Orbis: Composing a Light-and-Sound Installation with Min Waves Generated in Artificial Cells

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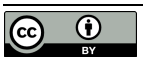
Figure 1: Orbis

Abstract

This study proposes a compositional approach that draws on the biological phenomenon of Min waves, reaction-diffusion waves, generated within artificial cells. When cells divide, they initiate cell division through ripple-like patterns called "Min waves". In the field of artificial cell engineering, researchers have successfully generated these waves within artificially constructed cells (artificial cells). Although cell division within artificial cells has not yet been achieved, the Min waves observed in artificial cells exhibit diverse behaviors under various conditions. In this study, we synthesize artificial cells that generate Min waves according to predefined chemical compositions, detect their dynamics, and explore how to integrate them into the structure and progression of artistic works. This study successfully developed a system for detecting the dynamic movements of Min waves generated in artificial cells through image analysis, allowing for the composition of a light-and-sound installation that directly integrates a quasi-lifeform into musical expression. Composers can construct the temporal and spatial development of light and music by modifying the synthesis conditions of the artificial cells, and intentionally design their



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dynamics. This compositional method utilizes the characteristics of Min waves generated in artificial cells to integrate the design of biological dynamics into the compositional process.

Keywords

Composition, Synthetic Biology, Artificial Cell, Min Wave, Sound Installation

1 Introduction

In contemporary science and technology, the question "What is life?" is being explored through attempts to reconstruct the structure and functions of cells, the fundamental units of life, particularly in the fields of molecular biology and synthetic biology. Kohyama et al. (2019) replicated the protein reaction-diffusion waves known as "Min waves" within artificial cells, creating phenomena observed in living cells from non-living materials [3]. This research represents a significant step toward elucidating the principles of order formation and self-organization in biological activities, bringing us closer to understanding the essence of life.

Min waves exhibit nonlinear behavior, making their dynamics unpredictable. Even under identical experimental conditions, Min waves generated in artificial cells display varied, nonlinear behaviors in each individual cell [13, 14]. This characteristic remains even when using specialized techniques designed to control Min wave properties linearly [14]. The coexistence of order and chaos in Min wave dynamics inspired the idea of using these properties as a basis for algorithmic music composition.

To explore this, we developed a system to track Min waves in artificial cells, enabling real-time acquisition of coordinate data from observational footage. Their oscillatory movements are used as oscillators for musical expression, allowing composers to synthesize artificial cells and adjust outputs accordingly. This compositional method is recursive and versatile, enabling interaction with artificial cells through feedback and modification.

As a case study, we experimented with altering acoustic spaces based on Min wave dynamics in artificial cells. Specifically, we created a system that treats Min wave movements as oscillators, enabling them to modulate spatial localization of sounds emitted from speakers arranged in a circular formation. This approach enables a compositional practice grounded in the real-world behavior of Min waves generated in artificial cells.

Through this study, we have developed a compositional algorithm that leverages the coexistence of order and chaos inherent in Min waves generated in artificial cells, contributing a perspective on how self-organizing biological dynamics can be integrated into musical composition.

2 Background

In electronic music, numerous attempts have been made to integrate natural phenomena and algorithms into the composition process. With the advancement of computer technology, innovations have emerged in the structure and generation of music, leading to research that applies randomness, probabilistic processes, and self-organizing phenomena to sonic expression [4, 8]. Within this history, efforts to incorporate biological activity occupy a significant position, and prior work can be organised along a spectrum that reflects how far upstream the composer intervenes in the biological system.

At the most downstream end, the composer maps signals generated by existing organisms into sound. Alvin Lucier's Music for Solo Performer (1965) pioneered this approach by converting a performer's EEG signals into sound in real time [11]. In a similar spirit, Miranda, Adamatzky, and Jones rendered the electrical activity of Physarum polycephalum into sound by coupling electrodes on a Petri dish to a bank of sinusoidal oscillators, treating the slime mould as a spatio-temporal sound source [5]. More recently, Ogawa, Nakahori, and Sareen presented Micro Orchestrism, an audiovisual installation in which fermenting sake yeast generate real-time soundscapes through the detection of microbial respiration bubbles [7]. In works of this kind, the composer designs the mapping between biological signal and sound but accepts the organism's intrinsic dynamics as given.

Further upstream, some approaches route musical signals through biological substrates used as unconventional computational media. Venkatesh, Braund, and Miranda, for instance, harness Physarum polycephalum as memristors to process MIDI data for popular music, with the composer controlling electrical parameters such as dwell time and measurement offset, and selecting which musical parameters are routed through memristors or linear resistors [15]. Here the composer designs the signal-processing framework around the organism, though the memristive behaviour of the organism itself remains a given property of the biological substrate.

