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ACOUSTIC AUGMENTATION OF THE TRUMPET — NAVIGATING CONTROL AND UNPREDICTABILITY IN A LONG TERM RESEARCH–CREATION COLLABORATION

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RÉSUMÉ

Nous décrivons ici une trompette audio-augmentée utilisant principalement le son de l'instrument lui-même pour piloter le traitement sonore, à la différence d'instruments augmentés traditionnels basés sur des capteurs. S'appuyant sur l'analyse sonore en temps réel pilotant des traitements tels que la synthèse additive, les résonateurs ou l'auto-convolution, ce projet a pour objectif principal d'explorer les relations entre l'humain et l'instrument augmenté qui introduisent de l'imprévisibilité, passant tant par des moments de contrôle que des moments d'adaptation à des situations de non-contrôle, ce qui est particulièrement intéressant dans la pratique de l'improvisation. Au cours de cette collaboration recherche–création sur le long terme, nous avons développé les *mappings* analyse–synthèse les plus pertinents musicalement. L'adoption d'une approche basée sur la pratique, fondée sur des principes auto-ethnographiques, a permis d'adapter et d'affiner le développement technologique en fonction des exigences musicales, allant au-delà du cadre des simples traitements audio vers un champ où l'environnement acoustique devient moins prévisible et plus un partenaire d'improvisation.

ABSTRACT

We describe an audio-augmented trumpet that mainly uses the sound of the instrument itself to control sound processing, unlike typical sensor-based augmented instruments. Using real-time sound analysis driving sound processing such as additive synthesis, resonators, and auto-convolution, we explore human/augmented-instrument relationships that introduce unpredictability, navigating between moments of control and moments of adaptation to situations of non-control, which is particularly relevant to the practice of improvisation. During this long-term research–creation collaboration, we developed the most musically relevant analysis-to-synthesis mappings. Adopting a practice-based approach, grounded in auto-ethnographic principles, enabled the adaptation and refinement of technological development driven by musical needs, extending beyond simple audio effects into a realm where the acoustic environment becomes less predictable and more of a partner in improvisation.

1. INTRODUCTION

This article describes a long term collaboration between Nicolas Souchal, trumpet player, improvising musician and musicologist, and Diemo Schwarz, researcher in interactive music technology and improvising musician. Its object is audio augmentation of the trumpet, based on real-time sound analysis driving additive resynthesis, resonators, and auto-convolution.

The four-years-long progression of our work, following a practice-based approach and first-person methods, shows the back-and-forth between, on the one hand, the technical ideas and implementation details of the non-standard interactive audio effects we developed, and on the other hand, artistic questions about control/non control and the unexpected [8] in human–instrument relation, and about the way of playing with feedback and space saturation phenomena [21]. We will report the insights we gained on questions of mapping, feedback, agency, and embodied control, and the mode of relationship with the instrument we have so far achieved, which can be described oxymoronically as *controlled unpredictability*. This research led to several public performances based on a musical form exploring the three sound processes,¹ a form destined to evolve towards more improvisation.

1.1. Background and Short History of the Project

D.S. and N.S. began their collaboration in 2016 in the improvised music trio *SMS* and quartet *Métamorphée* [36], with N.S. on trumpet and D.S. playing his gesture-controlled CataRT² [33] digital musical instrument. This project then originated in N.S.'s desire to augment his trumpet playing electronically. The first work sessions on the *Augmented Trumpet* project took place in 2020 at IRCAM, culminating in a first concert in the series *Les dimanches de l'impro* (Montreuil), December 2021. Then, in 2023, the project was extended by video generation [32, 9] controlled by the trumpet sound in a week-long residency at *Anis Gras* (Arcueil) under the name *Extense*,³ and was premiered at the *Aleph* theatre (Ivry sur Seine), June 2024.

*equal contribution

¹ Video available here: <https://youtu.be/yfur1yufR7w&t=0>

² <https://ircam-ismm.github.io/max-msp/catart.html>

³ However, for the purpose of this article, we will disregard the work on the control of video, as it would need a much longer description of

At this stage, control of the trumpet's sound processing was still in the hands of D.S.. The next step was to set up the interface enabling N.S. to play this augmented trumpet autonomously. A three-day residency followed by two concerts, early 2025 at the *Impromptissimo* series¹ and *Anis Gras*, brought this step to fruition.

Currently, the project is incorporated into N.S.'s practice-based research–creation PhD thesis entitled: *Loss of control in improvised processes: testing, analyzing, provoking, exploiting*, started in 2024 at Université Paris 8 | Vincennes–Saint-Denis / Ircam.

