Laser Phase Synthesis

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ABSTRACT

This paper presents a new interface – Laser Phase Synthesis — designed for audiovisual performance expression. The instrument is informed by the historical *Audio/Video/Laser* system developed by Lowell Cross and Carson Jeffries for use by David Tudor and Experiments in Arts and Technology (E.A.T.) at the 1970 Japan World Exposition in Osaka, Japan. The current work employs digital audio synthesis, modern laser display technology, and close collaboration between sound and image composition to illustrate the harmonic progression of a musical work. The authors present a micro-history of audiovisual laser displays, a brief introduction to the process of drawing visual figures with sound, a description of the Pure Data software and laser display hardware systems used for the Laser Phase Synthesis instrument, and a discussion of how this instrument shaped the composition process of one audiovisual performance of electroacoustic music. The paper concludes with speculations on how the system can be further developed with other kinds of live performers, specifically vocalists.

Author Keywords

media archaeology, reenactment, historical instruments, audiovisual synthesis, Pure Data, ILDA, laser, Lissajous, visualization

CCS Concepts

•**Applied computing** → **Sound and music computing;** Performing arts; •**Social and professional topics** → *History of hardware;*

1. INTRODUCTION

In 1970, David Tudor composed sound for an audio-controlled, four color laser display system designed by Lowell Cross and Carson Jeffries. The system was installed in the pavilion created by Experiments in Arts and Technology (E.A.T.) for Pepsi Cola at the Japan World Exposition in Osaka. Cross locates the genesis of this large-scale work in a feeling of dissatisfaction which he experienced with the visual component of electronic music presentations as a young student during the mid 1960's [3]. This desire for a stronger connection between sound and image was common during the 60's and 70s, and drove composers such as Iannis Xenakis [21], computer animators such as John Whitney Sr. [18] [20] and Larry Cuba [19], and video artists such as Steina and Woody Vašulka [4] all to push against the edges of existing analog and digital technologies.

When describing the electronic possibilities of the Experimental Television Center studio, Hank Rudolf describes four ways in which sound and image can be related [11]. In the first case, sound can be analyzed and used to modulate imagery (visualization). In the second case, imagery can be analyzed and used to modulate sound (sonification). In the third case, both sound and imagery can be controlled by an external source of information (i.e. MIDI or OSC). However, this paper is primarily concerned with the fourth situation, where sound and image are derived from the same signal source. We argue that establishing this direct relationship between sound and image in a single electronic instrument creates a feedback loop in the interaction process, within which sounds are crafted specifically for their visual effect alongside their musical expressiveness.

We have found the concept of reenactment, particularly as discussed within the field of performance art, incredibly useful towards understanding historical electronic instruments. Rather than seeing a reenactment as a faithful repetition or high fidelity imitation of an original work, one can approach reenactment as a process of working from the original piece as a reference [5], while allowing for radically different outcomes to take place [1].

What holds for historical events and performances holds equally well for audiovisual instruments of the past. By reenacting the processes through which such instruments were developed and employed, one gains unique insights into why those instruments function the way that they do, and subsequently how those objects shaped and channeled the creative expressions of their users into the forms which they took [8].

This paper describes a reenactment of one specific, historical audiovisual instrument — Tudor, Cross, and Jeffries' *Audio/Video/Laser* system — using contemporary technologies. We begin with a micro-history of the context from which this laser instrument emerged, alongside a brief technical introduction to the use of lasers for creating realtime, interactive visual displays. We then describe a software library created by the principle author for controlling laser display technology with sound, and a specific implementation of that library optimized for working with musicians for live performance. Following this, we present the findings of two sets of experiments involving collaborations with an electroacoustic composer and with several vocalists. Finally,

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we discuss how these findings contribute to our concept of an audiovisual instrument.

2. BACKGROUND

2.1 A Micro-history of Audiovisual Laser Displays

Cross' first student experiments with visualizing electronic sounds involved hacking a television set in order to manipulate its electron beam using recorded music and signal generators, in a manner similar to Ben Laposky's use of oscilloscopes to create visual artworks starting in the 1950's [9]. In 1966, Cross collaborated with Tudor on two audiovisual works which exploited the phase differences in the acoustics of the bandoneon (a concertina-like reed instrument from Argentina and Uruguay which emits sound from both its ends) to create Lissajous patterns on a cathode ray tube display [3]. By 1969, Tudor had abandoned the bandoneon in favor of a table full of self-made electronics. Meanwhile, Cross had approached physicist and kinetic sculptor Carson Jeffries to assist in the construction of a set of galvanometer-controlled mirrors to deflect the beam of a krypton ion laser system using audio signals.