Still further upstream, works such as Ben-Ary et al.'s cellF cultivate biological material specifically for musical purposes [6]. cellF employs a neural network derived from the artist's own skin cells via induced pluripotent stem cell technology, grown on a multi-electrode array to control an analogue synthesiser. In this case, the composer intervenes at the level of growing the biological substrate for the work, yet the intrinsic firing dynamics of the neural network, once cultured, are accepted as given.

The present study extends this spectrum by intervening at the earliest stage: the composer designs the biological dynamics themselves by engineering the synthesis conditions of artificial cells. In this sense, synthesis conditions operate as an upstream compositional parameter space, preceding the stages at which composers conventionally intervene (mapping, processing, and cultivation), as foregrounded by prior work.

This study focuses on the reaction-diffusion wave "Min wave," the symbolic processes of order formation and self-organization in biological phenomena, generating them within artificial cells and utilizing them for musical composition. Although Min wave behavior can be linearly adjusted to some extent through synthesis conditions, reaction–diffusion dynamics produce nonlinear, unpredictable fluctuations. This distinguishes our approach from simulation-based algorithmic music. Takada et al. (2022) report the Min wave period as [14]:

$$T = -52x + 95$$

Here, T represents the period of the Min wave (in seconds), and x denotes the ratio of dATP to the total concentration of ATP and dATP ($0 \leqq x \leqq 1$), which are energy molecules necessary for Min wave generation in artificial cells. However, the period of Min waves observed in actual synthesized artificial cells does not perfectly match the values predicted by this equation, exhibiting unpredictable fluctuations. Incorporating such a system with nonlinear dynamics

into music generation allows for a compositional method in which predictability and unpredictability coexist.

Through the use of artificial cells with physical substance, this research works with a biological system whose behaviour is shaped by synthesis conditions yet remains nonlinear and only partially predictable — a combination not obtainable from computer simulation alone. Synthesis conditions set the statistical tendencies of Min wave dynamics (such as wave mode and period), while the moment-to-moment behaviour of each individual cell fluctuates in ways that cannot be fully pre-specified. The compositional act, in this setting, is not to eliminate this fluctuation but to design the regime in which it occurs, and to translate the resulting Min wave dynamics into acoustic and visual representations.

3 Artificial Cells and Min Wave

3.1 Artificial Cells

Artificial cells are a general term for artificial objects imitating the structure of living cells. In biology, artificial cells indicate cell-sized spaces covered with membrane-like structures which encapsulate biological molecules such as proteins and DNA. Because artificial cells can reproduce biological phenomena in cell-size spaces, they are gaining traction as an experimental tool for precisely analyzing the dynamics of molecular reactions within cells.

Artificial cells have the following characteristics:

- Micrometer-sized closed space: This characteristic is beneficial to investigate the molecular placement mechanism within cell-size spaces and analyze how cell-size space affects biochemical reactions.
- Controllability of experimental conditions: It is possible to precisely adjust experimental conditions such as elements composition, temperature, and energy supply.

Owing to these characteristics, artificial cells have been widely used to study biological systems [10]. By utilizing artificial cell systems, researchers can reproduce and analyze molecular behaviors under controlled experimental conditions, enabling detailed investigations into self-organization dynamics.

3.2 Min System and Min Wave

In cells, self-organization of molecules regulate various biological phenomena. Especially, reaction-diffusion wave generated by coupling of biochemical reactions and molecular diffusions serves a key role in the regulation. Min system, which determines the cell division plane of bacteria, is a well-known reaction-diffusion wave.

The Min system consists of three proteins (MinC, MinD, and MinE) and form a reaction-diffusion wave (Min wave) where the high concentration regions of Min proteins change spatiotemporally [9]. Min waves belong to dissipative structures and maintain their patterns by utilizing energy molecules like ATP.

Min wave is generated by following reaction cycles:

1. Membrane binding of MinD by ATP-dependent manner: MinD in the cytosol binds to the membrane after forming the dimer structure by binding to an energy molecule ATP. MinD on membrane recruits another MinD dimer, which forms a high-concentration region of MinD.
2. ATP hydrolyzation by MinDE: MinE binds to MinD on the membrane and induces the activity of ATP hydrolyzation of MinD, which causes the dissociation of MinD from the membrane.
3. Molecular diffusion of MinD into the cytosol and repetition of the reactions: After dissociating from the membrane, MinD binds to ATP in the cytosol and binds to the membrane again.