1.2. Motivation

N.S.'s primary motivation for initiating this project was to explore audio augmentation of the trumpet, i.e. to extend the sound of the instrument by other timbres and temporalities. However, N.S. was adamant that the electronic sound processing should avoid conventional and widely used effects, such as reverb, delay, loops, or harmonization. Drawing on an instrumental practice influenced by Evan Parker, he envisioned a semi-controlled conception of the machine, producing a form of “controlled unpredictability” that stimulates improvisation. The attitude practiced with the acoustic instrument and extended to the augmented instrument can be described in the words of Evan Parker: *“It’s very necessary to listen closely to what happens when you try to do things, because usually at the fringes of what you’re producing is something that you’re not really in control of — that there is a central thing that you are fully in control of, and then a kind of halo of suggested other possibilities which have to come with the central thing that you’re in control of, whether it’s a wisp of breath escaping from the side of the embouchure, or an overtone that you could push harder, or some key noise which you can’t escape.”* [15]

1.3. Overview

This article will approach the question of audio augmentation by non-standard effects by first giving an overview of the technical and musicological context of the work in section 2, then describing the employed methodology in section 3, and explaining its technical implementation in terms of audio analysis, synthesis, and mapping in section 4. We will then analyse the musical aspects and form of the resulting piece in section 5, discuss the insights we gained on research–creation processes in section 6, and conclude in section 7 with an outlook on future work.

2. CONTEXT AND PREVIOUS WORK

Our work is at the crossroads of several artistic, scientific, and technological disciplines. We will here situate it in the contexts of human–computer interaction research (HCI,

¹the technical details. In addition, it is rather orthogonal to the acoustic augmentation.

regarding augmented instruments, human–machine relationship, first-person methodologies), digital signal processing (sound analysis and synthesis), and musicology (approaches to improvisation).

2.1. Augmented Instruments and Levels of Integration

Augmented musical instruments have been an important topic in research in the New Interfaces for Musical Expression (NIME) community since its beginning [18], when they were also called *meta-* [4] or *hyper instruments* [23]. Typically, it involves adding bespoke sensors to an existing acoustic instrument to allow nuanced and embodied control of sound transformations by the player, often tightly integrated with the habitual expert gestures, acquired during many years of practice, for playing the acoustic instrument.

Our approach differs from this in two ways: 1) our idea was to control the transformations of the instrument sound by the characteristics of the acoustic instrument sound itself, 2) the control of other parameters of the transformed output sound is effected by commercial control surfaces not integrated with the instrument. Initially, this control was wielded by the electronic musician D.S., but in the latest phase of the project, the acoustic musician N.S. took over this control. This asks the question whether embodied control of the augmented instrument can be achieved by the acoustic musician primarily via audio, and secondarily on a standard control interface which is not tightly integrated with the instrument.

We can offer an ad-hoc working definition of four levels of integration of sound processing with acoustic instruments, situated on a scale where the environment acquires more and more agency.

1. The first level would be augmented instruments like above, where the control of sound processing is tightly integrated with the acoustic instrument playing, with full agency situated with the musician.
2. The second level would be that the processing creates a sound environment which is more or less fixed. This is typically the level of classical sound effects such as reverb and echo.
3. The third level would be that the sound environment is not fixed but shows emergent, possibly unpredictable behavior.
4. The fourth level would be when the sound processing has agency of its own and can be seen as a musical partner instilling musical ideas.

Our approach described here spans the first three levels, mostly oscillating between levels 1 and 2, but sometimes abandoning direct control and opening up to deliberate unpredictability of the system as in level 3.

Outside of the context of augmented musical instruments, *content-based* or *adaptive* effects (A-DAFx) [39]

have also linked audio analysis and sound processing for music production and composition.

2.2. Augmented Trumpets

There have been many projects augmenting the trumpet, even going back to Miles Davis' innovations in sound. After starting out using the Harmon mute to change the timbre of the trumpet, Davis turned to electric effects in the 1970s such as wah-wah pedal and distortion. His aim was to venture into the realm of pop-rock music, to take jazz out of certain shackles, and also to reach a wider, younger audience (cf. track *Zimbabwe* on *Pangaea* [5]). Even if Miles Davis did not address the question of the relationship between human and machine, the aesthetic force of his choice to apply to the trumpet effects that had hitherto been used by electric instruments is inspiring in its vision.

In NIME research, we can mention, among many others, Jonathan Impett's *Meta-trumpet* [16], which captures bell position by ultrasound sensors, valve positions and additional switches. Hans Leeuw's *Electrumpet* [19] consists of bespoke controllers mounted on the trumpet, notably a touch strip to be played by the thumb, buttons, and an extra set of pistons with precise sensing of depression, to leverage on trumpet playing technique for control of electronic sound processing. The *Electrumpet* has a mount for a smartphone which serves as a wireless screen that gives feedback about the state of the system.

Recently, Sarah Reid's open source wireless MIGSI (Minimally Invasive Gesture Sensing Interface) [29] captures gestural data such as valve displacement, hand tension, and instrument position, to offer extended control and expressivity to trumpet players.

