CHOPIN UNIVERSITY OF MUSIC

sound engineering / composition / instrumental studies

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Technology-aided improvisation – digitally controlled acoustic instruments as an element of an improvised musical piece.

Synopsis of the PhD Thesis

Abstract

The thesis describes an artistic work titled AAAA (Acoustic Augmented Actuated Autonomous), created as a basis of the doctoral dissertation. AAAA is a multidisciplinary project developed from scratch, all aspects of which – timbral, compositional, and performative – are equally vital parts of the complete work. The project encompasses elements of sound engineering, composition, and musical performance.

During the course of the work on the project, I've built three new, acoustic-digital musical instruments. The pitch of their sound can be controlled via software, utilizing a series of algorithms which offer varying degrees of interference in the actions of improvising musicians. The remaining sound parameters – timbre, dynamics, articulation, and rhythm – can be fully controlled by the performers.

One of the goals of the project is to explore the boundaries between improvisation and composition, combining the search for the minimal number of factors constituting composition, with techniques from the generative art field. The instruments are used as a means to provoke the performers into selecting specific notes or to narrow down the choice of notes to certain scales, creating a form of an equivalent of aleatoric composition. The process of new instruments building, aside from serving the purpose of achieving new timbral qualities, aims to direct the performers into specific musical actions or to suggest certain musical solutions. The digital aspect of the instruments is intended to facilitate smooth changes in the instruments' impact on the behavior of the improvisers.

The introduction and the first chapter of the full thesis outline the context of the project and numerous issues concerning the relationship between art and technology, such as: generative art, key features of acoustic instruments, the relationship between the performer and the instrument, performative aspects of technology-assisted music, and the relationships between composition and improvisation.

Chapter two presents the research hypotheses of the AAAA project and their relations to the state of the art in the music technology field, with particular emphasis on hybrid instruments.

Chapter three details the work on the AAAA project – the construction of instruments, the development of software, and the emergence of performative strategies during ensemble rehearsals.

Chapter four aims to verify the research hypotheses based on the results of the work on the instruments, the analysis of live and studio recordings, a survey conducted among the audience members, as well as interviews with the performers.

This synopsis briefly outlines key elements of the full version of the PhD thesis.

Introduction

In the introduction to the full thesis, I'm describing two hypothetical composers – „Composer A" and „Composer B". They display different attitudes towards technology: the former uses it as an obedient tool, while the latter engages in a dialogue with it. My observations are consistent with those of Katya Davisson,[1] who describes similar categories as „narrow-sense" and „broad-sense" composition. Similarly, Brian Eno[2] outlines similar attitudes, calling their representatives „architects" and „gardeners". This dichotomy serves as a point of departure for the description of a wider context, in which the AAAA project is situated.

Context of the Work

Postdigital:

The term *post-digitality*, or simply *postdigital*, defined as an approach utilizing the optimal combination of digital and non-digital elements for a given application – the flexibility of code and the tangibility of physical matter – has become the starting point for the creation of the artistic project described in this work. This strategy can yield interesting and beneficial results from the perspective of both creative-performance practice and the aesthetics of the resulting work.

It is in this context that I'm including the concept of *hybrid instruments*, which is crucial for the AAAA project. This term can be used to describe instruments built using any combination of acoustic and digital elements. It is important to note that the hybrid approach is a manifestation of the post-digital perspective in the field of new instrument design or, more broadly, in the realm of music technology.

A Threefold Perspective on the AAAA Project

The phrase "digitally controlled acoustic instruments" used in the title of my PhD thesis, describes certain category of musical instruments in a rather clear manner. The instruments I've built are even better described by more precise terms, such as *hybrid instruments, actuated instruments*[3] and mechatronic instruments. However, a precise description of the meaning of these terms requires addressing many issues, often quite distant from one another.

To organize this process, the description can be conducted in a threefold manner: starting either from the perspective of the construction of the instruments – the "material part," from the perspective of the operational logic – the "logical part," or finally, from the perspective of the creative process and the relationship between improvisation and composition – the "human factor." The full thesis discusses each of these issues in detail; in the synopsis, only the key elements are touched upon.

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[1] K. Davisson, *Improvisation as a Method of Composition: Reconciling the Dichotomy*, „The British Journal of Aesthetics" 2022, t. 62, nr 3, DOI: 10.1093/aesthj/ayac018.
[2] *Composers as Gardeners | Edge.org*, https://www.edge.org/conversation/brian_eno-composers-as-gardeners [date of last consultation: 1 maja 2024 r.].
[3] D. Overholt, E. Berdahl, R. Hamilton, *Advancements in Actuated Musical Instruments*, „Organised Sound" 2011, t. 16, DOI: 10.1017/S1355771811000100.

Why Acoustic Instruments?

From the perspective of the audience, the performative component is an inseparable element of the direct experience of music in a concert setting. Digital tools – such as a laptop – offer undeniable advantages; however, using them as instruments in a pure form does not yield satisfactory results. Hence, in my opinion, there is a need to place them – or more broadly, to place the digital technology as such – in a post-digital context: combining their most desirable features with other technologies, supplementing the "digital skeleton" with tactile and visual elements, and – as is the case with the AAAA project – acoustically generated sound.