These reactions are coupled with the differences in diffusion rates of molecules in the cytosol and on the membrane, resulting in the generation of reaction-diffusion waves oscillating between cell poles. MinC, a cell division inhibitor, co-localizes with ATP-bound MinD, and oscillation of the Min wave makes MinC concentration gradient with the minima at mid-cell. Consequently, cell division initiates only at the center position of cells.

Researchers have successfully reconstituted Min waves in artificial cells, making them the only biological reaction-diffusion system reconstituted in artificial cells using defined factors. By using the artificial cell system, it has been revealed that Min waves behaviors in terms of their dynamic modes and velocity can be controlled by experimental conditions [2, 3, 13, 14]. For example, not only the oscillation of Min waves but also traveling waves and the pulsing mode appear in artificial cells (see Figure 2), and the differences in the generation conditions of each mode have been revealed. Characteristics of each wave mode are described as follows.

- Oscillation: Most of Min waves in living cells show this mode. Although it also appears in artificial cells, the conditions for its generation are limited compared to living cells. It is generated by repeating the formation of MinD domain on the membrane at one cell pole, membrane dissociation of MinD induced by MinE binding to the surrounding of the MinD domain, and the domain formation of MinD at another cell pole. This mode determines the cell division plane by inhibiting cell division at cell poles.
- Traveling wave: It propagates on the membrane continuously and appears mainly in artificial cells while it appears in living cells under only limited conditions. It cannot determine the cell division plane because the time-averaged concentration of MinC becomes homogeneously and MinC inhibits cell division throughout the cell. It is generated by MinD dissociating from only one side of its high-concentration region and rebinding on the MinD region. Due to the difference in the relative position of MinE to the high-concentration region of MinD between the oscillation and the traveling wave, the two wave modes are regulated by the balance of MinD and MinE. Although this mode is not physiologically important in bacteria, this mode has a role in various physiological events in the case of other reaction-diffusion waves in eukaryotes.
- Pulsing: It is a state in which MinD oscillates between the homogenous localization in the cytosol and on the membrane. Unlike the oscillation and the traveling wave, it has no spatial asymmetry. It appears mainly in the early stage of Min wave generation and transits to the oscillation

and the traveling wave. It seems that this mode shows no apparent physiological role.

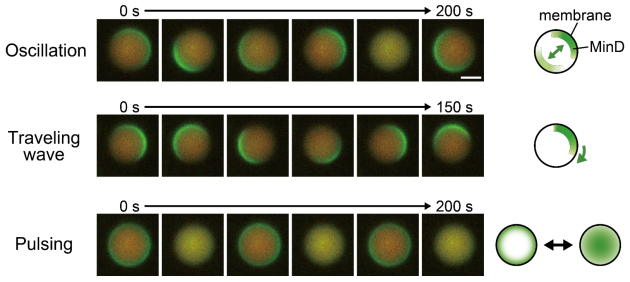

Figure 2: Various dynamics of Min waves reconstituted in artificial cells. Time-lapse images of sfGFP-MinD (green) and MinE-mCherry (red) in artificial cells encapsulating these Min proteins, ATP, and BSA (left). Schematic images of three types of dynamics of Min proteins are shown (right). Scale bar: 5 μm.

In addition to being useful for verifying the principles of wave formation, artificial cells exhibit a variety of behaviors of Min waves not observed in living cells. We explore how the dynamic behaviors of Min waves under these conditions can provide musical perspectives through practical implementation.

3.3 How to generate protein reaction diffusion waves (Min waves) in artificial cells

To express Min waves by music, Min waves generated in artificial cells by the protocol developed in previous studies [1, 3, 12] were used. Artificial cells used in this project consisted of a reaction solution containing biomolecules and lipid membranes that cover the micro-size droplets of the reaction solution. They were prepared by dispersing reaction solutions containing biomolecules (MinC, MinD, MinE, and ATP) into the mineral oil containing polar lipids of bacteria. First, 10 μL of the reaction solution containing 0.2 μM msfGFP-MinC, 1 μM MinD, 0.7 μM MinE, 2.5 mM ATP, and 100 mg/mL bovine serum albumin (BSA), 10 mM creatine phosphate, and 4 ng/μL creatine kinase was prepared in reaction buffer containing GluK and GluMg. The roles of each molecule are as follows.