All of the projects mentioned above are mainly focused on the hardware of the controller, using custom-built sensors needing electronics knowledge to construct and install, and are stressing the flexibility of mapping the sensors to various target parameters. The actual effect that the activation of the sensors has on the resulting sound is mostly left open. Our focus is on the augmentation of the sound of the trumpet through mapping of sound analysis to sound processing and synthesis parameters. This means that the main controller for the effects are the playing styles and nuances of the trumpet itself. We do use an additional off-the-shelf MIDI controller only for switching between the three sound processes, a few additional parameters, and control of volume.

2.3. Sound Synthesis and Processing Methods

Our audio-augmented trumpet uses three different methods of sound synthesis and processing the background of which is given in the following.

Additive synthesis is the generation of a sound spectrum by a sum of sinusoidal partials, controlled by their frequencies and amplitudes. It can be used to generate simple spectra from scratch (as we use here) with control of pitch, spectral tilt and harmonicity, or resynthe-

size existing sound recordings via spectral modeling [35]. In both cases, the FFT^{-1} method [11] can efficiently synthesise hundreds of partials by precisely constructing the short-time fourier transform (STFT) spectrum that, when the inverse fast fourier transform (FFT) is applied, will produce the partials at desired frequencies, amplitudes, and phases.

Resonance models [28] try to capture the salient resonances, or *modes*, of physical objects, each resonance being defined by its frequency, amplitude, and bandwidth (which determines its decay rate). These resonances can be excited by impulses, or other audio signals sent through them. In this case, they function like a group of narrow band pass filters. Again, we will use lists of resonances set up from scratch to form spectra with control of pitch, spectral tilt, and harmonicity.

Convolution is the mathematical process underlying phenomena like reverberation, resonances, or filtering. Seen in the frequency domain, when two signals are convolved with each other, their spectra are multiplied. Convolution as a mode of cross-synthesis has been used by sound designers and composers for many years, notably Barry Truax [38], mostly in deferred time. However, the use of real-time convolution as expressive means is not very present in DMI design literature, with the exceptions of Schwarz and Tremblay's work linking convolution and timbre spaces [34], where grains from a corpus of musical or voice sounds were used as impulse responses (IRs) to be convolved with a contact microphone signal in order to articulate the corpus sounds by intuitive contact interaction on any surface or object. That work is based on the *HISSTools Impulse Response Toolbox* [14] for MAX, allowing flexible and robust real-time exploration.

Brandsegg et al. introduced live-recording an impulse response from one instrument and then using it as a filter by convolving a different instrument signal with it in the *Crossadaptive* project.⁴ In that work, the IR can even be updated (recorded) continuously without introducing artefacts [2]. We employ a slightly simpler scheme where the performer chooses when to record an IR and then use it with his own sound as input.

2.4. Control/Non Control and the Unexpected in Human–Instrument Relation

In the field of human–instrument relationship, a central question is that of the stimulation of the musician by unexpectedness, particularly in light of improviser Jean-Luc Guionnet's distinction between unexpectedness and aleatoricism: “*Making ‘weird sounds’, for example, among other functions, amounts to making sounds that we do not really control and that, as a result, lead us by the end of the nose as much as we lead them. There is a kind of to-ing and fro-ing between the result and the action, which means that we no longer have the time to think about choice and that we have other things to do, that we*

⁴ <http://crossadaptive.hf.ntnu.no/>

surf on time. With all the tools that we now possess, including IT tools, improvisers invent ways to 'cause sound' that puts the unexpected into the circuit without making it aleatory. In contemporary music, composers often use aleatoricism, but this is not the case here. Improvisers put themselves at the limits of technical capabilities, or they loop a mixer by pushing it to places where it can tend towards silence or the opposite. The same thing goes for instruments. Once you manage to master this (because people do!), you start again from scratch. Therefore it's an endless process." (Jean-Luc Guionnet [8])

Continuing in the same way that noise musicians play with the feedback phenomenon, we have, notably in the *resonator* and *convolution* processings of the instrument, parameterized the device so that this feedback phenomenon is present, disrupting instrumental control and putting the instrumentalist in a state of adaptation to an unpredictable environment. This relationship is well described by Jérôme Noetinger: *"There is always a moment when I'm not fully in control, because of the feedback phenomena. There are times when there are phenomena that get out of hand. This is where improvisation comes in, because you can react to the sound phenomenon that's going on in front of you, take things somewhere else or react differently than you would do to something you could have predicted beforehand."* (Jérôme Noetinger [8])

2.5. Aesthetics and Human–Machine Relationships

Our approach is influenced by George E. Lewis' *Voyager* [20], both in terms of the developed human–machine relationship and in terms of aesthetics. As Lewis says: *"The improvised musical encounter may be seen as a negotiation between musicians, some of whom are people, others not."* [21]

Voyager, created during the 1980's as a nonhierarchical interactive musical environment that favors improvisation, displays some behaviors that make it perceivable by the human improviser as a partner. Although our augmented trumpet differs significantly from a machine improviser, it generates an environment that exhibits emergent behaviors, enabling the development of interplay with the human performer. This interaction may suggest the existence of an autonomous agent, yet it remains governed by both sound analysis and the interface.