Tudor and Cross premiered this instrument at Mills College on May 9 of 1969, presented it shortly after at the Pepsi pavilion in Osaka, traveled with the performance through the 1970's, and gave their final laser concert at Ars Electronica in Linz, Austria in 1980. As source material, Tudor would use manipulated field recordings and long chains of electronic instruments connected through feedback into a "giant oscillator" [10]. The latter would either be played live or from prepared tapes sent directly to both speakers and laser galvanometers. This way, the audience would see and hear the same signals manifested in two different domains — those of both sound and sight — and undoubtedly the visual forms created on the laser inspired Tudor towards different combinations of sonic elements and tools.

Donna Haraway cautions us against repeating time-worn narratives of "[a]utopoietic, self-making man" — narratives whose basis in neoliberal individualism she finds wholly unsuitable for life on a planet in crisis [6]. Thus, rather than casting Cross and Jeffries as self-sufficient and isolated innovators, it is important to understand that they conceived and designed their laser control system within a rich ecosystem of the sciences and arts of the time. In an adjacent pavilion at the same Osaka Expo, for example, Rockne Krebs presented laser light sculptures developed during his residency with Hewlett Packard through the auspices of the Art and Technology Program of the Los Angeles County Museum of Art [15]. Nor was Krebs the only other laser artist shown in Osaka that year. The *New York Times* reported that "[a]t least half a dozen pavilions [had] works of art incorporating laser beams and reflecting surfaces" at the Exposition [13].

Likewise, by the end of the 1970's a burgeoning scene of laser visuals design had emerged in southern California under the initiative of scientist and former E.A.T. member Elsa Garmire alongside filmmaker Ivan Dryer. Their *Laserium* light shows entered popular culture through venues such as planetariums, concert halls, and football stadiums. A key difference is that, while Tudor controlled the movements of the laser beam directly with his sound output and reveled in the resulting chaotic unpredictabilities [10], the *Laserium* shows played as choreographed visual accompaniment to more traditional classical, pop, and rock music. Similarly, Xenakis' use of lasers in his *Polytopes* of the 1970's functioned alongside other architectural lighting effects "to compose movement and evolve forms" [21] for the musical performances, rather than being integral to them.

While the earliest laser animations were created by analog consoles which shared a great deal of functionality with modular synthesizers, these consoles were gradually replaced as microcomputers became more accessible during 1980's. This resulted in laser shows consisting predominantly of the pre-programmed imagery and effects currently found in applications such as Pangolin QuickShow [1], further separating the processes of sound and image making. In recent years, a number of artists have challenged this established aesthetic by bringing direct audio control of the laser back into live performance. The works of Germany's Robert Henke [2] and Australia's Robin Fox [12] both stand as exemplary in this new field. In a similar vein, software like Modulaser [3] and hardware such as the Neon Captain Radiator [4] both take direct inspiration from the early, manually controlled analog systems to enable realtime interaction with animated, geometric laser figures (referred to as "abstracts" within the laser art community) created from the waveforms of basic signal generators.

2.2 Reenacting Tudor and Cross

A complete reconstruction of Tudor and Cross' laser performances proves challenging, since only photographs of Tudor's equipment [10] and audio recordings of it being used without the laser [16] are publicly available. However, their work does provide rich possibilities for reenactment using contemporary means and with different outcomes. Not only have the possibilities for audiovisual synthesis increased substantially since Tudor's rat-nest of cables and boxes, but the cost and complexity of laser display equipment has significantly decreased.

As we demonstrate in this paper, a common multichannel audio interface can easily provide control over a laser projector employing an audiovisual programming environment such as Pure Data, while simultaneously outputting stereo audio for loudspeakers. Additionally, modern audio softwares are capable of precise control over frequency, amplitude, and phase almost unimaginable in Tudor's day — even though Tudor himself preferred the chaos of his own constructions to the precision offered by sophisticated synthesizers such as the Moog modular [10]. The use of free software and consumer hardware offers an entry to this practice at a substantially lower cost than most specialized, commercial laser display packages.

We believe that these possibilities offer us new methods to engage with laser display technology in novel and artistically invigorating ways. We have chosen to investigate them through the reenactment of Tudor and Cross' instrument, with a special emphasis on the use of a unified signal source for both sound and image. Our current work involves the digital synthesis of harmonic waveforms for the continuous modulation of laser-drawn figures. This requires careful consideration, since interesting sounds do not always produce interesting laser visuals. Nor are the sounds which produce interesting laser visuals always interesting by themselves.