- MinD and MinE: Proteins required for the generation of Min waves.
- msfGFP-MinC: A fusion protein of msfGFP (a monomeric green fluorescent protein) with MinC, which co-localizes with Min waves. It enables the observation of Min waves by detecting fluorescent signals.
- ATP/dATP: An energy source for the generation of Min waves.
- BSA: A crowding agent used to mimic the molecular crowding environment in living cells.
- Creatine phosphate and creatine kinase: ATP regeneration system used for preventing depletion of ATP.

After the preparation of the reaction solution, 1 μL of the portion was added to the 50 μL of lipid oil containing E.coli polar lipid extract in a 0.6 mL tube. At this time, a single droplet with a several millimeters in diameter is formed in the lipid oil. To create artificial cells with a diameter of about 20 μm, the droplet of the reaction solution was dispersed by tapping the tube 15 times. This number of tapping is the optimum number for creating artificial cells with 20 μm in diameter, and larger artificial cells can be created by decreasing the number of tapping. Because lipid molecules have both hydrophobic and hydrophilic regions and assemble by weak molecular interactions, lipid membranes are formed spontaneously at the interface between the droplet and the oil, forming artificial cells. Although the oscillation of the Min wave appears in living cells, traveling waves appear mainly in artificial cells under the above condition of Min protein concentrations. This condition was selected because the velocity of traveling waves can be controlled by energy sources [14]. In this study, it was found that the velocity of the Min wave increased about twice by changing the energy source, ATP, to its analogue, deoxy ATP (dATP), because dATP-bound MinD binds to the membrane more weakly than ATP-bound MinD. To generate Min waves with different velocity for the conversion to various types of sounds, ATP in the reaction mixture was replaced to dATP, or mixture of ATP and dATP. In this case, artificial cells were created in the same manner as described above.

At the early stage of Min wave generation, the Min wave shows the transition of dynamic modes in the order of pulsing, oscillation, and traveling wave as mentioned in 3.2 [3]. In the case of using msfGFP-MinC, MinD, and MinE, however, it is difficult to observe this state transition because the transition ends quickly. To express the state transition of self-organized patterns of Min proteins by music, we used 1 μM sfGFP-MinD and 1 μM MinE-mCherry as Min proteins. These Min proteins are fusion proteins of fluorescent proteins (sfGFP or mCherry) and Min proteins (MinD or MinE). Because their diffusion speeds are slower than unfused Min proteins due to larger molecular weights, the changes of wave behaviors become more slowly, enabling the observation of the state transition. Therefore, when we focused on the transition of wave modes, we created artificial cells using fluorescent protein-fused MinDE.

While a single domain of MinD (a single wave) is formed in living cells and artificial cells with 20 μm in diameter, multiple high-concentration regions of MinD are formed in larger artificial cells. These multiple Min waves exhibit more complicated behaviors than single waves. Larger artificial cells were created by decreasing the number of times of tapping to form artificial cells. We used behaviors of multiple waves for the expression of the complexity of organisms by music.

3.4 Observation of Artificial Cell

The movement of the Min wave can be visualized by fluorescence microscopy of GFP fluorescence fused to the Min protein. Min waves generated in artificial cells were observed by detecting fluorescent signals of msfGFP and mCherry fused to Min proteins using a fluorescent microscope. Coverslip chambers for the observation of artificial cells were made by attaching two cover glasses (25 mm × 36 mm and 18 mm × 18 mm) with two strips of double-sided tapes (about 1 mm × 20 mm) as a spacer. 20–30 μL of artificial cells was gently injected into the slit between two cover glasses. Behaviors of Min proteins in artificial cells were observed by the fluorescent microscope, and time-lapse images were captured with 5–20 s intervals. Because the number of waves changes depending on the artificial cell sizes, the size of artificial cells for the observation was selected to be either smaller than or larger than 25 μm depending on whether single waves or multiple waves were observed.

4 Project Description

This system tracks the movement of Min waves occurring within artificial cells and reconstructs their behavior through sound and light based on the acquired data. This section provides explanations of each component.

We created a procedure to process the observational video of artificial cells to track the movement of Min waves generated within them. Six speakers and twelve light bulbs are arranged in a circle, and their volume and brightness are adjusted in real-time to correspond with the position of the Min wave. By synchronizing the position of sound and light with the movement of the wave, the installation creates dynamic changes in the space.