In terms of aesthetics, the incorporation of Afro-artistic principles such as 'multidominance' in *Voyager* has guided our research in directions that embrace and explore situations of profusion or saturation. Following the notion of *"multidominance, which means that a lot of things are happening at the same time, that different elements in this total sound are vying for the foreground—in fact, the notion of foreground and background starts to disappear"* [21], we developed the additive synthesis process by embracing and engaging with moments in which the acoustic trumpet and the electronic processing struggle to coexist, resulting in a saturation of the sonic space.

More recently, longitudinal research by Thelle and Wærstad [37], where four musicians from different cul-

tural backgrounds played with a musical AI system over 6 months, suggests that the musicians' human–machine relationship can move between an understanding of machine-as-tool to machine-as-co-creator, and between the idea of music-as-object and music-as-process. They note that *"When taking the agency of the machine seriously, co-creative spaces between humans and machines open up, and this can provide valuable new perspectives for musical co-creation in general. We posit that creativity arises in the absence of full control. It emerges when one's own will is attuned to what the environment affords and leads to surprises."*

Contrastingly, the long-term research–creation project of Davis et al. [6] compares three generative improvisation systems playing in duo with the first author, where the focus of the musician is learning the parameters of the different agents with an aim of musical control. We can wonder which setup better fosters gradual acceptance of the otherness and agency of the machine. All three projects mentioned in this section are situated on level four of our ad-hoc definition in 2.1.

3. METHODOLOGY

For this work, we draw inspiration from first-person research methodologies [13] such as autoethnography [1], duoethnography, or autobiographical design. First-person methods enable a richer analysis through *thick descriptions* [12] of the use of technology in artistic creation, acknowledging the subjectivity of the researcher/creator. In the course of the research, we muster first- and second-person methods by the observation that we have a double inside/outside view in the project: N.S. has an inside view of the musical experience and an outside view of technology, D.S. has an inside view of the technology, and outside view of the embodied musical experience. Based on a logbook compiled over the course of the research, we reflect on subjective experiences while developing the musical and technological aspects of the augmented trumpet, interspersing technical details with esthetic appreciations, and also report on directions that were explored but later abandoned.

4. IMPLEMENTATION

We will now explain the involved electronic sound processes, shown in the overview in figure 1.

The audio analysis process outputs audio descriptors (see section 4.1) that are available for mapping to audio transformation parameters (audio fx, see 4.2), and also to audio analysis parameters. A second loop can feed the transformed audio back into the audio analysis, mixing it with the audio input (see 4.4).

4.1. Audio Analysis

The analysis stage calculates these 5 audio descriptors from the input audio stream for signal windows of

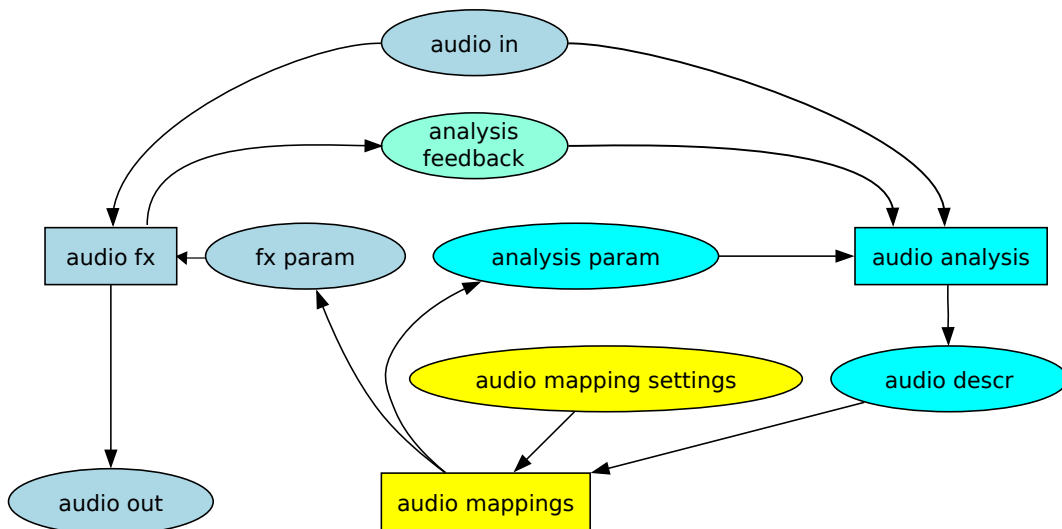


Figure 1. Overview of the signal and control flow in the audio augmented trumpet. Ellipses represent data or signals, boxes stand for processes.

size 40 ms and with a hop size of 10 ms: fundamental frequency (pitch), periodicity (corresponding to the continuum between tonal and noisy sounds), and first order autocorrelation coefficient AC1 (expressing spectral tilt related e.g. to vocal intensity), estimated by the time-based *yin* algorithm [7]; loudness, and the spectral descriptor centroid (the center of gravity of the spectrum [26], corresponding to the perceived brightness of a sound). Spectral spread, skewness, kurtosis (describing the overall shape and distribution of the spectrum) could be calculated by the analysis module, but are not used here.