Designing a sound to produce clear laser visuals requires careful control of frequency, amplitude, and phase relationships between two or more channels of audio. In fact, in-

[1]https://pangolin.com/pages/quickshow
[2]https://roberthenke.com/concerts/lumiere.html
[3]https://modulaser.app/
[4]https://www.neoncaptain.com/

jecting most stereophonic, musical audio signals into the laser can result in figures which appear random at best, and which are physically dangerous to the mechanics of the laser at worst. Additionally, monophonic sounds, such as those from vocalists or many solo instruments, cannot be used by themselves to create laser visuals which normally require two independent signals.

These concerns can add quite an additional burden to the creative process of a musical composer, particularly if they are not familiar with techniques for XY vector graphics. Therefore, by providing for a monophonic input signal, and reducing the technical considerations for the laser to a simple harmonic relationship, we set out to create an audiovisual synthesis instrument which simplifies the requirements for a composer, instrumentalist, or vocalist to use. Furthermore, it contains possibilities which can be expanded to be played in tandem with a visual artist for more complex visual effects. The following sections detail how this was achieved by first explaining how modern laser hardware functions, then discussing the Vector Synthesis software library created for audiovisual synthesis with the laser, and finally detailing the Laser Phase Synthesis instrument created with that library.

3. METHODS

3.1 How to Draw a Sound with Light

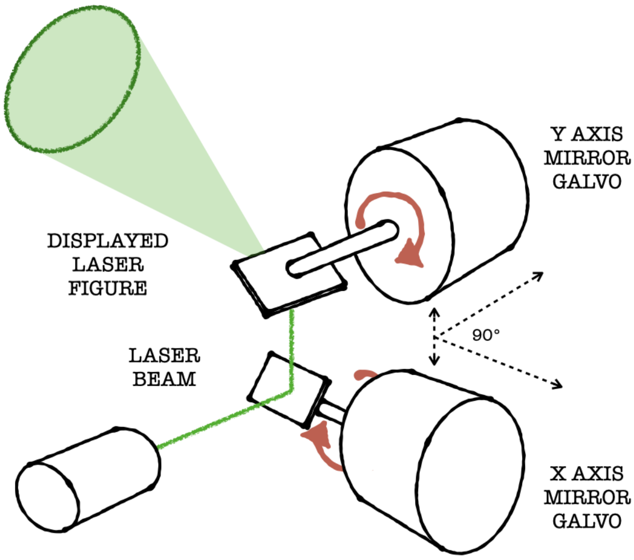

Figure 1: Galvanometers and mirrors in a laser display.

A laser display works by deflecting the beam of a laser to create repeating patterns. Deflections recurring below the flicker fusion threshold of approximately 25 Hz will be uneven in their intensity, while deflections faster than that will produce the illusion of a continuous line. The deflections themselves are produced by mirrors mounted on galvanometers ("galvos") which respond to an AC voltage by swinging back and forth. There is one mirror and galvanometer for each axis of movement — horizontal and vertical — mounted at ninety degree angles to each other, and the laser beam's trajectory is altered by each in series (Figure 1). A DC voltage offset sent to a galvanometer can be used to reposition the beam to draw a shape in a different location.

The International Laser Display Association (ILDA) specification [14] provides for the use of balanced, analog signals to control all the parameters of a laser. The horizontal and vertical signals are a ±10V differential voltage, while each of the three signals to the color diodes (red, green, and blue) is a 0 to +5V voltage. These levels are compatible with DC coupled computer audio interfaces such as the MOTU UltraLite or the Expert Sleepers ES-8, allowing the use of digital audio softwares to generate high resolution, continuous analog control signals for the laser galvos. The ILDA voltage levels are also compatible with signals produced by EuroRack format analog modular synthesizers and other consumer electronic sound instruments.

The shapes drawn by a laser display follow the principles of Lissajous figures, which display instantaneous differences in frequency, amplitude, and phase between a pair of signals as a two dimensional, linear figure drawn by a single point. Signals with integer harmonic ratios (Figure 2) will display a stable figure. Signals with inharmonic relationships will be unstable and appear as visual noise. Signals with frequencies close to a harmonic relationship will appear to rotate in space at a rate equal to that of an acoustic beating frequency (i.e. the absolute difference in Hz between the two).

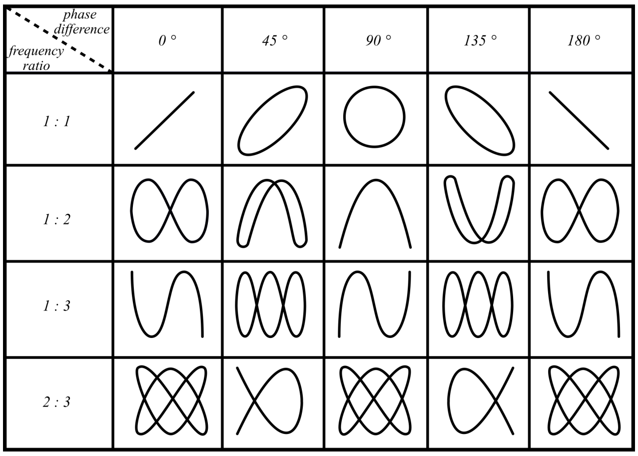

Figure 2: Harmonic and phase relationships of Lissajous figures.