This circular configuration was chosen in order to effectively convey the dynamics of Min waves observed inside artificial cells. In the microscopic observation video presented to visitors, artificial cells appear as circular forms, and the dynamics of Min waves are observed as spatial patterns unfolding within these circular frames. To translate such observed spatial dynamics into a spatial audiovisual experience, speakers and lights were arranged on a circle surrounding the central display, chosen as the minimum configuration that realises this circular arrangement. Visitors enter the space by passing between the stands holding the speakers and lights, and observe the artificial cells on the central display from within the circle. Through this configuration, visitors experience the Min wave dynamics as if they themselves had entered the interior of an artificial cell.

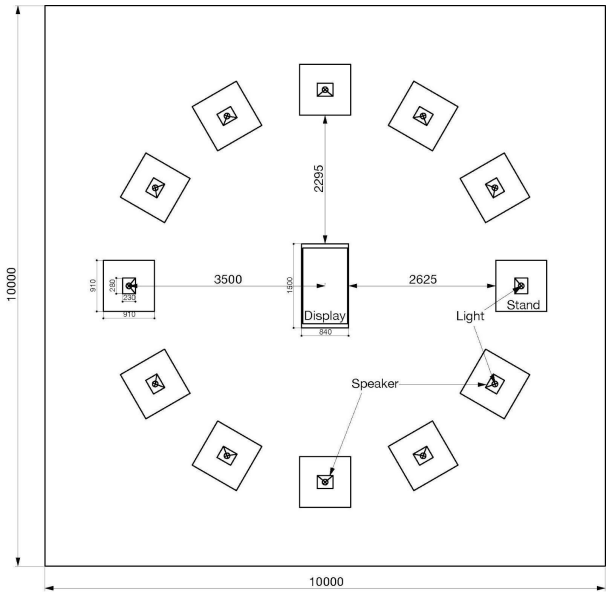

Figure 3: Layout diagram 1 (All distances are in mm).

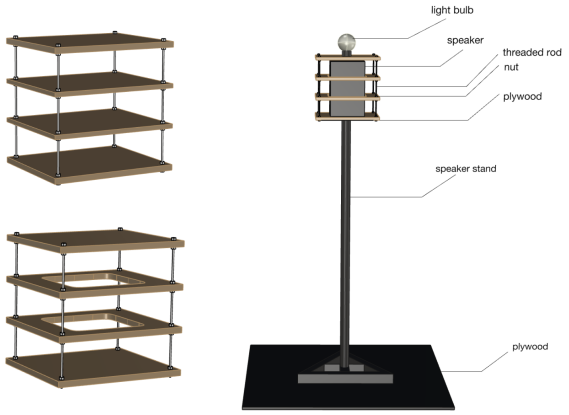

Figure 4: Speaker Stand / Enclosure
This enclosure protects the speaker and light bulb from damage without adversely affecting the sound emitted by the speaker. To ensure safety, the bottom of the stand was secured to plywood to prevent it from falling over.

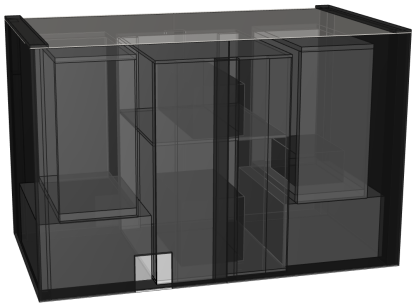

Figure 5: Display Enclosure / Machine Box
An LCD (with protective acrylic cover) is placed on top and serves as a display surface. The enclosure contains a laptop computer, a dimmer pack, and a Multi-Channel Audio Interface in its interior.

