create a 3D model of a real object. Among them: 3D scanning, AI-assited photogrammetry, measurement-based modelling and others. Taking into account availble resources, we opted in using the measurement-based approach to model the Terpsitone in MAYA 3D software. The primary data set for the 3D model consisted of 46 photographic images and a large number of detailed measurements, examples of which can be seen in Figures 14 and 16. The model in current implementation uses custom textures. Please see Figure 18.

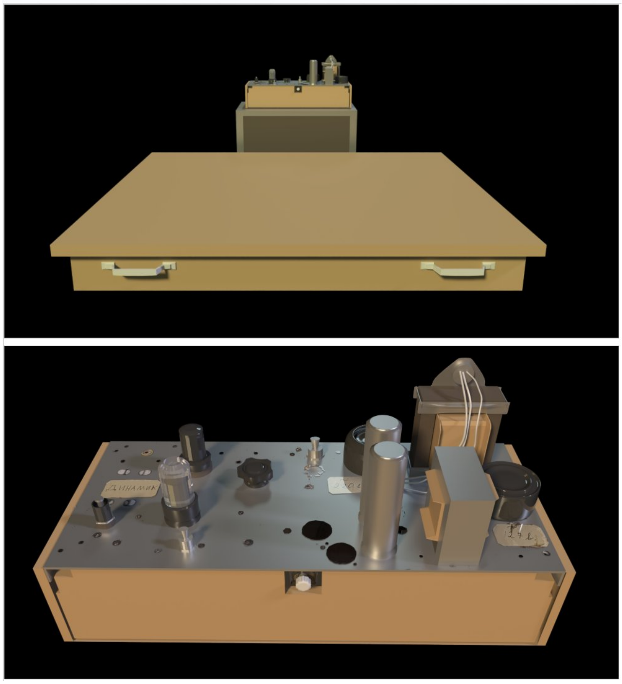

Figure 18: The full-size 3D model of the Terpsitone from 1978-1979.

5.2 Sound engine

Creation of a sound engine for this Digital Twin can follow two directions: trying to replicate the original sound as close as possible, or trying to model structure of the generator. We can describe the second approach.

The presented schematic (Fig.17) shows a clear resemblance with the schematics of RCA Theremin - the earliest version of Teremenvox in mass production [2]. The oscillators, used in both, can be identified as class of Armstrong Oscillators with feedbcak transformers, based on electrical ciruits with triods [17]. In digital domain this type of triode-based circuits known to be modeled as Van der Pol oscillators [34]. The standart description is following:

$$\frac{d^2x}{dt^2} - \mu(1 - x^2)\frac{dx}{dt} + x = 0 \tag{1}$$

- x: The position coordinate (dynamical variable).
- t: Time.
- μ: The nonlinear damping coefficient (scalar parameter).
  - If $\mu = 0$, the system is a simple harmonic oscillator.
  - If $\mu > 0$, the system has a stable limit cycle.

We use real-time DSP system Pure Data (PD) to prototype our engine and later implement it into procedural audio in VR. The given expression can be reinterpreted, using the syntax of `[fexpr]` object in PD [38]:

$$\begin{cases} y_1[n] = y_1[n-1] + x_2 \cdot y_2[n-1] \\ y_2[n] = y_2[n-1] + x_2\big(-y_1[n-1] \\ +x_3(1 - y_1[n-1]^2)y_2[n-1]\big) + x_1 \end{cases} \tag{2}$$

- y_1: Output signal (position).
- y_2: Internal state variable (velocity).
- x_1: External driving force (input signal).
- x_2: Time step (controls frequency/pitch).
- x_3: Nonlinear damping coefficient μ.

The final step is to modulate two oscillators in ultra- high frequencies to produce the heterodyning effect. The problem here, is that modelling such frequencies above the nyquist limit is practically impossible inside computer within the DSP context. To overcome this we create a patch, where very high audio frequencies are used to heterodyne and then filtered with low pass filters. The resulting patch is in Figure 19.

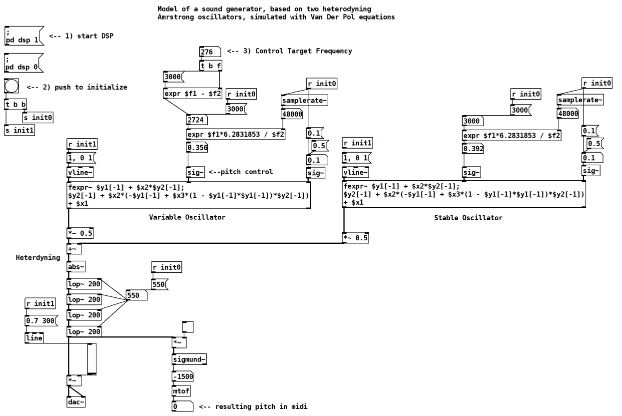

Figure 19: Please zoom for detail. The model of heterodyning Van der Pol oscillators is used to emulate the circuit of the Tone Block. The chain of low pass filters proved to be the simplest way to reinforce the filtering of the higher frequencies - the artifact of our approach.