Visual-Auditory and Tactile-Auditory Correlation

Our daily experience of the physical world tells us that most actions we can observe with our eyes are accompanied by sound. It seems quite natural, therefore, to expect that the sounds we hear from the concert stage result from some action that could also be observed with the sense of sight. Thus, musical controllers and instruments should ideally provide feedback via three sensory channels:

- From the perspective of the audience, the actions taken by the performer should provide both visual and auditory sensations – thus fulfilling the condition of visual-auditory correlation;
- From the perspective of the performer, it is beneficial if the sounds generated by the instrument are accompanied by tactile sensations, as the sense of touch constitutes the most important source of feedback regarding the precision and success of performing a given action.

Timbral Properties of Acoustic Instruments

The unique experience of listening to music performed on acoustic instruments is an important factor from the perspective of the audience. This may be accompanied by a subjective sensation of "intimacy," "naturalness," or "chamber-like" (as in „chamber music") sensations, which aren't always associated with listening to electronically amplified music, projected through speakers.

The aforementioned phenomenon of tactile-auditory correlation, experienced by performers while interacting with acoustic instruments, is a crucial element of the relationship between the musician and their tool. The performer's satisfaction – especially in improvised music – translates into the quality of the music, which in turn contributes to the audience's satisfaction.

Generative Art:

The use of digital technology and mechatronic components allows for the design of complex, physical interactions between the performer and the instrument. Combining traditional instruments with contemporary technology may be realized in many ways. For the AAAA project, it seemed that the use of the generative art techniques to control the instruments' behaviour would be the most appropriate choice.

Philip Galanter, who specialises in the field of generative art, is the author of perhaps the most frequently cited definition of the term:[4]

[4] P. Galanter, *Generative Art Theory*, [w:] C. Paul (red.), *A Companion to Digital Art*, New York 2016.

"Generative art refers to any art practice where the artist uses a system, such as a set of natural language rules, a computer program, a machine, or other procedural invention, which is set into motion with some degree of autonomy contributing to or resulting in a completed work of art." [5]

In this approach, the primary area of the artist's activity is to design and initiate the generative process. In turn, in response to the results generated by this process, the artist can modify the details of the process until satisfactory artistic results are achieved. The benefit of this approach is the ability to create artifacts with a high degree of complexity without the need to directly oversee all of their individual components.

As Galanter notes, referring to the **complexity theory**, *"In terms of our human ability to extract meaning from a given experience we require a mix of surprise and redundancy, i.e. a signal somewhere between extreme order and disorder."* [6] Galanter calls this optimal combination of predictability and unpredictability **effective complexity**. This feature is a crucial element of a satisfying work of art. Achieving effettive complexity requires maintaining a perfect balance between the elements that provide order (such as algorithms) and introduce chance.

Why Not AI?

Recent developments in generative tools based on artificial neural networks made it a subject of mainstream interest. In casual discourse, artificial intelligence seems to be regarded as a kind of "swiss army knife," capable of performing any task and solving any problem. [7] Indeed, the level of sophisticaation of images, videos, and music, generated by the newest AI-based systems tools, is impressive. It may thus seem that using AI for the development of technology-assisted art is the most obvious direction.

From the perspective of the AAAA project, however, another aspect is crucial: the problem of **AI interpretability.** [8] In short, the decentralised structure of artificial neural networks, which is the source of their high effectiveness, is also the reason behind the difficulty of analysis of their internal mechanics. Understanding the processes occurring within the network which leads to a specific response (text, image, or sound), becomes more challenging as the complexity of the network increases.

All components of the AAAA project – physical instruments, digital algorithms, human operators (i.e., performers) – constitute integral, interrelated elements of a global generative system. According to the aforementioned elements of the complexity theory, a properly designed generative system should consist of a proper balance of predictable, structure-building elements, with elements that introduce chance or randomness. In the case of the AAAA project, the physical and human factors are somewhat unpredictable – thus largely serving as sources of random events; therefore, the algorithms used to control the behavior of the instruments must be transparent and easily interpretable to prevent the entire generative system from falling into chaotic behavior.

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[5] P. Galanter, *What is generative art? Complexity theory as a context for art theory*, 2003 r., http://philipgalanter.com/downloads/ga2003_paper. pdf [date of last consultation: 19 maja 2024 r.].

[6] Ibid.

[7] F. Alizadeh, G. Stevens, M. Esau, *I Don't Know, Is AI Also Used in Airbags?: An Empirical Study of Folk Concepts and People's Expectations of Current and Future Artificial Intelligence*, „i-com" 2021, t. 20, nr 1, DOI: 10.1515/icom-2021-0009.

[8] D. Castelvecchi, *Can we open the black box of AI?*, „Nature" 2016, t. 538, nr 7623, DOI: 10.1038/538020a.

Improvisation vs. Composition

As the audience members, while witnessing an improvised musical performance, we experience the creative process in its pure form – consisting of both its bright and dark sides (moments of pure inspiration, intervined with uninspired or seemingly erratic passages). However, in the case of improvisation (as well as other experimental creative or research activities), this arduous process is often the only way to achieve surprising, refreshing aesthetic phenomena.

For the reasons described, musicians seek ways to harness the best qualities of improvisation – the rare and unpredictable moments of inspiration and spontaneous creativity – while minimizing its inherently undesirable traits of risk and uncertainty. The use of generative techniques in the AAAA project is one of such attempts to reduce the aforementioned undesirable factors.

Improvisation vs. Flow

One of the factors distinguishing improvisation from composition is the state of *flow*. [9] Although the process of music composition often includes elements of improvisation, it nevertheless involves an element of self-correction or even self-censorship – continuous refinement or modification of spontaneously arising musical phrases or motifs. During the improvised performance, these acts of self-correction happen rarely – the improviser can't go back in time, they're only in control of the present moment. [10] So – even though one might improvise while composing, it is this self-awareness, expressed by the constant evaluation and correction of spontaneously emerging music, that can hinder achieving the state of flow.