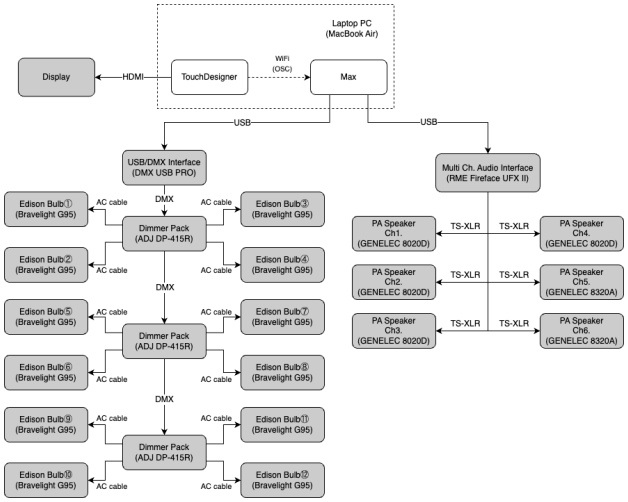

Figure 6: System diagram 1

4.1 Algorithm

The tracking of the Min waves uses microscopic observational videos and adopts a method that combines TouchDesigner and OpenCV.
The system is built on the technology to accurately capture the movement of Min waves within artificial cells and extract their position data as coordinate information. During the video processing, the image is inverted to black and white using TouchDesigner, and the behavior of the Min waves is extracted from the difference in brightness within the artificial cell. The extracted Min wave video is then analyzed in real-time using OpenCV, and the coordinates of the Min wave in the video are quantified in two dimensions (X and Y). These coordinate data are transmitted to Max via the OSC (Open Sound Control) protocol, where they are used for sound and light outputs.
In the acoustic algorithm, the obtained coordinate data is used to control the output of six speakers arranged in a circle, reconstructing the movement of the Min waves as sound using Max. Similarly, in the lighting algorithm, twelve light bulbs are arranged in a circle, and the brightness of each bulb is controlled based on the coordinate data.

4.1.1 *Preparation of artificial cells*

The general protocol for the preparation of artificial cells is the same as the Min wave generation described in Section 3.3.
To observe Min waves with different periods, artificial cells were synthesized under three conditions with varying ATP and dATP mixing ratios:

- Condition 1: ATP : dATP = 0 : 100
- Condition 2: ATP : dATP = 50 : 50
- Condition 3: ATP : dATP = 100 : 0

Oscillation and traveling waves were captured using a fluorescent microscope at 5-second intervals, and the footage was converted into videos (avi files) at 10 fps. This method was adopted to obtain the smoothest possible Min wave footage.

4.1.2 *Tracking system of Min waves*

As a pre-processing step for tracking, TouchDesigner is used to extract the movement of Min waves from the observation video of the artificial cells. The specific method involves converting the footage to grayscale, adjusting the brightness to emphasize the Min wave regions, and using the difference in brightness to isolate only the Min waves (see Figure 7.1).
Next, the monochrome video of the Min waves obtained from the steps above is then tracked in real-time using the Blob Track TOP model, which uses OpenCV within TouchDesigner. By quantifying the coordinate data on the screen, the dynamics of the Min waves are detected. Specifically, the difference of pixels between monochrome video and background are detected, and the detected areas are enclosed in rectangles (see Figure 7.2, 7.3). The center of mass of the X and Y coordinates of these rectangles are then calculated and output as the Min wave coordinates (see Figure 7.4). The Min wave coordinate data obtained from the video was scaled to a range of -1 to 1 and sent to Max via OSC. This enables the real-time tracking and quantification of the Min wave movement in the observation video, allowing the dynamics of the Min waves to be utilized for music generation.

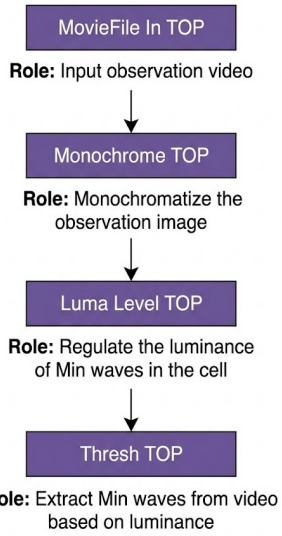

Figure 7.1: Preparation for Min wave tracking.

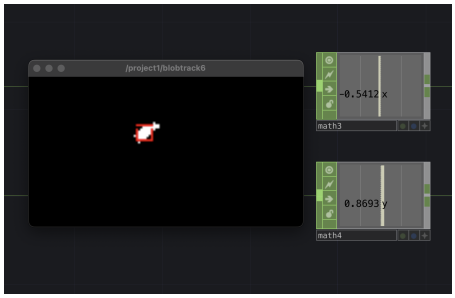

Figure 7.2: Min wave tracking in BlobTrack (Traveling wave).

Figure 7.3: Min wave tracking in BlobTrack (Oscillation).