5.3 Interaction

The purpose of interaction design for the Digital Twin is to preserve the IKC of the original instrument. Following analysis of historical sources and available recordings of the Terpsitone's performance, we were able to determine the main IKC as the control of pitch by the movement in vertical axis (see Sections 1.2 and 2). One of the difficulties though is the mapping of the original interaction on the availble set of controllers and processing power. The test system available to us consist of META Quest 3 VR Headset, connected via Link to a Windows-based PC. The integrating environment is Unity 3D game engine.

Here is one of the most complete IKC descriptions for a Terpsitone class instruments by Leon Theremin himself given in [23]:

> When a dancer's body is low, you hear the lowest pitch. When the dancer raises her body, the pitch also goes up. It's also possible to dance without changing the sound. For instance, if the dancer raises one arm and lowers the other, there will be no change in pitch. But if the dancer raises both arms - then the pitch will go up.

The Meta Quest 3 has three main user tracking positions in Virtual Reality: head via the helmet itself, and both hands via the stick controllers. The IKC descriptions suggest that the optimal mapping will be represented through calculation of the mid-point in between the vertices of the dynamic graph comprised of the three tracking points mentioned above, which is mathematically described as the average centroid in 3D. Let the three tracked positions be:

$$H = (x_h, y_h, z_h), \quad L = (x_l, y_l, z_l), \quad R = (x_r, y_r, z_r).$$

The average point (centroid) C is given by:

$$C = \frac{H + L + R}{3}.$$

In component form:

$$C = \left(\frac{x_h + x_l + x_r}{3}, \frac{y_h + y_l + y_r}{3}, \frac{z_h + z_l + z_r}{3} \right).$$

The next step is calculation of distnace between the resulting `C` and the stable coordinate, embedded into the model of the Antenna Panel in VR. The current stage of this research is in development of set of custom scripts in C#, which can allow this type of mapping. Finally the connection between interaction and real-time audio processing in current prototype is achieved with LibPD integration in Unity3D [27]. This allows a direct compilation of Pure Data patch (see Section 5.2) into Unity build.

6 Conclusion

In this paper, we described the creation of a Digital Twin of the last Terpsitone built by Leon Theremin. We provided a detailed historical introduction to the instrument based on primary sources and demonstrated the current development stage of the interactive instrument in Virtual Reality. It is important to note that the volume of primary data collected for this research exceeds the scope of this publication and will be analyzed in future studies. Future work will focus on developing a more stable sound engine and high-precision interaction scripts, as well as exploring possibilities for performative tests. One of the main features of the Terpsitone is that its constrained design stimulates the refinement of motion. This is similar to the Thereminvox, but engages the entire body. The graceful, fluid lines of the human body - while the machine interface remains almost invisible in the background - are a consistent visual theme in all documentation of Terpsitones from the 1930s to the present. It is an elegant technical design that uses sound interaction to naturally enhance human aesthetics. By creating a Digital Twin of this machine, we - beyond historical and technical exploration - aim to highlight this synthesis of technological and human beauty.

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8 Ethical Standards

This research has been performed without any external funding. No animals, except the authors, were involved.

References

[1] Jack Atherton and Ge Wang. 2020. Doing vs. Being: A Philosophy of Design for Artful VR. *Journal of New Music Research* 49, 1 (2020), 35–59.
[2] Andrew Baron and Mike Buffington. 2026. *RCATheremin.com: The RCA Theremin Registry and History.* https://www.rcatheremin.com
[3] CarnegieHall 1932. Carnegie Hall Concert Program Archive: Léon Théremin and the Theremin Electrical Symphony Orchestra. Concert program, Carnegie Hall, Main Hall. Performance at 8:30 PM. Orchestra: Theremin Electrical Symphony Orchestra. Conductor: Albert Stoessel (1894–1943). Presenter unknown..
[4] Simon Crab. 1995-2025. *The 'Terpsitone', Leon Termen, USA Russia,1932.* https://120years.net/the-terpsitoneleon-termenusaussr1930/
[5] D.Yurchenko, L.Theremin, Y.Kornilov, E.Obukhov, V.Matveev, and E.Valikovskaya. 1968. *Report on research, engineering and academic works for year 1967.* Laboratory for Acoustics and Sound recording of Moscow State Conservatory.