Research Hypotheses and Innovative Aspects of the AAAA Project

Research Problems and Hypotheses:

- examining the impact of digital algorithms on the performative and musical choices of the improvising musicians;
- shaping generative compositions in real-time through digital, inter-instrument feedback;
- exploration of new methods of Integrating acoustic sound with digital technology.
- Investigating the boundaries between improvisation and composition via testing different degrees of digital intervention in the behavior of instruments indirectly affecting the performers' playing style;
- studying complex feedback loops by using instruments that "listen" to environmental sounds and respond to the notes played with other instruments;
- practical verification of the hypotheses by building prototypes of new musical instruments.

Research hypotheses for Individual instruments are included in the description of each instrument.

Research Methods:

- construction of experimental musical instrument prototypes in an iterative proces;
- development of software, which facilitates feedback between instruments;
- rehearsals and consultations with musicians;
- public presentations of the project;

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[9] *Idem*, *Finding Flow. The Psychology of Engagement With Everyday Life*, New York 1998.

[10] E. Hart, Z. Di Blasi, *Combined flow in musical jam sessions: A pilot qualitative study*, „Psychology of Music" 2015, t. 43, nr 2, DOI: 10.1177/0305735613502374.

- conducting a survey among the audience members at one of the public performances;
- analysis of the recordings of improvised musical pieces created with the instruments;
- interviews with performers;

Outline of the Instruments

Autoviola:

Initial inspiration for the concept of the Autoviola was the instrument known as autoharp (also called chord zither). The primary assumption guiding the construction of the Autoviola was the use of digitally controlled mechanisms for selective muting of twelve chromatically tuned strings, which in turn should enable full control over the played chords in one octave range. Additionally, the digital control of the muting mechanisms was intended to allow for digital extensions such as automatic chord generation and remote control of harmonies based on algorithms. Another assumption was to build the instrument in a form that allows for *arco* playing. Secondary assumption was the use of balsa wood as a material for a floating top plate.

After a couple of iterations, the final, fourth prototype of Autoviola was a fully functional, complete instrument. As such, it was used for the rehearsals and live performances. The necessity for combining all considerations - aesthetic functional, mechanical and ergonomic - determined the final form of the instrument. After experiments with various types of steel strings, I eventually settled on "synthetic gut strings" originally made for tennis rackets, which only come in two very similar gauges. This quality required variation in the string lengths, necessary for receiving desited tuning, resulting in a distinctive harp-like appearance of the instrument's neck. The neck was also designed in a way that provided space for the mechanical and electronic components, which reside in the central part of the instrument.

Aesthetically, the instrument's form is inspired by three historical instruments:

- the shape of the body is modeled after the *vielle*;
- the construction and form of the neck, refer in certain aspects to the *viola di bordone*;
- the aesthetic of the entire instrument were also inspired by the *lira da gamba* (also known as *lirone*), which, like Autoviola, primarily serves a function of a harmonic instrument, providing chordal accompaniment for other instruments;

A distinguishing feature of the Autoviola, as compared to lirone and most other plucked or bowed string instruments is the ability to play chords composed of arbitrarily small intervals (e.g., clusters consisting solely of major or minor seconds), which would not bepossible to play with any other string instruments (with the obvious exception of keyboard instruments).

Initial idea of using motorized felt mutes for string deactivation proved to be inefective – while playing *arco,* string would always produce some sound, even while the mute is engaged. After a couple of experiments, I've settled on a solution with utilised mechanisms that phisically displace the string by pulling it towards the body of the instrument, hence the bow is in physical contact only with the strings that stay in the original position (unaffected by the mechanism).

The string mechanisms are based on RC servos of the micro type, coupled with the strings via mechanisms that translate the rotary movement of the servos to the linear movements of the string „hooks”. A significant challenge in developing the final version of the Autoviola was reducing the servo noise to an acceptable level.

The digital user interface consists of a small, single-octave keyboard and two switches, allowing muting and unmuting all strings, as well as switching between digital augmentation modes.

Electronic and Mechatronic Elements of the Autoviola

The central part of the instrument serves as the enclosure for its mechanical and electronic components, which consists primarily of the Bela Mini microcomputer, responsible for interpreting the control signals sent from the user interface as well as transmited from other instruments via OSC protocol. Bela Mini sends data to a Teensy 3.2 microcontroller via the serial protocol. Teensy in turn controlls movements of the string mechanisms with an additional servo controller. The instrument is powered by an external 12-volt power supply.

Software and Performance Considerations

The software of Autoviola consists of two elements: a Pure Data patch, running on the Bela Mini microcomputer, as well as a script running on the Teensy 3.2 microcontroller, which converts data from the Pure Data patch into control signals for the servo mechanisms. The Pure Data patch consists of several modules - from the performer's perspective the most important ones are the *algorithm handling module* and the *digital extensions module*.