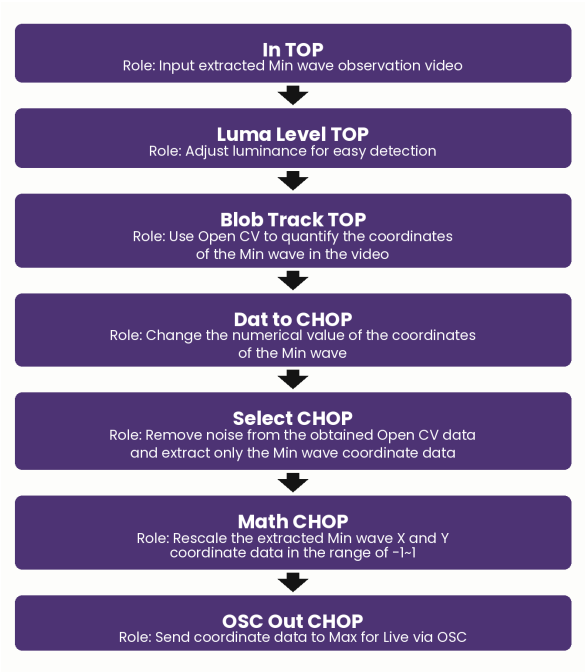

Figure 7.4: Min wave tracking process.

4.1.3 *Multi-speaker algorithm*

The six speakers are placed at six equally spaced positions along the circumference of a circle with a radius of 3.5 meters from the central display. The diagram on the bottom depicts only the speakers from a top-down view. The center coordinates were defined as (X, Y) = (0, 0), and the coordinates of the speakers were defined within the range of +1 and -1.

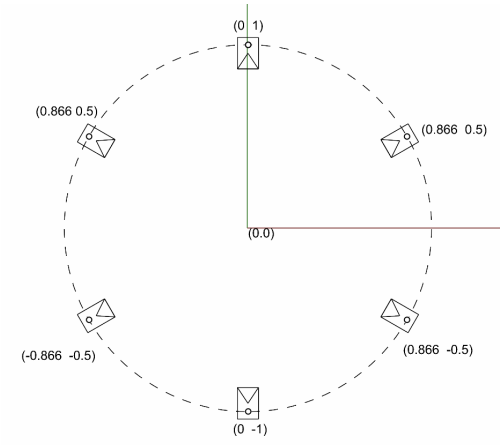

Figure 8: Speaker layout diagram

Then, using TouchDesigner, the arctangent function is applied to the Min wave's XY coordinate data to calculate the angle θ between the line segment connecting the origin and the Min wave coordinates and the line y = 0 (see Figure 9). The volume of each speaker is set to increase as the angle θ approaches the position of each speaker.
This enabled the Min wave movement in artificial cells to be reconstructed through the audio output from speakers arranged along the circumference.

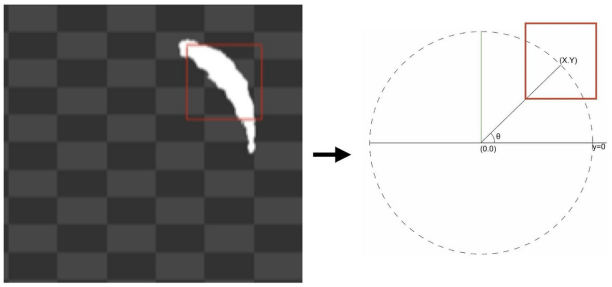

Figure 9: Angle detection schematic diagram

4.1.4 *Lighting Algorithm*

Light bulbs were chosen over LED light sources for their capacity to softly illuminate entire surfaces and the surrounding space. The physical emission from a heated filament produces a warmer and more diffuse quality of light than point-source LEDs, creating an ambient luminous field that resonates with the self-organising, fluctuating character of the Min wave dynamics being represented.
The twelve light bulbs are placed at twelve equally spaced positions along the circumference of a circle with a radius of 3.5 meters from the central display (see Figure 10). The diagram on the bottom shows only the light bulbs, depicted from a top-down view. The center coordinates were defined as (X, Y) = (0, 0), and the coordinates of the light bulbs were set within the range of +1 and -1.

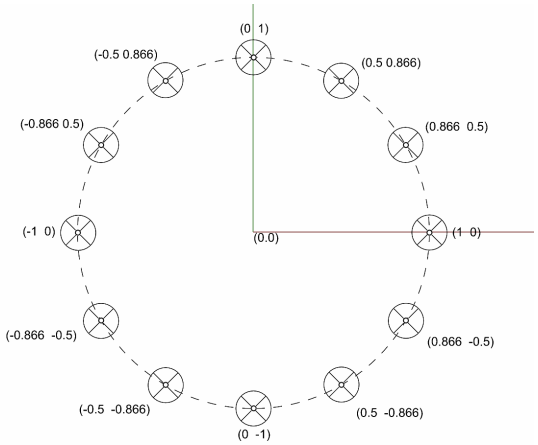

Figure 10: Lighting layout diagram

4.2 Previous exhibition

This study was exhibited at the "ZOU-NO-HANA FUTURESCAPE PROJECT 2024" held from December 6 to December 8, 2024, at the Zounohana Terrace in Minato Mirai, Yokohama. Since this exhibition was held in an urban venue open to the city, we provided an interactive musical experience designed around a fusion of observation and experience. The composition of the installation consisted of a stereomicroscope and display placed at the center, surrounded by two concentric rings of surround speakers and light bulbs (see Figure 11). Visitors could choose one of three Petri dishes containing artificial cells, place it in the microscope enclosure (see Figure 13), and trigger a dynamic interaction of music, light, and visuals. Each Petri dish was assigned a unique sequence, allowing visitors to experience different sensory journeys with each artificial cell.

