Cellular Au-Tonnetz: A Unified Audio-Visual MIDI Generator Using Tonnetz, Cellular Automata, and IoT

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Abstract. This paper presents a detailed description of an innovative tool for music creation that merges sound and light through a unified system. By leveraging the Tonnetz approach, cellular automata, and embedded electronics, the project offers users an intuitive platform to explore musical harmony and synesthetic experiences. Key features include real-time synchronization of sound and light, the implementation of scales and chord progressions, and the integration of web-based control for multi-unit management. This tool aims to democratize music creation, making complex musical concepts accessible through an interactive, multi-sensory interface.

Keywords: Tonnetz · Cellular Automata · IoT · Music Generation · Audio-Visual Integration · Synesthesia

1 Introduction

Traditional approaches to integrating visuals with music often involve sound-reactive systems where visuals respond to audio input. While effective, these systems typically treat sound and visuals as separate entities, limiting the potential for a truly unified audio-visual creation experience. This paper presents a detailed description of a novel tool that transcends traditional boundaries by generating sound and light simultaneously, offering a cohesive platform for music creation that is both interactive and immersive.

Interactive tools have a significant impact on music education and creative expression, enabling users at every level of ability to explore musical concepts in an accessible manner [5]. By integrating sound and light generation, the tool fosters a deeper understanding of musical harmony and structure, aligning with theories on the benefits of multi-sensory learning environments [12].

The inspiration for this project stems from artists like Max Cooper, Four Tet, and collectives like Squid Soup, who integrate visuals directly into the music-making process, creating immersive experiences where sound and light are intrinsically linked [3,14,13]. Their work highlights the potential of synchronized audio-visual systems to enhance live performances and engage audiences on multiple sensory levels.

In this paper, a unified audio-visual music creation tool is introduced that leverages the Tonnetz [18], a geometric representation of tonal space, and cellular automata [17] to generate evolving musical patterns and synchronized light displays. The system is built using embedded electronics and IoT technologies, providing real-time control and scalability for multi-unit installations.

The paper begins by discussing the personal journey and motivation behind the project, followed by a review of related work in music theory, cellular automata, and synesthetic experiences in music. The system design and implementation are then detailed, including hardware and software components and the algorithms used. The focus is on describing the technology developed rather than evaluating its performance. Finally, the implications of this work and potential future developments are discussed.

2 Background and Related Work

2.1 Tonnetz and Its Applications

The Tonnetz, or "tone network," is a conceptual lattice diagram representing the relationships between pitches in just intonation, initially developed by Leonhard Euler in the 18th century [2]. It visually maps out harmonic relationships, such as fifths, thirds, and their inversions, providing a geometric representation of tonal space.

In music theory, the Tonnetz has been instrumental in analyzing harmonic progressions and voice leading, particularly in neo-Riemannian theory [6]. Its applications extend to computational musicology and the development of musical interfaces, where it serves as a foundation for creating intuitive layouts that reflect harmonic relationships [1].

This work leverages the Tonnetz to map musical notes in a two-dimensional grid, facilitating the use of cellular automata to generate harmonically coherent musical sequences. By utilizing the inherent harmonic proximities within the Tonnetz, it enables the automatic generation of evolving melodies through simple rule-based algorithms.

2.2 Cellular Automata in Music

Cellular automata (CA) are discrete, abstract computational systems that have been employed in various fields for modeling complex behaviors [11]. In music, CAs have been explored for algorithmic composition, offering a means to generate musical structures based on simple, local interactions [10].

2.3 Synesthetic Experiences in Music

Synesthesia, a phenomenon where stimulation of one sensory pathway leads to involuntary experiences in another sensory modality, has long intrigued artists and scientists [4]. In music, synesthetic concepts have been applied to create multi-sensory experiences, linking sound with visual elements such as color and light [9]. Composers like Alexander Scriabin explored the association between musical notes and colors, aiming to create a unified sensory experience [16]. Others have combined Tonnetz approaches and color mapping for video game music generation [7].