The digital extensions module influences only the Autoviola - its role is independent of the global algorithms that control the overall generative system of the AAAA project. The module receives data from the user interface (keyboard) and modifies or augments it differently for each of the following modes:

- **Mode 1 - "Direct":** The keyboard controls the movements of the string mechanisms directly;
- **Mode 2 - "Five Latest Notes":** The active string arrangement mirrors the latest five keys that had been pressed by the performer;
- **Mode 3 - "Parallel Chords":** The keyboard serves two functions based on the number of keys pressed simultaneously; pressing three or more keys stores the selected chord voicing in the instrument's memory, pressing a single key recalls the previously stored chord with transposition based on the key pressed (i.e. c – no transposition, d – transposition by a major second, and so on);
- **Mode 4 - "Chord Memory":** Works similarly to Mode 3 but allows storing one chord for each note of the chromatic scale (i.e. after playing C major and D minor chords, pressing the „c" key will recall the first chord, pressing the „d" chord will recall the second);

Conclusions

As evidenced by the above description, the multi-stage work on the instrument allowed for a successful verification of the basic thesis – the use of mechanical deactivation of selected string to enable chordal playing with a bow. The initially assumed technical means to achieve this functionality – the use of string dampers – proved ineffective and had to be replaced with a tring deviating mechanism. This mechanism in turn caused a side effect of varying the string pressure on the soundboard, which rendered the floating soundboard made of balsa wood impractical (as it bent undern the changing tension of the strings). However, the key aspect of the entire process was the positive verification of the basic initial assumption and the ensuing performance possibilities.

The mechanical solutions applied in the Autoviola have a noticeable drawback – the movement of the servomechanisms is not instantaneous, resulting in a response time of about half a second, which prevents rapid changes of chords or individual notes and requires adaptation of the playing technique.

The digital extensions enhance the capabilities of the Autoviola with functions available almost exclusively in electronic instruments. However simple, these digital augmentations - combined with the tonal, dynamic, and articulation possibilities inherent to acoustic instruments - result in unique performance capabilities, unattainable by either fully acoustic instruments or those based entirely on digital technology. The combination of features from digital and acoustic realms makes the Autoviola a truly hybrid instrument, a practical realisation of the post-digital approach.

Aeromembranophone

Initial Assumptions

- a pitched percussion instrument, serving as a fully-fledged element of an algorithmically controlled generative system, utilizing the principle of a percussion aerophone commonly known as "tubafon"; [11]
- pitch change implemented in a similar fashion as in woodwind instruments, by altering the length of the air column, using digitally controlled, mechanized keys;
- digital control of pitch enables for digital augmentations/extensions, as well as using the instrument as one of the elements of the generative system;

In the AAAA project, the Aeromembranophone serves the function of a rhythmic instrument , however its also capable of producing definitely pitched sounds.

The initial concept behind Aeromembranophone was to use the principle of operation of an instrument commonly known as "tubafon". [12] The name refers to a percussion aerophone in which the air column within a long plastic tube is set into vibration by hitting the edge of the tube with rubber-covered paddles.

However, these paddles are a rather crude solution, making it difficult for the performer to execute nuanced articulation. Therefore I decided to equip the instrument with a membrane (drum head), allowing the use of various types of drumsticks and mallets, which is a standard solution for percussionists. Unlike the previously mentioned "paddle," this allows for use of the usual playing techniques, such as tremolo, paradiddle, etc.

The drum head and the air column, rather than acting as two separate generators, tend to behave like a single generator, which can be explained with the concept known in acoustics as a *coupled system.* [13]

The final dimensions of the instrument's body (length - 100 cm, circumference - 15 cm / 6'') are a compromise between acoustic considerations and playing technique requirements – a larger drumhead would be more comfortable to play, but it would require a pipe with a larger radius, which in turn would require bigger key mechanisms. During earlier experiments on various prototypes of the instrument, larger keys proved to be an issue from the mechanical standpoint.

Soundoles and Keys

The placement of the soundholes in the final version of the instrument is a result of observations made during the work on earlier prototypes. The final arrangement of the holes approximates a diatonic scale; the remaining notes of the chromatic scale are produced by using various combinations of open and closed keys, which is an equivalent of fork fingerings, used in woodwind instruments. The benefits of this solution are as follows:

- reducing the number of keys (from the planned eleven to seven) minimizes the negative impact that incomplete key sealing has on the sustain;

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[11] *Maszyna i tubafon*, dwutygodnik.com, https://www.dwutygodnik.com/artykul/8840-maszyna-i-tubafon.html [date of last consultation: 28 maja 2024 r.].

[12] as used by Krzysztof Penderecki in his Symphony no. 7; not to be confused with the *tubaphone* – a pitched idiophone;

[13] A. Chaigne, J. Kergomard, *Coupled Systems*, [w:] A. Chaigne, J. Kergomard (red.), *Acoustics of Musical Instruments*, New York 2016.

- The use of "fork fingerings" allows for the correction of intonation issues resulting from imperfect soundhole placement.

Electronic Components and the User Interface

The Aeromembranophone, uses a standar laptop computer as the central element of its electronic setup,rather than Bela Mini microcomputer used in other instruments. The Pure Data patch, used by the instrument, converts the data received from the user interface, the sound sensor and OSC messages (sent by the other instruments and the control patch), into control signals, sent to an Arduino microcontroller, which in turn controls the movement of the instrument's keys via a RC servo driver.

The user interface of the instrument consists of a foot controlled keyboard, covering one octave of the chromatic scale. An additional footswitch, located between the D# and F# notes, switches between the two modes of the instrument's digital extensions. The keyboard is accompanied by an expression pedal, which controls the speed of the key mechanisms, which influences in the character of the note transitions.