Amplitude modulation of the signals drawing a figure can be used to impress one waveform's shape upon another, for example by modulating the size of a circle with an additional audio signal. Phase is the more complicated parameter, however. Two signals of the same frequency, and in phase with each other, appear as a diagonal line, as does a monophonic sound sent to both galvos. Changing phase differences of between 0 and 180 degrees produces the illusion of a figure rotating in three dimensional space. This principle explains Tudor's use of a variety of phase-shifting signal processors to obtain Lissajous figures from monophonic input signals [10], a practice likely informed by his early use of the out-of-phase signals captured from the bandoneon.

While French physicist J.A. Lissajous' 1855 experiments employed mirrors attached to tuning forks to deflect a beam of sunlight focused through a lens onto the wall of a dark room, most contemporary artists interested in producing his namesake figures employ more technological means such as oscilloscopes, vector monitors, and ILDA lasers. However, many frugal alternatives to these sometimes rare and often expensive devices have been crafted by members of the DIY audiovisual arts community. One finds many examples of televisions modified to accept external XY signals [2], as well as laser projectors constructed by using laser pointers, speakers, mirrors, and even balloons to deflect the laser beam into shapes driven by audio signals (Figure 3).

So while the methods described in this paper may not be particularly frugal on their own, the underlying principles could otherwise be implemented using free and open source software or simple analog electronics.

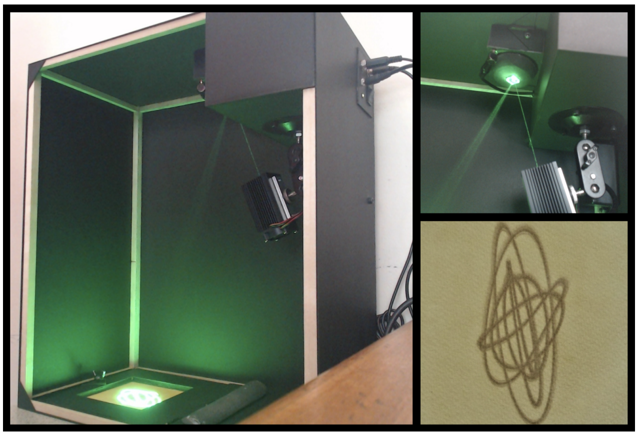

Figure 3: An inexpensive DIY monophonic laser projector using a balloon stretched over a loudspeaker and a mirror to deflect Lissajous-type figures onto photosensitive paper. Photos and device by Pablo Guerra/polwor.cl, reproduced with kind permission.

3.2 The Vector Synthesis Pure Data Library

The primary toolkit used in creating the Laser Phase Synthesis instrument is the Vector Synthesis [5] library for the free and open source Pure Data programming environment. The project evokes seminal graphics technology from the 1960's such as Ivan Sutherland's Sketchpad, or vector video games from the 1980's such as Battlezone, reimagining these primarily visual environments as opportunities for audiovisual synthesis [7] . Additionally, by using the GEM external in Pure Data, the library can reenact key affordances of historical scan processing animation computers from the 1970's, such as the Rutt/Etra Video Synthesizer and the Scanimate [8]. Taken together, this collection of tools was conceived as a media archaeological investigation of early computer animation techniques using more contemporary means.

In functional terms, the library allows the creation and manipulation of vector-based graphics, using audio signals to display these graphics on XY displays. A number of useful tools in a modular, patchable form allows users to quickly build up complex, interactive audiovisual animations. It contains modules for drawing two and three dimensional shapes, scaling them in size, translating them in location, rotating them in three dimensions, morphing between two or more shapes, multiplexing a number of shapes by splitting up the time the CRT or laser beam spends drawing each figure, and projecting a three dimensional figure into two dimensions with perspective applied. Finally, the library also provides a module for manipulating and modulating the RGB color values and overall brightness of an ILDA laser beam, as well as some safety features which deactivate (or "blank", in laser terminology) the beam when it travels outside of a predefined area (called the "zone"), or when the beam is not in motion (referred to as a "scan fail").