This project draws inspiration from these ideas, integrating light directly into the music-making process by associating specific hues with musical notes on the Tonnetz grid. This integration enhances the user's engagement and provides a visual representation of harmonic relationships.

2.4 Inspiration and the Role of Modern Music Production

The idea to create a system that could act as a virtual orchestra, generating evolving compositions based on cellular automata, was inspired by a video on how Radiohead and Hans Zimmer collaborated to create the soundtrack for *Blue Planet II* [15]. Their innovative use of orchestration and technology to craft immersive soundscapes inspired the development of an electronic orchestra, albeit on a smaller scale.

The goal was to create a system where each virtual orchestra member, represented by a point in a 2D array, could contribute to a dynamic, ever-changing composition. By limiting each member to playing only when no neighboring members were active, a sense of movement and progression in the music could be maintained. This approach allowed for a focus on sound design, knowing that the underlying structure would remain musically coherent.

2.5 Discovering the Tonnetz

During the early stages of development, the concept of the Tonnetz was discovered while researching geometric music theory. The Tonnetz, a means of arranging notes by their proximity to harmonic neighbors, provided an elegant alternative to the traditional piano keyboard layout, which can feel esoteric and unintuitive to non-musicians. By combining the Tonnetz with the array of virtual orchestra members, it became possible to move beyond simple, single-tone outputs. The proximity of harmonic neighbors in the Tonnetz allowed for the automatic generation of unique, evolving melodies through cellular automata rules. This discovery was pivotal in advancing the project from a single-tone soundscape generator to a tool capable of producing complex, layered musical compositions.

2.6 Integrating Synesthetic Elements

The association of colors with musical notes enhances the multi-sensory experience of the system. Drawing inspiration from Scriabin's color theories [16], each note on the Tonnetz grid was linked to a specific hue, creating a visual manifestation of harmonic relationships. This synesthetic integration not only enriches the user experience but also serves as an educational tool for understanding music theory [8]. Figure 1 demonstrates one of the many possible mapping choices that evenly space the RGB color palette for straightforward hardware realization.

Fig. 1: A typical circle-of-fifths approach to the mapping of Western music notes to color.

3 System Design and Implementation

This section presents a comprehensive description of the technology developed for the latest iteration, TZ5, focusing on its architecture and functionality. The TZ5 system is designed to provide an desktop audio-visual music creation experience by integrating web technologies, wifi connected embedded systems, and algorithmic composition techniques.

3.1 System Architecture Overview

The TZ5 system comprises four main components:

1. **Web Application**: Captures user inputs and provides configuration parameters, saved in a mysql database. Hosted here.
2. **Control Board**: Handles the generation of music and visual outputs based on parameters from the web application.
3. **Audio Synthesis**: Generates the actual audio output from MIDI signals.
4. **Hexagonal LED Array**: Generates the light output from the control board's addressable LED signals.

Figure 2 illustrates the overall system architecture.

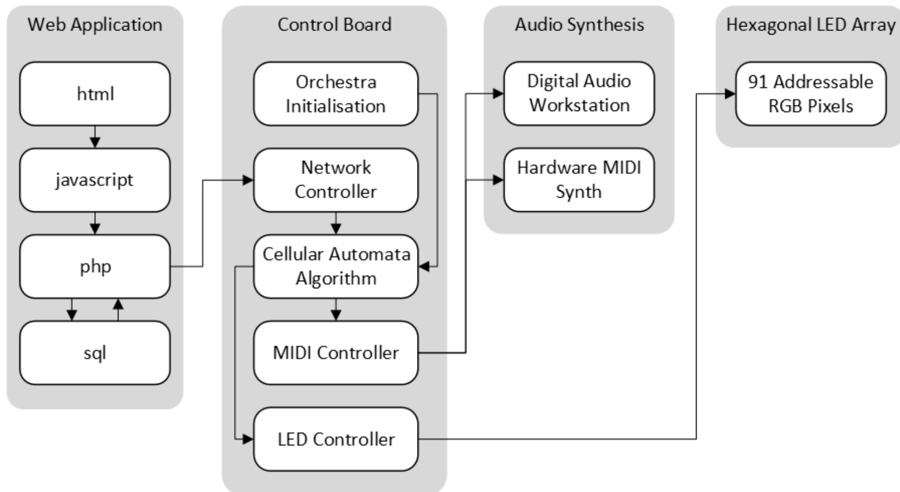

Fig. 2: System architecture of the TZ5 tool, highlighting the interaction between the web application, control board, LED panels, audio synthesis subsystem, and user interface.