Software and Performance Considerations

The software developed for the Aeromembranophone consists of two parts: a Pure Data patch and an Arduino script. The structure of the patch is similar to that of the Autoviola, although the implementation of individual functions differs significantly due to the different operating principles of the two instruments. The patch consists of several modules, the most important ones being the algorithm handling module and the digital extensions module, which offers following modes:

- Mode 1 - "Direct": The footswitch controls the instrument's keys directly;
- Mode 2 - "Relative Pitch Change": This mode allows for an unorthodox form of interaction with the instrument: The individual foot switches, rather than calling up specific notes, transpose the

latest note by a specified interval. For example, starting from the C note and repeatedly pressing of the G key (which in Mode 2 transposes the pitch up by a major second) will result in a following note sequence: D – E – F# - G# - A# - C – D, and so on.

Conclusions

Regarding the timbre of the Aeromembranophone, soft and hard felt mallets produce most clearly defined notes, while typical wooden drumsticks emphasize the higher harmonics, although they can also produce a clearly defined pitch at higher dynamics. The timbral palette of the Aeromembranophone and the accompanying changes in pitch definitione, influence perception of the instrument's role in the ensemble. Playing techniques that emphasizes the fundamental tone (e.g., soft mallet tremolos at low dynamics) creates distinctly defined notes or melodies, promoting the perception of the Aeromembranophone as one of the three instruments with a defined pitch. Conversely, Using articulation that emphasizes the inharmonic component changes the perceived character of the Aeromembranophone role to a strictly rhythmic instrument.

The Aeromembranophone bears certain similarities to orchestral *timpani*: firstly, it enables production of multiple notes from a single membranophone; secondly, the pitch change is controlled by the performer's feet. However, the Aeromembranophone enables precise pitch changes (quantised to specific notes) also offering functions, such as relative pitch change and digital control of pitch, which are not typically found in acoustic instruments.

Post-Digital Sax

Initial Assumptions

The frequency of reed vibrations in a traditional woodwind instrument depends on the resonant frequency of the air column in the instrument's pipe. However, the fundamental principle of the P-D Sax is different - the reed's vibration frequency is dictated by a variable electromagnetic field, generated by an electromagnet attached the mouthpiece. Nevertheless, the air blown by the performer into the mouthpiece remains an essential factor - the air pressure directly affects the sound dynamics. Since the reed is in contact with the performer's lower lip, thetimbre can be controlled by the embouchure.

Thus the mouthpiece serves a function of a air valve (in a way similar to a musical siren, [14] pneumoatic gramophone[15] or a reed pipe) [16] which - by periodically interrupting the airflow from the performer's mouth - creates a sound wave of a specific frequency. The digitall controll over the frequency of the alternating magnetic field that moves the reed, allows for a wide range of digital interventions in the musical material and the control of the pitch by the means of the algorithms.

Technical details of an earlier prototype of P-D Sax are descibed in a separate paper, published in the proceedings of 2022 NIME conference.[17]

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[14] B. Hopkin, J. Scoville, *Musical instrument design: practical information of musical instrument making*, Tucson 2010.
[15] D. Self, *The Auxetophone*, http://www.douglas-self.com/MUSEUM/COMMS/auxetophone/auxetoph.htm#aux [date of last consultation: 4 czerwca 2024 r.].
[16] M. Drobner, *Instrumentoznawstwo i akustyka*, Warszawa 1993.
[17] K. Cybulski, *Post-digital sax - a digitally controlled acoustic single-reed woodwind instrument, International Conference on New Interfaces for Musical Expression*, 2022.

The practical implementation of the described principle required the use of a specially constructed mouthpiece, which differs significantly from a standard one. The primary difference is the way in which the reed is attached to the mouthpiece – rather than being firmly secured by a ligature, its secured in the middle with a flexible o-ring, which allows for a hinged movement of the reed. A permanent magnet is attached to the far end of the reed, enabling it to be set in motion by the electromagnet.

The frequency of the reed vibration is controlled with a set of simplified keywork, using custom proportional-action keys, allowing smooth note transitions and glissandi.

In comparison to the earlier prototypes, final version of the P-D Sax offers improved performance in terms of overall loudness and dynamic range, as well as less"reedy" sound, due to a larger sound horn/resonator. A breath sensor, designed and fabricated from scratch, offers improvement in playing technique over the lip sensor, used in the earlier prototype.

Design of the Final Form of the Instrument

The final form of the instrument is a result of both acoustic, ergonomic, and aesthetic considerations. An important aesthetic premise was to retain the key visual elements of the instantly recognizable form of the alto/tenor saxophone.

The asymmetric shape of the instrument, developed with numerous sketches and models, allowed for the ergonomic placement of the keys, while retaining the qualities unmistakably associated with a saxophone. The square cross-section of the pipe/acoustic tube clearly facilitated the instrument's construction, but it's nevertheless a result of a conscious aesthetic decision. The inspiration for this design came from wooden organ pipes and, indirectly, the Paetzold recorder,[18] as well as Bart Hopkin's wooden saxophones[19] and Moe Sax. [20] The final "angular" form of the instrument is, in a way, a synthetic representation of the overall aesthetic idea of the saxophone.

Electronic Components

As was the case with the Autoviola, the primary electronic component of the P-D Sax is the Bela Mini microcomputer. It's attached to a main PCB, which distributes power and control signals among the electronic components. Additional custom PCBs are used for the proportional Hall sensors, utilised in the user interface (keys). The user interface is completed with an octave switch and a thumb joystick.