Especially the AC1 analysis has a significant meaning for the trumpet: it correlates strongly to the *brassyness* of the sound, i.e. an enrichment of the spectrum at high air pressure levels at the mouthpiece. It extends the acoustic loudness measure which plateaus with higher pressure. All these descriptors are passed through a median filter for smoothing, and both the raw and smoothed versions are made available for mapping to the synthesis parameters.

The analysed fundamental frequency is treated specially to derive the pitch of the current note, which is only sent when both the amplitude and the periodicity factor are above respective thresholds. It is quantised to an integer MIDI note number. We did also implement a quantisation to the pitches of the harmonic series of the trumpet but abandoned this option. An onset detector based on loudness outputs the events `onset-note` and `onset-volume`, and provides a random number event `onset-random`, used in certain mappings. The end of a trumpet sound (when both amplitude and periodicity are below their thresholds) is also detected and we estimate the slope of the sound’s release loudness envelope as a source parameter for mapping.

The analysis is implemented using the PiPO [31] framework, part of the MUBU⁵ [30] extension package for the MAX audio programming environment.

⁵ <https://ircam-ismm.github.io/max-msp/mubu.html>

4.2. Audio Transformation Algorithms and Parameters

Three non-standard algorithms for sound transformation were proposed by D.S. and accepted by N.S., after which they were refined and made controllable by the trumpet sound analysis. The algorithms and their parameters, accessible via the audio mappings, are described in the following.

4.2.1. Additive Synthesis

The additive synthesis variant used here is the synthesis from scratch of a stereo spectrum made of a fixed number n of sinusoidal partials (here 10) calculated as in equation 1, relative to a given fundamental frequency f_0 and with a controllable base amplitude a_0 . Each partial frequency f_i follows the harmonic series but is multiplied by a harmonicity factor h which can squeeze or stretch the spectrum into inharmonicity. The partial amplitudes a_i follow a harmonic rolloff r in dB. Individual harmonics’ frequencies and amplitudes can be fine-tuned by giving a list of detuning octave factors f_i^d and amplitude deviations a_i^d in dB, respectively.

$$\begin{aligned} f_i &= (if_0h + f_0) 2^{f_i^d} \\ a_i &= ir + a_0 + a_i^d, \quad \text{with } 0 \leq i \leq n \end{aligned} \quad (1)$$

All of these parameters are available for manipulation individually for the left and right channel, but the mapping targets affect both channels. Pitch f_0 and base amplitude a_0 are given by a fixed mapping from the analysed live input pitch and loudness. The other parameters are affected by varying mappings explained below. We use MUBU’s `mubu.additive~FFT`¹ implementation for efficient additive synthesis.

4.2.2. Resonators

The resonators are a more subtle variant of additive synthesis above. It creates $n = 10$ resonances in a harmonic spectrum as in equation 1 above, with the additional parameter of decay time. These resonances are excited by the trumpet input signal.

Pitch is given by a fixed mapping from the analysed live input pitch at the attack of a trumpet sound, or picked from the current pitch manually. The global amplitude of the resonances is fixed, since the input sound completely determines the resulting output loudness.

As above, both frequencies and amplitudes can be individually fine-tuned by giving a list of frequency factors and amplitude deviations, respectively. All of these parameters are available for manipulation individually for the left and right channel, but the mapping targets affect both channels. The other parameters are affected by varying mappings explained below. We use CNMAT's `resonators~` object,⁶ implementing parallel banks of two-pole resonators [17].

4.2.3. Convolution

The convolution effect proceeds by recording a segment of audio which is then used as an impulse response (IR) for convolution with the subsequent input audio. Recording is triggered by a button or footswitch, where a press down starts a new recording lasting until the button is released, and a short press and release records the input audio mixing it with the existing IR (over the duration of the existing IR). This transformation has no other parameters. Its effect can be described as being in between a looper and a filter or resonator. We use CERENEM's *HISSTools Impulse Response Toolbox's* `multiconvolve~`⁷ for convolution [14] with two IRs, in order to keep the current IR running until it is finished, while recording a new one. This avoids discontinuities in the signal audible as clicks.

4.3. Mapping and Presets

The mapping component of the augmented trumpet system links audio analysis output values to parameters of the sound processing algorithms [25]. It involves scaling the analysis output values to a normalised range of 0 to 1, then sending them to the mapping target, and finally scaling them to a choosable range of the respective algorithm output parameter. Mappings are one-to-many and can be clipped and enabled/disabled individually, and ensembles of their settings can be stored and recalled, together with the algorithm parameters.