All of these transformations can either be adjusted manually, modulated slowly by low frequency oscillators (LFOs) with a number of waveforms, or modulated at audio frequencies by faster oscillators. Modulations at slow periods produce singular or repetitive movements associated with traditional animation, while modulations at audio rates can produce entirely new shapes depending on their harmonic relation to the fundamental drawing frequency. The resulting audio signals are sent simultaneously to display and loudspeakers through a balanced, DC coupled audio interface, providing a direct, non-symbolic relationship between sound and image.

[5] https://github.com/macumbista/vectorsynthesis

3.3 The Laser Phase Synthesis (LPS) Instrument

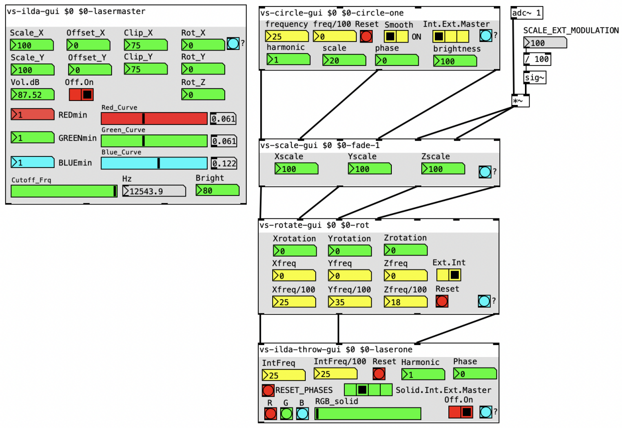

Figure 4: A patch using the Vector Synthesis library for Pure Data, which forms the basis of the Laser Phase Synthesis instrument.

The core of the Laser Phase Synthesis (LPS) instrument relies on a fairly simple arrangement of Vector Synthesis library modules. Figure 4 shows a simple patch for drawing a circle at 25 Hz using the *vs-circle-gui* module, modulating its size (*vs-scale-gui*) with an external audio signal (*adc*), rotating it with LFOs in three dimensions (*vs-rotate-gui*), cycling through the RGB color space (*vs-ilda-throw-gui*), and sending it to the audio interface as ILDA standard signals (*vs-ilda-gui*). This creates the visual effect of a multicolored circle of light drawn by the laser, whose size and shape is changed by the audio waveform of the input audio through a fairly straightforward process of amplitude modulation. A MOTU UltraLite digital audio interface both captures audio from a source such as a performer, and sends a complete set of ILDA signals to the laser, with additional stereo outputs which can be sent to a pair of loudspeakers. The musical and laser performers are all located facing the projection surface in order to see how the laser responds to the sound input.

The LPS patch is simplified and plotted in Figure 5, using primitive objects from the Pure Data environment. In this example, the circle itself is drawn by a pair of phase-locked, 200 Hz sine waves which are offset by 90 degrees. The first sine wave represents the movement on the X axis, and the second represents the movement on the Y axis. The amplitude of these two sine waves is modulated by a third sine wave at a frequency six times that of the oscillators drawing the circle. The amplitude modulator is scaled by the size modulation amount (here described as a percent) and summed with a fixed size constant to control the depth of the modulation. Modulator waveform peaks in the positive domain expand the visual shape outwards, while waveform peaks in the negative domain contract the figure inwards.

The modulated X and Y signals are plotted linearly in the time domain in the *vs-seeme* module, alongside the modulator waveform. The resulting figure is plotted in Cartesian space with an oscilloscope simulator, where we can clearly see the six positive peaks of the modulator signal. A video demonstration of the LPS multiplexing several laser figures together can be found in the first part of the supplementary video to this paper [6].

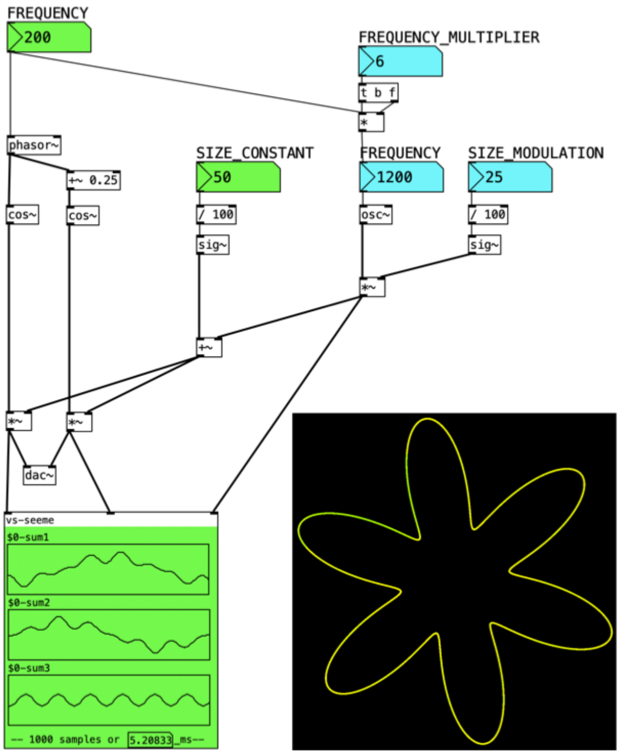

Figure 5: A simplification and plotting of the Laser Phase Synthesis patch, showing the effects of harmonic amplitude modulation on the X and Y carrier waves.