3.2 Web Application

The web application serves as the user interface and configuration manager for the TZ5 system. Developed using HTML, JavaScript, PHP, and SQL, it allows users to adjust parameters through sliders, buttons, and other controls, which are then stored in an SQL database.

Key functionalities of the web application include:

- **User Interface**: Provides an interactive platform for users to control various parameters such as algorithm update rate, scale selection, chord progressions, CA rules, neighbor counting methods, looping options, and other settings.
- **Backend Processing**: Utilizes PHP scripts to handle user interface submissions and store parameter values in the SQL database.
- **Data Serving**: Supplies the latest configuration parameter values to the control board via HTTP GET requests, formatted as JSON data.

The parameters retrieved from the server are discussed in relation to the feature descriptions in Table 1.

3.3 Control Board

The control board is the core of the TZ5 system, built around the ESP32-S3 microcontroller. It is responsible for generating the musical and visual outputs based on the parameters received from the web application. The control board comprises several subsystems:

Orchestra Initialization The controller initializes the Tonnetz grid by assigning MIDI numbers to each orchestra member, building up from the bottom of the grid. Figure 3 illustrates this assignment.

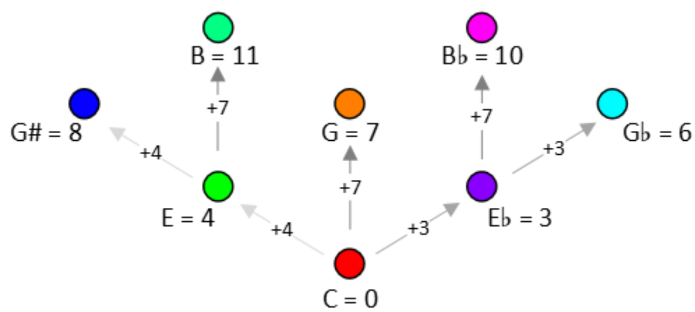

Fig. 3: MIDI number assignment in the Tonnetz grid. Each cell represents an orchestra member with a specific MIDI note.

The assignment of MIDI numbers allows for harmonically coherent note generation, as neighboring cells in the grid are harmonically related.

Network Controller The network controller handles the communication between the control board and the web application. It periodically polls the server to retrieve the latest parameter data, parsing the JSON responses into usable C data types. This ensures that the control board operates with the most recent user configurations.

Cellular Automata Algorithm The cellular automata (CA) algorithm determines the states of the virtual orchestra members on the Tonnetz grid. It uses the parameters received from the web application to apply specific CA rules, influencing how the musical composition evolves over time.

Initialization Mechanism The random initialization mechanism is used to initiate activity in the CA algorithm when no initial state is specified by the user, or when all virtual orchestra members have died. If the system detects that there are no active orchestra members, it can randomly activate a member to kick-start the algorithm. This can occur automatically or be synchronized with the BPM, depending on user settings.

Looping Functionality Looping allows the user to switch between random selection of the next note and looping through past note selections. When looping is enabled, the CA algorithm will replay the sequence of coordinates stored during previous iterations, creating repeating patterns.

Neighbor Counting Methods Users can choose between local neighbor counting (considering the six immediate neighbors) and extended neighbor counting (considering the eighteen nearest neighbors). This choice affects the variation and complexity of the CA behavior.