Software and Performative Considerations

The P-D Sax's software consists of a Pure Data patch, running on the Bela Mini microcomputer. It consists of several modules, which perform functions similar to the corresponding modules in the other instruments, although the details of these functions are tailored to the specific characteristics of the instrument. The most notable difference is that the P-D Sax patch is the only one that generates actual sound wave (in a form of the alternating current), based on data from sensors (keys, octave switch, breath sensor, and joystick) and structures formed by algorithms and digital extensions. The sound wave, taken from the Bela Mini's audio outputs is then amplified and sent to the electromagnet, controlling the reed's movement.

The digital extensions module of the P-D Sax patch offers the following modes:

- Mode 1 - "Direct": The keyboard directly controls the vibration frequency of the reed.
- Mode 2 - "Looping," activated by moving the joystick to the right: This mode allows the looping of the latest phrase. The loop can be sped up by moving the joystick further to the right; the notes in the loop can be transposed with the keys – fingering for a D note transposes the loop by a major second, fingering for the E note transposes the loop by a major third, and so on.
- Mode 3 - "Relative Pitch Change": This mode works similarly to Mode 2 of the Aeromembranophone, allowing the pitch of the played note to be transposed by specific intervals, assigned to the P-D Sax keys.

Conclusions

The P-D Sax combines the features of an acoustic instrument (a vibrating reed and the player's breath apparatus as the actual sound source) with the digital pitch control, enabling a wide range of digital interventions in the musical material. Therefore, P-D Sax is a fully-fledged hybrid instrument. Since the reed of the P-D Sax is the actual sound source of the instrument, its vibrations and the resistance it offers to the player's lower lip provide direct tactile feedback. It is also noteworthy that the P-D Sax is the first wind instrument that meets the criteria for an actuated instrument. [21]

A feature discovered during the initial experiments, namely the practical lack of a lower limit to the pitch generated by the P-D Sax, has become a key direction for further development of the instrument.

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[18] S. Conforti, A. Güsewell, *PRIME Gesture Recognition applied to the Paetzold recorder: New paradigms for the interaction between recorder players and machines in live electronic music*, „Dissonance/Dissonanz” 2015, nr 132.
[19] *WOODEN SAX*, 8 marca 2017 r., https://barthopkin.com/instrumentarium/wooden-sax/ [date of last consultation: 5 czerwca 2024 r.].
[20] *MOE SAX*, 8 marca 2017 r., https://barthopkin.com/instrumentarium/moe-sax/ [date of last consultation:5 czerwca 2024 r.].
[21] K. Cybulski, *Post-digital sax - a digitally controlled acoustic single-reed woodwind instrument*…

Achieving sounds even below the lower limit of human hearing range does not require changing the physical dimensions of the instrument, which would be necessary for a traditional aerophone.

Instruments as Elements of the Generative System

In the original concept, communication between the instruments (which is necessary for the correct implementation of digital algorithms) was to be conducten acoustically- through the sound itself. The sound was then to be analyzed with th Pure Data ~fiddle module, conducting the Fast Fourier Transform.

The imperfections of this sound analysis method, especially in conjunction with the microphone placement (attached to the instruments) made it impossible to effectively verify the impact of the algorithms on the instruments' behavior and to establish a clearly perceivable cause-and-effect relationship between the sounds played by the leading and following instruments in algorithms 1, 2, and 3. This led to the decision to use the Open Sound Control (OSC) protocol for communication between the instruments.

Apart from the Pure Data patches controlling the functions of individual instruments, an additional patch – AAAA_OSC_master – was created to control the behavior of the entire system, using the OSC protocol as well.

Algorithms

The digital extensions, outlined in the descriptions of individual instruments, are already a implementation of a post-digital approach. By utilizing the optimal combination of acoustic instruments features and digital technology, they offer a range of features, unavailable in standard acoustic instruments. However, the primary goal of applying the post-digital approach in the AAAA project was to utilise the digital aspects of the instruments as a means of creating a global generative system. This system, in turn, would enable digital interventions in the group improvisation proces.

The key element of this system is a set of carefully crafted algorithms, which determine how the notes played by individual performers influence the performance of the other musicians. The algorithms create some sort of rudimentary compositional structures, or a framework for improvised musical pieces. They are, therefore, one of the key elements of the entire AAAA project.

As already mentioned, the interpretability of the algorithms was a crucial feature of the generative system, which constitutes the AAAA project. Thus, thealgorithms should display following qualities:

- they should be easily understandable (interpretable);
- it should be possible to formulate the essence of any given algorithm in a single sentence of the natural language;
- it should be possible to reverse-engineer the rules governing any given algorithm merely by observation of the interaction between the instruments;

In the final version of the AAAA project, the following algorithms were used:

Algorithm 0 - free improvisation (no algorithm used);

Algorithm 1 - Post-Digital Sax imposes notes on other instruments

Algorithm 2 - Autoviola imposes notes on other instruments

Algorithm 3 - Aeromembranophone imposes notes on other instruments

Algorithm 1A - Post-Digital Sax suggests notes to other instruments

Algorithm 2A - Autoviola suggests notes to other instruments

Algorithm 3A - Aeromembranophone suggests notes to other instruments

Algorithm 4 – pitch change possible only while playing solo

Algorithm 5 – most played notes become gradually impossible to play

Algorithm 6 – instruments are forced to play digitally generated note sequence

Performers

The project involves my active participation as a performer using the P-D Sax. The following musicians have accepted the invitation to participate in the project:

- Piotr Zalewski [22] - A musician, who combines many years of experience with historical string instruments, (alto and bass viola da gamba) with activities in pop and rock music, as a guitarist, bassist and synth player. I had the pleasure of collaborating with Piotr previously and proved to be an exceptionally open-minded musician, eager for new experiences.
- Hubert Zemler [23] - A classically trained percussionist who combines experience across a wide range of styles (contemporary music, jazz, rock, and broadly defined experimental music) with his own work as a composer and solo artist in the experimental and electroacoustic music genres.