In the course of the project we tried different implementations for the mapping, all making use of standard MAX objects and mechanisms. This is due to the fact that third-party solutions for mapping [27, 22, 24], although offering advanced functionality, often involve a buy-in

⁶ <https://cnmat.berkeley.edu/downloads>

⁷ <https://research.hud.ac.uk/institutes-centres/cerenem/projects/thehisstools>

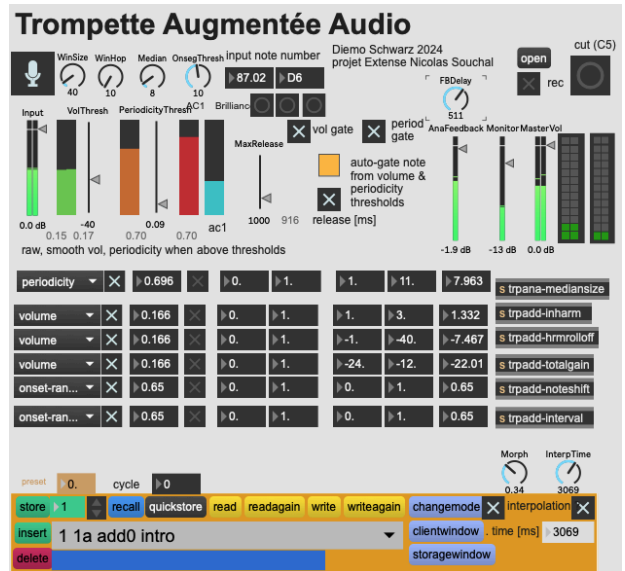


Figure 2. Main patch of the augmented trumpet system showing, from top to bottom, the analysis parameters and output values, the mapping settings, and the preset chooser.

into several technical layers for organising patches into name-spaces. We were looking for a simpler, yet flexible solution. The mapping settings can be seen in the middle of figure 2. For each of the 6 free mapping targets (median filter size, inharmonicity factor h , harmonic rolloff r , total gain a_0 , note shift, interval — the mapping targets current note, on/off, and release have fixed mappings), we can choose which analysis parameter will be mapped to it, its source and target ranges, activation, and clipping. Note that also one of the analysis parameters (the size of the median filter) is a target for mapping, creating a first feedback loop in the system.

All mapping, analysis and synthesis parameters can be stored in presets, in order to compose and differentiate the parts of the piece. Here, over the course of the development, we first tried manual switching on and off of mappings (while the piece still had a very simple structure), then, using MAX's built-in snapshot system. The latter provides a convenient user interface for storing, recalling, visualising, and reordering snapshots, but does not offer interpolation and post-hoc editing of snapshots, and feels overall more fragile and prone to errors. That's why we fell back to the preexisting `patr` system with a bespoke user interface, shown at the bottom of figure 2. Especially the interpolation of presets containing different detuned additive synthesis spectra was felt necessary in the third rough phase of the project (see 6), for N.S.—now in control of the audio processing—to create subtle variations in the additive synthesis sound with just one knob.

4.4. Analysis Feedback

During the last phase of work sessions and concerts starting at the end of 2024, N.S. and D.S. became aware how

the inevitable feedback from the loudspeakers back into the microphones generated interesting musical patterns with additive synthesis: When the trumpet stopped playing, the additive resynthesis alone was often still coming back into the microphones above the gate threshold, which meant the process didn't stop. Moreover, the prominent resynthesised partial was often of a higher or lower pitch, due to the per-partial detuning and inharmonicity settings. This means that at the end of a trumpet sound a synthesised glissando followed, that could be interrupted again by the next trumpet note (forcing a different, stable pitch on to the resynthesis).⁸ Note that this particular acoustic-to-synthesis feedback could never explode in sound volume, because the additive synthesis features a built-in spectral domain loudness limiter. This effect was deemed by N.S. a welcome unpredictability, but still semi-controllable: When the analysis gate threshold was set higher, the feedback didn't occur.

However, it was highly dependent on the loudspeaker placement and the acoustics of the rehearsal or concert space. To be independent of this, and to foster more experimentation, D.S. proposed to implement a direct internal feedback path from the synthesised audio back to the audio analysis input (without going through the loudspeakers). The feedback is controllable by a gain factor and a time-delay, both accessible via knobs on the hardware control surface. This was quickly mastered by N.S. and integrated into the expressive capabilities of the augmented trumpet.

4.5. Control Interface

Contrary to the bespoke interfaces tightly integrated with the trumpet mechanics common in the augmented instrument literature, we use off-the-shelf MIDI controller and footpedals, which are cheap, reliable, and easily replaceable because they are ubiquitous: N.S. chose the Arturia *MiniLab* control keyboard, depicted in figure 3. Although the piano keyboard is unused, it was chosen for its foot pedal input jack, 8 pads, 4 sliders and 8 knobs.

One foot switch was initially used for note picking of resonators and recording for convolution, a second (continuous) foot pedal for master volume control. It turned out to be complicated for N.S. to switch his foot between the two pedals, and it was very important to keep the master volume under control at any instant, thus the foot switch was abandoned in favour of a pad on the controller.