CA Algorithm Implementation The CA algorithm operates in a loop, performing the following steps:

1. **Update Orchestra Members**: Iterate through each cell in the Tonnetz grid to update the state of orchestra members based on note durations.
2. **Select Coordinates**: Determine the coordinates for the next cell to evaluate, either from loop data (if looping is enabled) or by random selection.
3. **Apply Population Limits**: Check if the number of active members is within the specified maximum and minimum population limits.
4. **Random or User Defined Initial State**: If the active member count is below the minimum and tickling is enabled, activate a random member or set an initial state.
5. **Evaluate Neighbors**: Count the number of active neighbors using the selected neighbor counting method.
6. **Apply CA Rules**: Based on neighbor counts and user-defined thresholds, determine whether to activate or deactivate the current cell.
7. **Manage MIDI and LED Outputs**: For cells that become active, send the corresponding MIDI notes and update the RGB LEDs to reflect the changes.

MIDI and LED Controllers The MIDI and LED controllers are responsible for generating the audio and visual outputs:

- **MIDI Controller**: Sends MIDI note on and note off messages to the connected audio synthesis subsystem or hardware synthesizer. It supports both USB MIDI and hardware MIDI over serial connections.
- **LED Controller**: Updates the RGB LEDs based on the active cells in the Tonnetz grid. Each note is mapped to a specific color using the HSV color model, providing a visual representation of the music. Figure 4 shows the mapping of notes to hues.

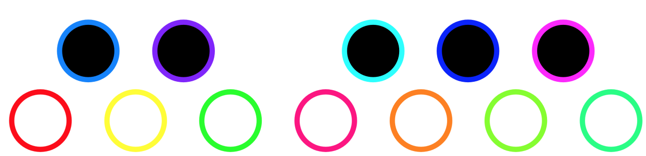

Fig. 4: Mapping of Western notes to color hues.

3.4 Audio Synthesis Subsystem

The audio synthesis subsystem is responsible for generating the actual audio output from the MIDI signals sent by the control board. This can be achieved using:

- **Digital Audio Workstation (DAW)**: The control board sends MIDI over USB to a DAW such as Ableton Live, where virtual instruments and effects can be used to produce the desired sounds.
- **Hardware Synthesizer**: The control board also supports hardware MIDI over serial connections, allowing it to interface with external synthesizers or sound modules.

3.5 LED Panel Subsystem

The LED panel subsystem provides the visual component of the audio-visual experience. The control board can drive various configurations of LED panels, as long as the number of LEDs and the protocol (WS2811 or other single serial data line protocol) remain consistent.

LED Panel Configurations

- **91-LED Custom PCB Panel**: A 10 cm circuit board with 91 2020 RGB SMD LEDs arranged in a hexagonal grid, providing a compact and high-density visual display. A sheet of paper or opaque acrylic can be deployed to diffuse the light. See Figure 5.

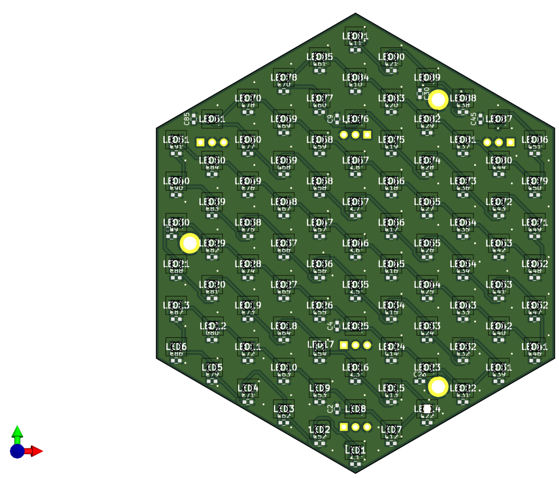

Fig. 5: A 10 cm bespoke printed circuit board with 91 addressable RGB LEDs.