Research Hypotheses Verification

Main research hypotheses regarding individual instruments had been verified positively, with only minor technical changes to the original assumptions. The AAA project as a whole performer as expected on the technical level – algorithms indeed influenced the instruments' performance in a controlled manner, which in turn served as a basis for various modes of improvisation.

Innovative Aspects of the AAAA Project

Based on the most significant achievements of recent years in the field of music technology, in areas similar to those addressed by my artistic work, I will attempt to demonstrate how the AAAA project stands out against the current state of research and what unverified research hypotheses I set for myself upon embarking on such a broadly scoped experiment:

1. The starting point for constructing the set of instruments was perceiving them as elements of a global generative system. Therefore, some basic principles apply to the entire group of instruments:

- all the instruments are fully acoustic;

[22] *Zalewski, Piotr. Międzynarodowy Festiwal Muzyki Współczesnej Warszawska Jesień*, https://warszawska-jesien.art.pl/2023/program/wykonawcy/zalewski-piotr [date of last consultation: 7 czerwca 2024 r.].
[23] H. Zemler, *Bio*, https://hubertzemler.com/bio/ [date of last consultation: 7 czerwca 2024 r.].

- for all three instruments, the only parameter subject to digital control is the pitch; all other parameters (dynamics, articulation, rhythm, phrasing) remain under the performer's control, thus the instruments are semi-autonomous;
- all instruments fulfill the criteria of *actuated instruments* - despite the use of mechatronic components, the performer maintains uphysical contact with the key sound-generating elements of each instrument (strings, drumhead, reed) and the user interface.
- the instruments' design aims to eliminate the interface elements typically present in digital instruments (such as screens, displays, touch panels or distance sensors) - in favor of physical elements, ensuring a specific form of interaction, intrinsic to acoustic instruments; this enables intimate and direct interaction;
- The behavior of the instruments is controlled by simple and clearly defined algorithms; the complexity of their behavior results from interactions with the material world (the physical form of the instruments) and the spontaneous actions of the performers. Thus, the feedback occurs at the instrument-performer and performer-performer level, making the behavior of the entire system easily interpretable, which is not the case with instruments which use artificial neural networks, or feedback at the software-hardware level

2. Specific principles has been assumed only for the two out of the three instruments:

- both P-D Sax and Autoviola meet the criteria of embedded acoustic instruments;
- P-D Sax and Aeromembranophone offer the possibility of relative pitch change through transposition by specific intervals assigned to various elements of the interface;

Each individual instrument offers additional, unique features detailed in their respective descriptions.

To the best of my knowledge, based on a review of the current state of research, most of the assumptions outlined above have not yet been realized in a practical form or as an artistic work. Therefore, a comprehensive work that materializes these assumptions represents an original contribution to the development of the discipline.

Reviews, Survey, Interviews

In the full version of the thesis, I referred to a couple of press reviews – some of the reviewers noticed the „different type of futurism"[24] represented by the projetct. One reviewer remarked, that he found it hard to follow the relations between the algotrithms and resulting music[25]. However, a survey conducted among the audience members during the second AAAA performance revealed, that – given a proper introduction - they found it relatively easy to follow the relations, as well as distinguish music pieces played under the influence of different different algorithms.

Musicians themselves generally regarded their experiences with the instruments as rewarding and insporing, and the impressons from playing in an ansamble under the influence of the algorithms as refressing and creatively stimulating.

[24] *Warsztaty ze słuchania. Warszawska Jesień 2023*, „Glissando", 19 października 2023 r., http://glissando.pl/aktualnosci/warsztaty-ze-sluchania-warszawska-jesien-2023/ [date of last consultation: 24 czerwca 2024 r.].

[25] P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 12 czerwca 2024 r.].

Selected Recordings

The recordings presented in the thesis originate from three sources: the premiere of the AAAA project during the opening of the 66th International Festival of Contemporary Music Warsaw Autumn at the National Philharmonic in Warsaw, a recording session conducted at Studio S1 of the Chopin University of Music, and the second performance at the Hashtag Lab Contemporary Music Space. Selected recordings present the effects that each of the six algorithms has on improvised musical pieces. Each of the algorithms is featured in two versions. The recordings can be downloaded from the following website: krzysztofcybulski.com/aaaa.php

It should be emphasized that the phonographic aspect of the presented recordings does not constitute an element of the artistic work in the doctoral dissertation; the recordings are only a means of documentation of the improvised pieces, created with the elements of the AAAA project.

The subsequent recordings demonstrate the evolution of the AAAA project—the improvised pieces in Studio S1 and Hashtag Lab exhibit a higher level of musical maturity. This is likely due to both a gradual mastery of the playing techniques and the experience in dealing with the algorithmically controlled generative system, gained during previous performances and recordings.

Premiere Performance at the Inauguration of the 66. International Festival of Contemporary Music Warsaw Autumn:

„WARSZAWSKA_JESIEN_algorytm_0-5.mp4”
Recorded by Remigiusz Czechowicz, mixed by Krzysztof Cybulski.