4. RESULTS

4.1 Experiment I: Audiovisual Composition

The first practical experiment with the LPS system was a collaborative, light and sound composition between audiovisual artist Derek Holzer and electroacoustic composer Luka Aron. This collaboration began in a quite free form manner, and eventually crystalized into a strict harmonic framework used to produce sound and image for a work entitled *Laser Phase Synthesis[XXI VII III I]*. Once this framework had been agreed upon ahead of time, each artist developed elements of the work in their own medium before bringing them together for a live performance.

The harmonic framework underlying the compositional method employed is a network of closely related harmonic series, whose fundamentals are derived from the subharmonic series. Certain combinations of harmonic series will have several partials in common, giving way to the possibility of modulating between them. It is a just intonation system of varying complexity, derived from the observation of certain auditory and acoustic phenomena, such as difference tones and (non)-beating, as well as the periodicity of composite sound waves.

[6]https://youtu.be/PURQxFVX3F0

In the case of *Laser Phase Synthesis[XXI VII III I]*, the fundamental 1/1 was first assigned to 25 Hz, which matched the initial drawing frequency of the laser forms. Three other subordinate fundamentals, each containing their own subset of unique harmonic partials, were chosen (4/3: 33.333 Hz, 8/7: 28.571 Hz, 32/21: 38.095 Hz). Subsequently, their order was determined by calculating their respective closest relative. An excerpt of the resulting sequence is illustrated in Figure 6. Each fundamental is held for a given amount of time, while the common partials overlap. It is important to note that the octave identity of each fundamental and partial may be changed, depending on the timbre used. During

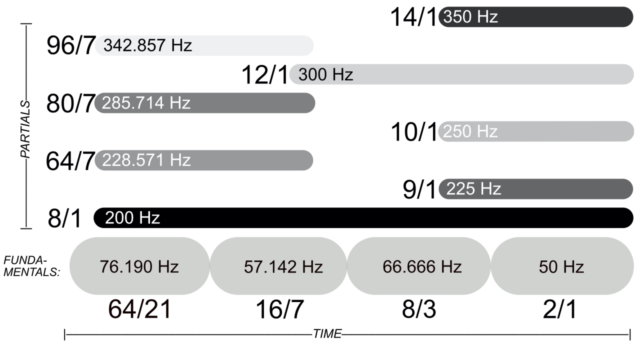

Figure 6: A timeline of the fundamental and partial frequencies, derived from a laser drawing frequency of 25 Hz, during the first section of audiovisual composition "Laser Phase Synthesis[XXI VII III I]".

the performance of the piece, the drawing frequency of the laser remains matched to the 1/1 fundamental frequency of the partials, even as this fundamental changes through the musical composition. This allows for a wide range of movement, both visually and audibly, while maintaining a close harmonic alignment. The primary timbres used as sonic material for *Laser Phase Synthesis[XXI VII III I]* were sine waves, and samples of several gongs and bells. While the sine waves were tuned to precision in the Pure Data environment, they interacted with the inharmonic spectra of the percussion instruments, resulting in rich interference patterns apparent in both sound and image.

Beyond the basic amplitude modulation of the LPS patch using a monophonic mixdown of the audio composition as modulator of a circular form, three dimensional rotations and color modulations of the figure added additional visual complexity. The signals driving the laser were not mixed back into the performance audio, only seen in the shape of the laser, and smoke was used to create a volumetric illusion with the laser beam. A selection of some of the resulting patterns can be seen in Figure 7. A video excerpt of the live performance can be found in the third part of the supplementary video to this paper.

4.2 Experiment II: Vocal Improvisations

During the development process of the LPS, a number of experiments were conducted with vocalists to investigate how the bodily interaction of singing through the laser could create new audiovisual expressions. For these experiments, the basic LPS amplitude modulation patch was used, with the voice of the singer captured with an SM58 microphone as the modulating signal. The RGB color of the laser beam was also affected by the amplitude and polarity of the input sound.