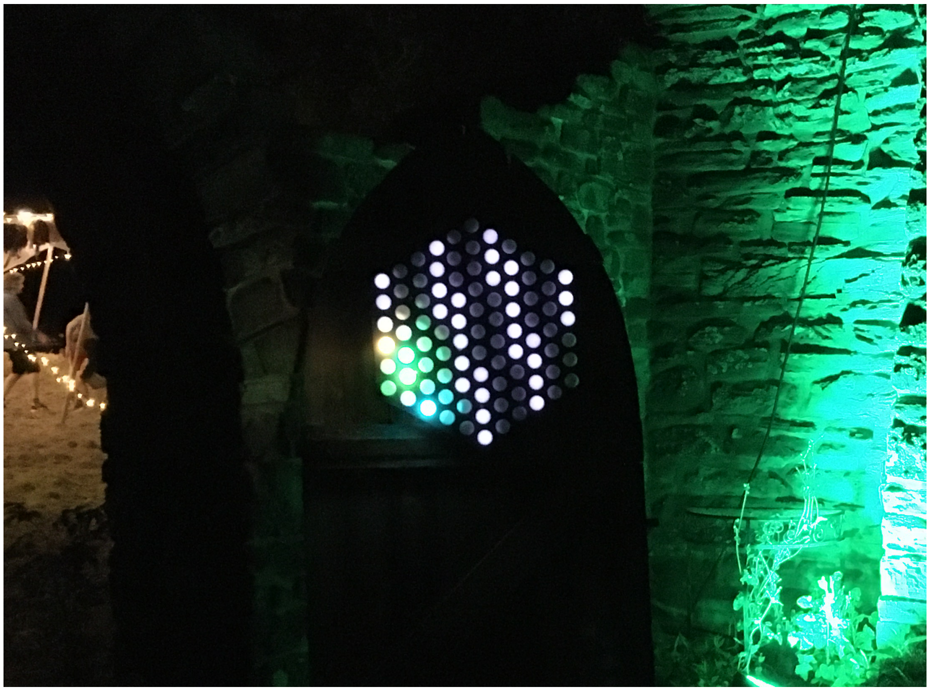

Fig. 6: A 70 cm panel with 91 40 mm diameter pixels, installed on a barn door at a music festival.

- **70 cm Plywood Panel**: A larger panel using waterproof LED strips mounted on plywood, offering a more expansive visual field. See Figure 6.

The control board's ability to drive different sizes of hexagonal arrays allows for versatility in installations, from small-scale personal devices to large-scale performance setups.

3.6 Integration and Scalability

The modular design of the TZ5 system enables scalability and flexibility. Multiple control boards and LED panels can be synchronized and controlled via the web application, supporting collaborative performances and complex installations.

The system's reliance on standard protocols (MIDI over USB or serial, WS2811 for LEDs) ensures compatibility with a wide range of audio and visual equipment, further enhancing its adaptability.

The web application has been developed as a self contained docker container, to allow straightforward transition to the field with a local server and WiFi network, disconnected from the internet.

4 Results

An example of a performance can be viewed here. The system's capabilities are showcased through a separate video demonstration, highlighting features such as:

- **Real-Time Control**: Users can adjust parameters on the web interface and observe immediate changes in the musical and visual output.
- **Evolving Compositions**: The CA algorithm generates dynamic musical patterns that evolve over time, providing a continuously changing audio-visual experience.
- **Looping and Variation**: Users can enable looping to repeat past note sequences or allow for random variation, influencing the predictability and novelty of the compositions.
- **Musical Scales and Chord Progressions**: The CA algorithm can be constrained to any Western scale, and multiple scales can be defined as a sequence, offering chord progressions and key changes.
- **Scalability**: Multiple TZ5 units can be controlled simultaneously, enabling collaborative performances and large-scale installations.

The video demonstration has been conducted to illustrate the system's functionality. Table 1 details the features and video demonstration timestamps. The MIDI data for the central unit can be seen in Figure 7.

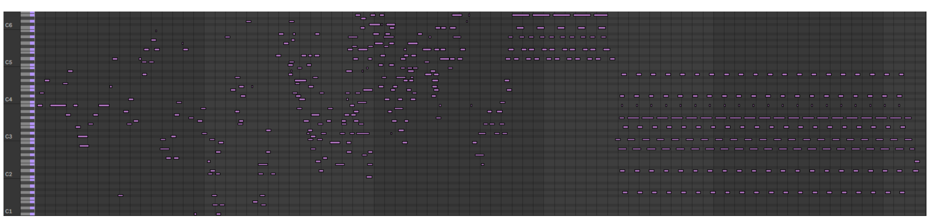

Fig. 7: The MIDI data as viewed in Ableton's piano roll. Periods of slower and faster CA algorithm update rates can be distinguished (first and second quarters), and periods of looping can also be identified in the second half.