Recording sessions, conducted at the Studio S1 of the Chopin University of Music:

„UMFC_take_1_algorytm_0-2A.wav”, „UMFC_take_1_algorytm_6.wav”, „UMFC_take_2_algorytm_6.wav”
Recorded and mixed by Jan Olejniczak.

Second Performance at the Hashtag Lab Contemporary Music Space:

„HASHTAG_LAB_algorytm_3-3A.wav”, „HASHTAG_ LAB_algorytm_4.wav”, „HASHTAG_ LAB_algorytm_5.wav”
Recorded by Wojciech Blazejczyk, mixed by Krzysztof Cybulski.

Conclusion

The recordings presented in this work document only a few possible realizations of the project— in other words, they showcase selected musical artifacts that result from the generative system, constituted by the AAAA project. The physical instruments and digital algorithms that make up the system create conditions for a specific form of interaction between improvising musicians. The musical artifacts are largely dependent on factors such as the performative strategies adopted for a given performance, the selection and sequencing of algorithms, and, last but not least, the factors which are ever-important for the proces of group improvisation, such as the emotional state of the musicians. This is evidenced by the differences between the various renditions of the work, documented in the recordings.

The evaluation of the aesthetic outcomes of the endeavor is certainly a subjective matter. However, it remains a fact that the AAAA project constitutes a platform for a new form of interaction between musicians, resulting with each performance in the creation of new musical works.

Importantly, the AAAA project is an open system, allowing for creation of many more artifacts through the modification of the aforementioned performance strategies, the use of different algorithms, or further evolution of the instruments themselves.

Synopsis bibliography

Alizadeh F., Stevens G., Esau M., *I Don't Know, Is AI Also Used in Airbags?: An Empirical Study of Folk Concepts and People's Expectations of Current and Future Artificial Intelligence*, „i-com" 2021, t. 20, nr 1, DOI: 10.1515/icom-2021-0009.

Castelvecchi D., *Can we open the black box of AI?*, „Nature" 2016, t. 538, nr 7623, DOI: 10.1038/538020a.

Chaigne A., Kergomard J., *Coupled Systems*, [in:] A. Chaigne, J. Kergomard (red.), *Acoustics of Musical Instruments*, New York 2016.

Composers as Gardeners | Edge.org, https://www.edge.org/conversation/brian_eno-composers-as-gardeners [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 1 maja 2024 r.].

Conforti S., A. Güsewell, *PRIME Gesture Recognition applied to the Paetzold recorder: New paradigms for the interaction between recorder players and machines in live electronic music*, „Dissonance/Dissonanz" 2015, nr 132.

Csíkszentmihályi M., *Finding Flow. The Psychology of Engagement With Everyday Life*, New York 1998.

Cybulski K., *Post-digital sax – a digitally controlled acoustic single-reed woodwind instrument*, [in:] *Proceedings of the International Conference on New Interfaces for Musical Expression*, Zenodo 2022.

Davisson K., *Improvisation as a Method of Composition: Reconciling the Dichotomy*, „The British Journal of Aesthetics" 2022, t. 62, nr 3, DOI: 10.1093/aesthj/ayac018.

Drobner M., *Instrumentoznawstwo i akustyka*, Warszawa 1993.

Galanter P., *Generative Art Theory*, [in:] C. Paul (red.), *A Companion to Digital Art*, New York 2016.

Galanter P., *What is generative art? Complexity theory as a context for art theory*, 2003 r., http://philipgalanter.com/downloads/ga2003_paper. pdf [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation:: 19 maja 2024 r.].

Hart E., Di Blasi Z., *Combined flow in musical jam sessions: A pilot qualitative study*, „Psychology of Music" 2015, t. 43, nr 2, DOI: 10.1177/0305735613502374.

Hopkin B., Scoville J., *Musical instrument design: practical information of musical instrument making*, Tucson 2010.

Maszyna i tubafon, dwutygodnik.com, https://www.dwutygodnik.com/artykul/8840-maszyna-i-tubafon.html [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 28 maja 2024 r.].

Mika P., *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 12 czerwca 2024 r.].

MOE SAX, 8 marca 2017 r., https://barthopkin.com/instrumentarium/moe-sax/ [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 5 czerwca 2024 r.].

Overholt D., Berdahl E., Hamilton R., *Advancements in Actuated Musical Instruments*, „Organised Sound" 2011, t. 16, DOI: 10.1017/S1355771811000100.

Self D., *The Auxetophone*, http://www.douglas-self.com/MUSEUM/COMMS/ auxetophone/auxetoph.htm#aux [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 4 czerwca 2024 r.].

Warsztaty ze słuchania. Warszawska Jesień 2023, „Glissando", 19 października 2023 r., http://glissando.pl/aktualnosci/warsztaty-ze-sluchania-warszawska-jesien-2023/ [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 24 czerwca 2024 r.].

WOODEN SAX, 8 marca 2017 r., https://barthopkin.com/instrumentarium/wooden-sax/ [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 5 czerwca 2024 r.].

Zalewski, Piotr. Międzynarodowy Festiwal Muzyki Współczesnej Warszawska Jesień, https://warszawska-jesien.art.pl/2023/program/wykonawcy/zalewski-piotr [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation:7 czerwca 2024 r.].

Zemler H., *Bio*, https://hubertzemler.com/bio/ [P. Mika, *Warszawa, jak się bawicie?*, https://ruchmuzyczny.pl/article/3652-warszawa-jak-sie-bawicie [date of last consultation: 7 czerwca 2024 r.].