The participants in these experiments were provided with

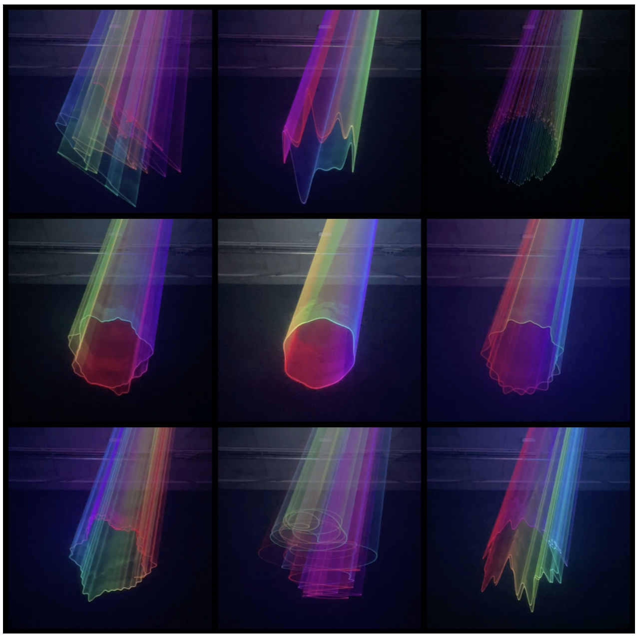

Figure 7: A selection of laser patterns from the live electroacoustic performance "Laser Phase Synthesis[XXI VII III I]".

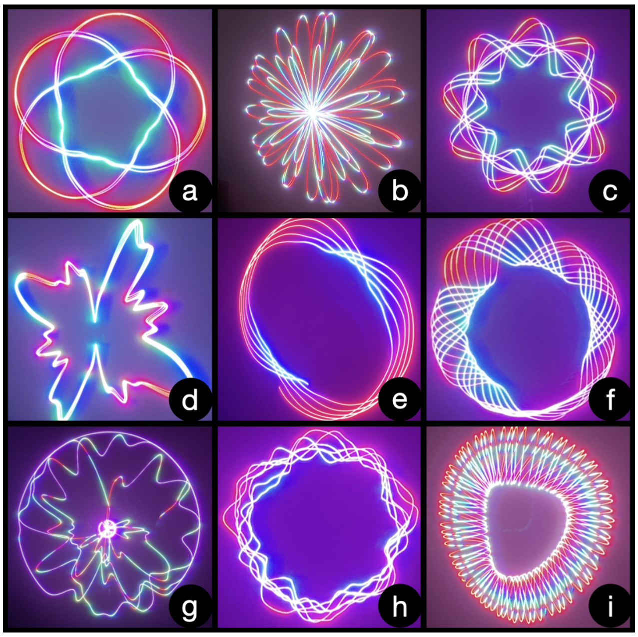

Figure 8: Laser patterns resulting from surveyed vocal techniques (see Table 1).

a MIDI keyboard, with which they could select the fundamental frequency which draws the laser circle, and which could be heard as a tone over a pair of loudspeakers. They were also instructed that if they made sounds which were harmonic to the fundamental they heard, the visual shapes they saw would be fairly stable. Conversely, the more inharmonic their sounds, the more unstable the figure would be. They were also told that neither approach was preferable, and that they were free to experiment however they chose. Finally, a camera made a video recording of the laser shapes alongside an audio recording of the singer's voice and subsequent conversations.

Participants were encouraged to comment freely during their experiments according to the think aloud protocol, and were verbally asked several open ended questions about the quality and character of the interaction after the experiment. Five participants were interviewed in total. Four singers identified as female and one as male, of which four were trained professional vocalists while one was a trained amateur. They held diverse backgrounds in classical, opera, Nordic folk, and experimental styles. Transcripts of these sessions were later analyzed for thematic similarities.

Even with such a small sample size, several observations could be made regarding common techniques, the visual results which they produced, and the quality of the feedback the results provide in helping the vocalist understand the interaction between the laser image and the vocal improvisation. Table 1 summarizes observations on each technique. A video demonstration of some of these techniques can be found in the second part of the supplementary video to this paper.

5. DISCUSSION

The two experiments with the LPS instrument employed quite different methods to structure the interaction between sound and image. The first relied on a pre-arranged series of harmonic partials to ensure controlled visual effects, while the second encouraged freeform improvisation to establish a bodily relationship with the laser image. However, in both cases one can observe an interaction process feeding back from the resulting laser images into the process of sound production.

In the case of the electroacoustic composition, even if the composition itself was not occurring in a realtime relationship with the laser visuals, the composer was mindful of the effects on the laser which he had previously witnessed. His experience with those effects led him to choose specific partials and progressions in the work, and furthermore to introduce metallophone sounds with complex timbres and waveforms for more visual variety and complexity. As is the case with many reenactments, the resulting work diverged substantially from the aesthetics of Tudor and Cross' original performance. Where Tudor's wild electronic feedback systems constantly teetered on the edge of chaos, Aron's composition applies a high level of control to delicate and subtle changes of timbre and harmonic which slowly unfold over the duration of the piece.