4.1 Initial State

The system is provided an initial state via the web application. In this instance, the central pixel of the 91-pixel hexagonal panel has been selected. Figure 8 shows the first few transitions from the initial state as the device is taken out of reset (00:00 to 00:09).

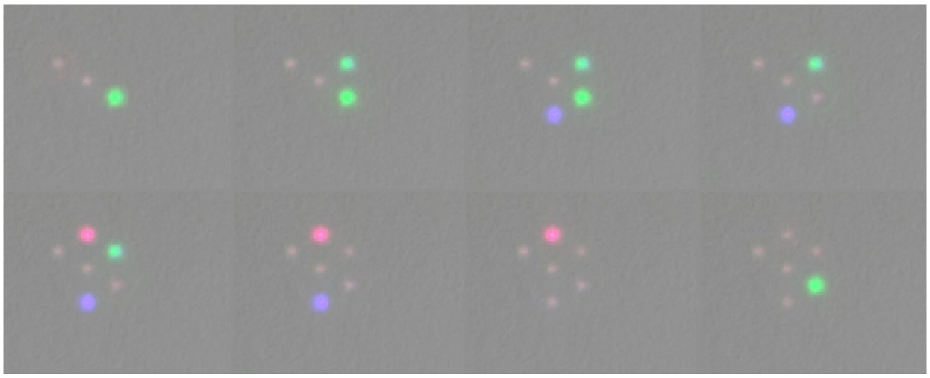

Fig. 8: Eight frames of video demonstrating the transition from the initial green orchestra member (note C) to turquoise (G) and purple (A). Turquoise triggers pink (B) before all members deactivate and the orchestra is re-initialized.

4.2 Maximum Neighbors

The maximum number of neighbors parameter determines how many local orchestra members are allowed to activate. Figure 9 shows four transitions from 01:01 to 01:03, where the maximum neighbors parameter has been increased from 2 to 6.

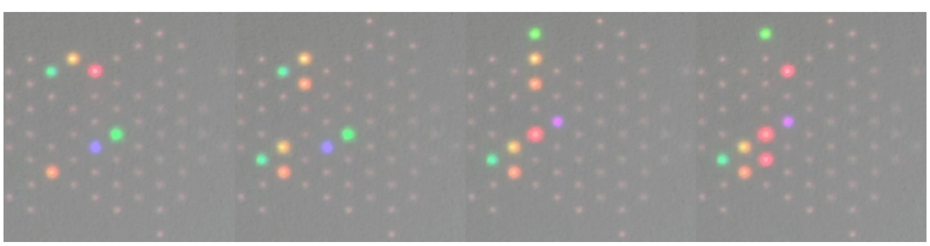

Fig. 9: Four frames of video showing the evolution from strings of notes to clusters, as a result of the increase in the maximum number of permitted neighbors.

4.3 Multiple Units

The web application allows independent control of multiple units. Each unit has been assigned a slight variation of control parameters and assigned to different digital instruments in the digital audio workstation. Figure 10 is a still from the video showing the additional units contributing to the ensemble.