In terms of visual feedback, we used a computer screen showing a part of the patch, which can be unobtrusively placed on a chair. However, the only feedback necessary for N.S. is which preset is currently chosen, and a level meter next to the pitch analysis gate slider. These two could possibly be displayed on a much smaller screen, e.g. on the MIDI controller display or a smartphone (as is done on Leeuw's *Electrumpet* [19]).

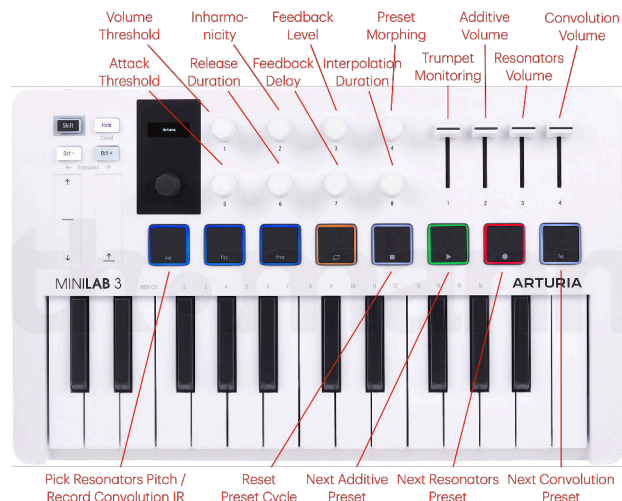


Figure 3. The Arturia *MiniLab* 3 control keyboard for the augmented trumpet, showing the assigned functions.

5. MUSICAL INTERACTIONS AND FORM

During working sessions and long-term exchanges, we explored the affordances of the three sound processing algorithms, which led to various modifications and refinements.

First, in additive synthesis processing, noticing that the release length was stereotypical, the release detector (see 4.1) was added. This followed N.S.'s desire to vary the ending of notes transformed via additive synthesis, where the mapping of volume to inharmonicity often created a characteristic spectral evolution in the release phase. We chose to create a fixed mapping of the estimated trumpet release slope to the envelope release time of the additive synthesis and to allow exaggerating the release to up to 4 seconds. To create evolution in the temporal dynamics of the augmented trumpet sound, we map its periodicity to the median filter size for smoothing the analysis. This (rather untypical) mapping creates the effect of deliberately erratic additive synthesis for non-pitched sounds, and a stable synthesis pitch for pitched sounds. We also map the input sound volume to the inharmonicity factor h , the inverse harmonic rolloff r , and the total gain (to compensate the loss of output volume due to a higher rolloff). In one part of the piece, the `onset-random` event is mapped to the note shift of additive synthesis, i.e. at each onset, the resynthesis is detuned by a random interval. Next, by gradually adding controls on attack and volume threshold, feedback level, and delay, we introduced the ability to make rapid and varied adjustments to additive synthesis settings. As a result, the playing of the trumpet was adapted to accommodate rapid and unexpected changes. By lowering the input thresholds, feedback was activated, so that the system “played itself” without N.S.'s intervention (see 4.4). This resulted in the effect where the trumpet's role was to interrupt the feedback by playing into the microphone. This type of phenomenon, typ-

⁸ Video example <https://youtu.be/yfur1yufR7w&t=380> 6:20 to 7:02



Figure 4. Nicolas Souchal playing the audio augmented trumpet at the *Impromptissimo* concert series Jan. 2025.

ically considered a problem to be eliminated, was instead viewed as a stimulating means of interaction.

Second, in the resonator processing, practice led to trumpet playing consisting of pianissimo attacks, impulses⁹ that excite the resonator in small bursts, and at the same time generating and cutting feedback.

And third, in convolution processing, the initial decision was to avoid “loop” effects by excluding the playing of melodic–rhythmic patterns. Instead, by placing the microphone inside the trumpet’s bell, low frequencies were emphasized, paving the way for the composition of feedback layers.

For the first public solo performance, the piece was structured around the sound processes we had developed: additive synthesis, resonators, untreated trumpet, convolution, and an open section integrating all three processing techniques. Each section had a more or less predetermined duration. This segmented structure will need to be reworked in future public performances in order to explore ways of improvising within the musical form and to counteract the tendency towards producing segmentation. Indeed, the instrument augmentation results in both modification and sedimentation of the improvisation situations [3]. Each process, by suggesting particular modes of use, generates a distinct set of characteristic *affordances*, such that a phenomenon of enclosure emerges, assigning to each process its own specific playing modes, instrumental gestures, and discursive possibilities, none of which are easily transferable across processes. By introducing random preset changes, this closed segmentation could in the future be disrupted, enabling interpolations between the improvisational contexts associated with each treatment.

⁹ Video <https://youtu.be/yfur1yufR7w&t=780> 13:00 to 13:36

6. DISCUSSION

In retrospect, we can identify three phases in the development of the augmented trumpet.