In the case of the vocal improvisations, the feedback happened in real time and facilitated a much faster negotiation of the sound/image relationship. At first, experiment participants employed vocal techniques from their own repertoire and tradition in order to explore how the laser visuals would react to the sound. However, all the participants became very interested in aspects of predictability, repeatability, and mastery of the laser image. During each session, their search for points of control over the image started to strongly affect both their choice of technique and the delivery of their chosen vocalizations. Most participants reflected that this exploration was highly demanding in mental and physical ways, but that the process was very akin to learning any instrument, and started to become intuitive after some amount of practice.

This feedback is precisely what prevents the LPS instrument from remaining a simple visualization tool. Because the results of a sonic interaction with the laser can directly affect what sounds are chosen next, the LPS becomes an active agent in the creation of sound, and therefore an audiovisual instrument. Furthermore, since the parameters of sonic interaction with the instrument are fixed and lim-

Table 1: A survey of vocal techniques and their visual results with the Laser Phase Synthesis instrument.

TECHNIQUE	MEANS	RESULTS	NOTES
Melodic singing	Repetition of existing song melodies; only non-improvisational technique surveyed	Stability of visual figures dependent on harmonic relationship of sung melody to laser fundamental	Poor interaction feedback; participants felt they were only "driving" visuals rather than interacting; results unpredictable
Harmonic singing (Figure 8a)	Sung fundamental at whole number harmonic ratios to laser fundamental	Very stable and predictable Lissajous figures; visible lobes indicate exact harmonic ratio; perfect unison gives only phase distortion	Excellent interaction feedback; very intuitive; dependent on skill of vocalist
Inharmonic singing (Figure 8b)	Sung fundamental not at whole number harmonic ratios to laser fundamental; by error or intention	Multi-lobed, unstable Lissajous figures which appear to spin rapidly	Poor to fair interaction feedback; unintuitive; not easily predictable or reproducible
Glissando singing (Figure 8c)	Sweeping sung fundamental through varying harmonic ratios to laser fundamental	Multi-lobed Lissajous figures which transition between stable and unstable states	Good interaction feedback; a dramatic visual effect, particularly with skilled vocalist
Vibrato singing (Figure 8d)	As harmonic singing; with small, regular changes in pitch	Visual pulsing or shimmering of stable Lissajous figures	Good interaction feedback; dependent on skill of vocalist
Harmonic humming (Figure 8e)	As harmonic singing; with closed lips and air expressed through the nasal cavity	Reduced higher harmonics soften and stabilize shapes of Lissajous figures	Good interaction feedback; requires less vocal skill than harmonic singing for similar results
Overtone singing (Figure 8f)	As harmonic singing; with timbral manipulations made by throat, tongue, lips	Added waveforms to peaks of the figures; no change to fundamental singing frequency	Good to excellent interaction feedback; requires high level of vocal skill
Plosives (Figure 8g)	Explosive bursts of breath and sound; i.e. the sounds *ba* or *pa*	Unstable figures; extremely short time duration; resemble fireworks or flashbulbs	Fair to good interaction feedback; easy effect; short duration prevents better feedback
Sibilants (Figure 8h)	Sustained noisy sounds; breath passed through lips or teeth; i.e. the sounds *sh* or *fff*	Highly unstable figures; character determined by density and amplitude rather than pitch	Very good interaction feedback; easiest and most reproducible effect
Inhaling singing[17] **(Figure 8i)**	Inhalation combined with tightening of vocal folds; higher sung fundamentals than exhaling singing	Increased number of visual nodes and density of lines; interesting phase distortions	Very good interaction feedback; physically demanding; can be harmonic or inharmonic

ited to harmonic ratio, amplitude, and timbre, the system can easily be integrated with existing musical performance practices. This allows the LPS to be understood, learned, and eventually mastered to a degree that skilled live performance becomes possible.

6. CONCLUSIONS

Through the design, experimental testing, and live performance Laser Phase Synthesis instrument, we have reenacted the development process of Tudor, Cross, and Jeffries' *Audio/Video/Laser* system during the late 1960's, as well as further the ambitions they held for their own audiovisual laser system. This is done through the historically informed use of contemporary digital audio and laser display technologies alongside close collaboration between music and visual composition and performance. We believe this process offers new insights into potential relationships of sound and image within a musically expressive context, and foresee developing the LPS further in collaboration with other composers, vocalists, and instrumentalists.

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8. ETHICAL STANDARDS

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