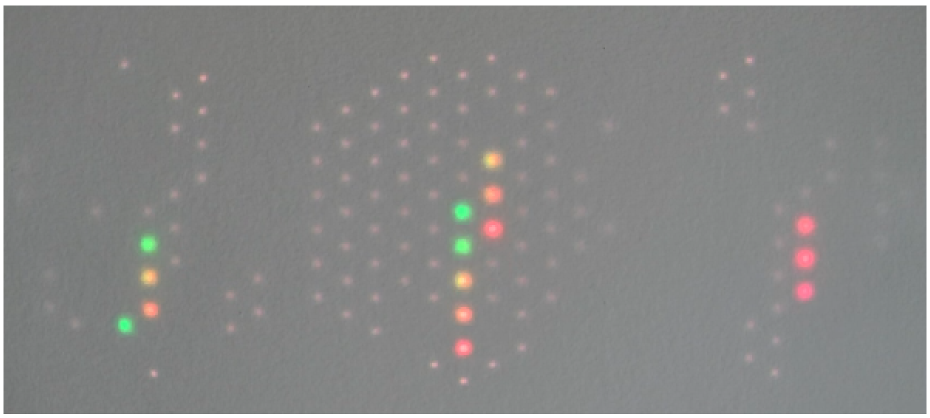

Fig. 10: Three units playing simultaneously. Each has been given the same scale; however, the leftmost unit is updating at a slower rate (33 ms) and limited to six maximum simultaneous players and two neighbors. The rightmost unit is operating at a faster update rate (6 ms).

5 Conclusion

5.1 Summary of Contributions

This paper presented the development of the TZ5 system, a unified audio-visual music creation tool that integrates Tonnetz-based harmonic mapping, cellular automata, and IoT tools. Focusing on the development process and informal observations, the project demonstrates how iterative enhancements and user-centric design can lead to a versatile tool for music creation and exploration.

Key contributions include:

- The innovative integration of cellular automata within the Tonnetz framework to generate harmonically coherent musical sequences.
- The synchronization of audio and visual outputs, providing an engaging multi-sensory experience that appeals to both musicians and non-musicians.
- The development of scalable features and remote control capabilities, enabling collaborative use and potential for multi-unit installations.

5.2 Future Work

Future developments aim to build upon the current system by:

- **Evaluation**: Detailed analyses of the usability, performance, and impact of the TZ5 on various user groups, in terms of its musical and visual output, as well as its value as a creative aide.
- **Quantitative and Qualitative Analysis**: Conduct formal studies using tools like Music21 or MATLAB to analyze the musicality of the system's output and gather structured user feedback.
- **Implementation of Presets**: Develop a library of presets that users can select from and contribute to, making the system more accessible to beginners and facilitating community engagement.
- **Enhanced Interactivity**: Integrate additional input methods, such as utilizing an accelerometer for gesture control, to allow more expressive user interaction.
- **Educational Applications**: Explore the use of the system as an educational tool for teaching music theory concepts through interactive and visual means.
- **Increasing Size**: Ongoing work includes building a 3-meter diameter panel using custom laser-cut mylar and 60 mm "pixels," significantly expanding the scale of the visual display.

By addressing these areas, the TZ5 system has the potential to democratize music creation, foster collaborative creativity, and serve as a bridge between technology and musical expression, fostering immersive audio-visual experiences.