[6] etheremin. 2013. *N/O/D/E - Terpsitone*. YouTube. https://www.youtube.com/watch?v=gH0Y5M46Gqc
[7] Aldo Faisal. 2017. Computer science: Visionary of virtual reality.
[8] Emma Frid. 2019. Accessible Digital Musical Instruments—A Review of Musical Interfaces in Inclusive Music Practice. *Multimodal Technologies and Interaction* 3, 3 (2019). https://doi.org/10.3390/mti3030057
[9] M. Grieves. 2019. Virtually Intelligent Product Systems: Digital and Physical Twins. In *Complex Systems Engineering: Theory and Practice*, S. Flumerfelt et al. (Ed.). American Institute of Aeronautics and Astronautics, 175–200.
[10] Peter Hehenberger and David Bradley (Eds.). 2016. *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and Their Designers*. Springer.
[11] J. Hutson, J. Weber, and A. Russo. 2023. Digital Twins and Cultural Heritage Preservation: A Case Study of Best Practices and Reproducibility in Chiesa dei SS Apostoli e Biagio. *Art and Design Review* 11 (2023), 15–41.
[12] Alexander Refsum Jensenius. 2022. *Sound actions: Conceptualizing musical instruments*. MIT Press.
[13] Lydia Kavina. 2013. *Memories of Lev Termen*. LiveJournal. https://kavinal.livejournal.com/697.html originally posted November 30, 2013.
[14] Lydia Kavina. 2023. *Lydia's memories of Lev Theremin*. LydiaKavina.com. https://lydiakavina.com/memories
[15] Lydia Kavina. 2026. Personal communication. Interview with the author, February 11, 2026.
[16] Henry E. Lowood. 2025. *Virtual Reality*. https://www.britannica.com/technology/virtual-reality Last updated 8 Jan. 2025.
[17] TutorialsPoint Pty Ltd. n.d.. *Armstrong Oscillator Circuit with Feedback Transformer*. Electronics-Tutorials.ws. https://www.electronics-tutorials.ws/oscillator/armstrong-oscillator.html
[18] Thor Magnusson. 2019. *Sonic Writing: Technologies of Material, Symbolic, and Signal Inscriptions*. Bloomsbury Academic.
[19] Oleg Makarov. 2026. Personal communication. Interview with the author, 2025-2026.
[20] C. P. Mason. 1936. Theremin "Terpsitone" A New Electronic Novelty. *Radio-Craft* 8, 6 (Dec. 1936), 335, 365.
[21] Max Mathews and Richard Boulanger. 1997. The 1997 Mathews Radio-Baton & Improvisation Modes. In *Proceedings of the International Computer Music Conference*.
[22] Olivia Mattis. 1989. *Interview of Leon Theremin*. https://archive.org/details/vasulka11859/mode/2up Also available at: https://archives.stanford.edu/catalog/ars0107_aspace_ref45_woi.
[23] Olivia Mattis and Robert Moog. 1992. Pulling music out of thin air. *Keyboard magazine* 18, 2 (1992), 46–54.
[24] Guerino Mazzola and Moreno Andreatta. 2007. Diagrams, gestures and formulae in music. *Journal of Mathematics and Music* 1, 1 (2007), 23–46.
[25] Guerino Mazzola, René Guitart, Jocelyn Ho, Alex Lubet, Maria Mannone, Matt Rahaim, and Florian Thalmann. 2018. The topos of music III: Gestures. *Third volume of second edition of* (2018).
[26] Dimitris Menexopoulos, Pedro Pestana, and Joshua Reiss. 2023. The state of the art in procedural audio. *Journal of the Audio Engineering Society* 71, 12 (2023), 826–848.
[27] Niall Moody. 2021. *LibPd Unity Integration*. https://github.com/LibPdIntegration/LibPdIntegration updated Oct 24, 2021.
[28] Valerio Saggini. 2004. *The Last Terpsitone on Earth*. https://thereminvox.com/stories/instruments/last-terpsitone-earth/
[29] Harold C. Schonberg. 1967. Music: Leon Theremin; Inventor of Instrument Bearing His Name Is Interviewed in the Soviet Union. *The New York Times* (26 April 1967), 40. https://www.nytimes.com/1967/04/26/archives/music-leon-theremin-inventor-of-instrument-bearing-his-name-is.html
[30] Stefania Serafin, Cumhur Erkut, Juraj Kojs, Niels C. Nilsson, and Rolf Nordahl. 2016. Virtual Reality Musical Instruments: State of the Art, Design Principles, and Future Directions. *Computer Music Journal* 40, 3 (2016), 22–40.
[31] Andrey Smirnov. 2020. *In Search of Lost Sound: Experimental Sound Culture in Russia and the USSR in the First Half of the 20th Century*. Garage Museum of Contemporary Art.
[32] The New York Public Library. n.d.. *Front cover of flyer for Leon Theremin program at Metropolitan Opera House, Tuesday Jan. 31, 1928*. https://digitalcollections.nypl.org/items/38dd7840-c6ca-012f-8b42-58d385a7bc34
[33] Leon Theremin. 1966. Attachment to the patent application.
[34] K Tomita. 1986. Periodically forced nonlinear oscillators. *Chaos* 10 (1986), 211–36.
[35] unknown. 1932. Radio Squeals Turned to Music for Entire Orchestra. *Popular Science* 120, 6 (June 1932), 51.
[36] unknown. 1932. Theremin Concert Given. *The New York Times* 81, 27 097 (March 1932), 13.
[37] unknown. 1932. Theremin's electric Symphony. *The New York Times* 81, 27 091 (March 1932), 154.
[38] Shahrokh Yadegari. 2020. *Expr, Expr , Fexpr* . https://yadegari.org/software/expr/