1. The first phase from 2020 to 2021 focused on establishing the sound analysis and synthesis algorithms and elaborating their most musically useful parameters, and how they influence each other (the analysis to synthesis mappings).
2. The second phase from 2023 to 2024 focused on deeper musical exploration of the algorithms without changing the mappings, while the control of the parameters and switching the sections of the performance was still in the hands of the electronics player. In this phase we did however add the foot switch control for picking the pitch of the resonators, and for recording the convolution signal.
3. The third phase end of 2024 to 2025 was concerned with transferring full control over the algorithms’ parameters to the acoustic musician, and adding the feedback path for additive synthesis. It entailed a more intimate discovery of the emergent musical behavior of the algorithms under changing parameters, use of the microphone, and playing style.

6.1. Interaction with the Three Algorithms

The final mode of control by N.S. for additive synthesis and resonators mainly involves initiating impulses to create changes or variation in the processing parameters, without precisely controlling these parameters. In other words, this type of control serves to introduce mobility into the processing, destabilizing the installed play–processing balance, and provoking an adaptation in the instrumental performance—essentially, causing less predictable musical developments.¹⁰ More specifically, the musician primarily influences the following parameters: inharmonicity, release duration, feedback level, feedback delay, and interpolation speed. For example, in the case of additive synthesis, the instrumentalist’s action sometimes involves activating interpolation between different presets and adjusting the interpolation speed in order to transition more or less quickly from one preset to another, continuing to play while adapting to this shift. In the case of resonators, by varying the inharmonicity and frequently adjusting the pitch, the instrumentalist either promotes or cuts off the feedback effect. An interplay can then develop between the desire to excite the resonators with the sound of the trumpet and the intention to interrupt the feedback. It is important to note the role of the foot pedal, which allows for immediate intervention when audio feedback becomes uncontrollable (especially in the resonator and convolution sections), as well as the significance of detection thresholds (such as attack and acoustic pressure), which determine whether or not the performance engages

¹⁰ Video example <https://youtu.be/yfur1yufR7w&t=139> 2:19 to 4:20

in interaction with feedback. In these three cases (additive: adaptation to rapid changes, space saturation; resonators: gesture and feedback; convolution: zooming inside the bell), the impulses initiated by the musician, N.S., sometimes under control and other times simply shifting parameters to unexpected settings, seem to lead to a complete embodiment of augmentation and intimate, stimulating control. We can thus consider the oxymoronic notion of *controlled unpredictability*. This notion enables the conception of a solo performance with an augmented instrument in which interactive processes are structurally embedded. By articulating multiple levels of agency for N.S., the system induces states of adaptation and heightened responsiveness, which prove to be fertile ground for exploratory improvisational practice.

7. CONCLUSION AND FUTURE WORK

The three audio-controlled effects we chose can be musically interesting for augmentation of an acoustic instrument, going beyond simple audio effects into an area where the acoustic environment becomes less predictable and more of a partner for improvisation. This entails a shift of the mode of interaction between musician and machine away from a perspective of control towards an acceptance of artefacts as surprises and propositions borne out of the algorithm, seen as an individual entity. However, in the end, what worked best was when the sound effects were controlled intimately and most directly by the musician, completely integrating the augmented sound into the instrument. This control paradoxically includes pushing the algorithms into states where the output becomes less predictable.

We can also affirm the advantage of our long term music-driven research–creation process that allowed the deep exploration of the musical affordances of each of the three algorithms, and adaptation and refinement of the technological capabilities driven by musical needs. This echoes findings in dance-related HCI performance-led research [10], where a long term autoethnographic inquiry shows that different degrees of control and ambiguity foster serendipity and emergence.

For the future, we intend to work on better integrating the visual feedback for N.S. with the controller by using its display or a small screen close to it, with the hope that control can become even more embodied and intimate. One of our objectives is also to find means to move away from fixed musical form in favour of random/intuitive changes. And one avenue to explore will be that of acoustically augmenting the trumpeter's instrumental gestures. For example, when practicing lip flexibility, certain sound bends and loss of vibration are gestures that can be specifically analyzed and augmented. These kinds of gestures (with varying degrees of control) can be considered elements of construction. We also intend to deepen and document the work on generation of visuals [32, 9] controlled by the trumpet sound, the preliminary work on which was left aside for this article.

Another avenue of research into the trumpet's very sound is as follows. Starting from the fact that the trumpet is an instrument that projects or diffuses sound outward, N.S.'s university research led him to envision what an "inner trumpet" might be, or what an instrumental gesture directed toward the player would look like, eliminating the distinction between interior and exterior. In geometric terms, imagining this centripetal space, we can think of Klein's bottle. Without delving into technical details, it's important to note that for such an object, it is impossible to define an inside and an outside, and that, conceived in four-dimensional space, any representation in three-dimensional space is inherently flawed. The challenge of this line of inquiry is to determine what treatments, effects, and developments might emerge from this (albeit purely imaginary) concept of an inner trumpet.

8. REFERENCES

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