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References

1. Besada, J.L., Bisesi, E., Guichaoua, C., Andreatta, M.: The tonnetz at first sight: Cognitive issues of human–computer interaction with pitch spaces. Music & Science **7**, 20592043241246515 (2024)
2. Cohn, R.: Neo-riemannian operations, parsimonious trichords, and their" tonnetz" representations. Journal of Music Theory **41**(1), 1–66 (1997)
3. Cooper, M.: Max cooper official website. `https://maxcooper.net/`, accessed: 2024-11-13
4. Cytowic, R.E.: Synesthesia: A union of the senses. Bradford Book (2002)
5. Frid, E.: Accessible digital musical instruments—a review of musical interfaces in inclusive music practice. Multimodal Technologies and Interaction **3**(3), 57 (2019)
6. Gollin, E., Rehding, A.: The Oxford handbook of neo-Riemannian music theories. OUP USA (2011)
7. Hembree, P.: Audiovisual alchemy. Millennium Biltmore Hotel, Los Angeles, CA p. 9 (2016)
8. Leotsakos, S.: A tonnetz in practice. `https://www.stephanieleotsakos.com/research-and-pedagogy#/a-tonnetz-in-practice`, accessed: 2024-11-13
9. Peacock, K.: Synesthetic perception: Alexander scriabin's color hearing. Music perception **2**(4), 483–505 (1985)
10. Phon-Amnuaisuk, S.: Composing using heterogeneous cellular automata. In: Applications of Evolutionary Computing: EvoWorkshops 2009: EvoCOMNET, EvoENVIRONMENT, EvoFIN, EvoGAMES, EvoHOT, EvoIASP, EvoINTERACTION, EvoMUSART, EvoNUM, EvoSTOC, EvoTRANSLOG, Tübingen, Germany, April 15-17, 2009. Proceedings. pp. 547–556. Springer (2009)
11. Preston Jr, K., Duff, M.J.: Modern cellular automata: theory and applications. Springer Science & Business Media (2013)
12. Shams, L., Seitz, A.R.: Benefits of multisensory learning. Trends in cognitive sciences **12**(11), 411–417 (2008)
13. Soup, S.: Squid soup official website. `https://www.squidsoup.org/`, accessed: 2024-11-13
14. Tet, F.: Four tet official website. `https://www.fourtet.net/`, accessed: 2024-11-13
15. Vox: How hans zimmer and radiohead transformed "bloom" for blue planet ii. `https://www.youtube.com/watch?v=cIsewG2g-1g`, accessed: 2024-11-13
16. Wikipedia: Alexander scriabin. `https://en.wikipedia.org/wiki/Alexander_Scriabin`, accessed: 2024-11-15
17. Wikipedia: Cellular automaton. `https://en.wikipedia.org/wiki/Cellular_automaton`, accessed: 2024-11-13
18. Wikipedia: Tonnetz. `https://en.wikipedia.org/wiki/Tonnetz`, accessed: 2024-11-13

Table 1: Feature description of the TZ5 System

Feature	Description	Timestamp
Real-Time Control		
Hold in Reset	Keeps the unit in a standby state, maintaining connection to the server for parameter information but resetting the orchestra states and ensuring no MIDI or light output.	00:00
Initial State Setup	Allows user-defined initial state for the CA algorithm, enabling custom starting configurations.	00:02
Random Re-initialization	Enables random selection of initial active cells to kick-start the CA algorithm without a predefined state.	00:15
Evolving Compositions		
Max Notes	Sets the maximum number of active orchestra members, limiting the density of the composition.	00:33 (3 to 8)
Min Notes	Sets the minimum number of active orchestra members, ensuring a baseline level of activity. Set to 1 throughout and set to 0 to bring the orchestra to a stop.	03:00 (1 to 0)
Neighbor Counting Method	Selects between local (six neighbors) and extended (18 neighbors) neighbor counting for CA rules, affecting pattern complexity. Only local demonstrated in video.	N/A
Max Neighbors	Sets the maximum number of neighbors from 2 to 6 in the case of local neighbor counting.	01:01 (2 to 6)
Rate	Sets the update rate of the CA algorithm. Any value from 1 to 999 ms can be selected and updated in real time.	00:45 (50 ms down to 20 ms)
Looping and Variation		
Loop On/Off	Enables or disables looping of past note sequences, allowing for repetition or continuous variation.	01:30
Loop Steps	Sets the length of the looped sequence, controlling the duration of repeated patterns. Every time the CA algorithm is updated, the state is saved, so loop duration is a multiple of the rate and number of loop steps.	01:50 (changed from 300 to 200 steps)
Musical Scales and Chord Progressions		
Scale Selection	Allows selection of musical scales, constraining the CA algorithm to specific tonalities.	01:16 (Chromatic to C Major)
Chord Progressions	Defines sequences of scales to create chord progressions and key changes.	N/A
Looping with Chord Progressions	Combines looping functionality with chord progressions for complex evolving compositions.	N/A
Scalability		
Multi-Unit Synchronization	Controls multiple TZ5 units simultaneously with the same parameters for synchronized performances.	02:10
Distinct Parameters per Unit	Allows each TZ5 unit to be controlled with distinct parameters, enabling collaborative and diverse outputs.	02:19