This design ensured that the surround sound and lighting movements were closely synchronized, enabling visitors to experience the rhythm and flow of self-organization within the artificial cells both visually and acoustically throughout the entire space.

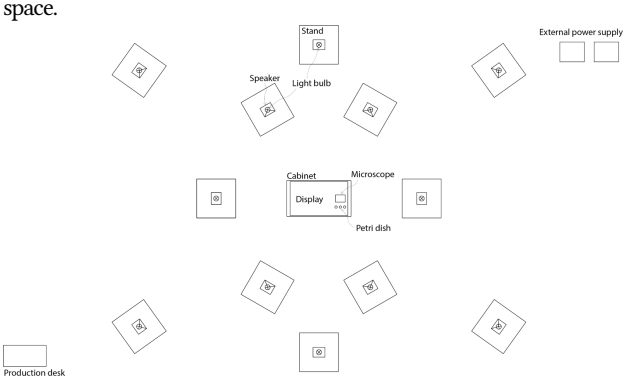

Figure 11: Layout diagram 2

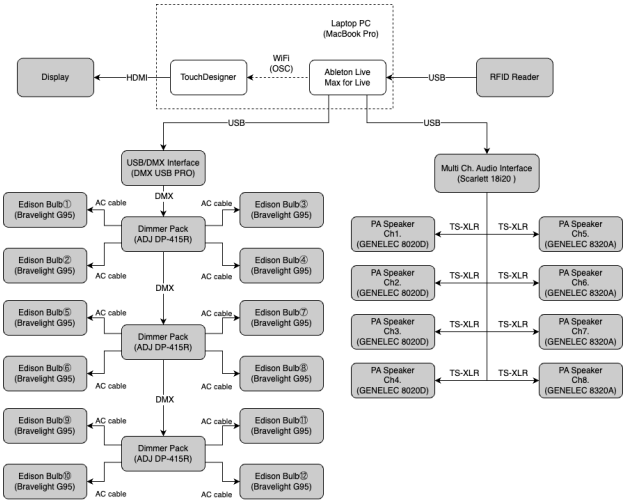

Figure 12: System diagram 2

4.2.1 Preparation of artificial cells

General protocol for the preparation of artificial cells was the same as Min wave generation in Section 3.3. The inner solutions of artificial cells were replaced with msfGFP, mCherry, or its mixture in a 20 mM HEPES-KOH buffer. For outdoor observation, artificial cells in oil solution were directly dispensed on cover glasses for microscopy.

4.2.2 System

The process of the detection system is as follows.

First, an RFID tag with a unique UID is attached to the side of each Petri dish. When the Petri dish is placed into the microscope enclosure (see Figure 13), the built-in RFID reader reads the tag's UID information and transmits it via serial communication to Max for Live(M4L). The system that detects these three Petri dishes is integrated within the microscope enclosure. The microscope enclosure is designed with a pull-out stage for placing the Petri dish, which, upon being closed, creates a dark environment within the microscope enclosure to facilitate better observation of the artificial cells in the outdoor exhibition space. M4L analyzes the received UID information and determines the corresponding sequence (sound, light, and visuals).

Then, the playback position of the corresponding sequence is adjusted according to the starting position of sequences A, B, and C which are pre-programmed in Ableton's arrangement view, where the respective sequence begins. The audio is output to the speakers through a Multi-Channel Audio Interface from M4L, creating an 8-channel surround sound experience. The lighting is controlled by sending signals to the light bulbs via a USB/DMX Interface, generating lighting effects in response to the movements in the Min waves. The visuals are generated in TouchDesigner and output to the display located in the center, providing visual feedback. The light and sound were designed to move in sync with the video projected on the central display.

In this system, three sequences (Sequence A, B, C) and four scenes (see Figure 14, 15, 16) have been designed to allow the viewer to intuitively experience different behaviors of the Min waves. Placing a Petri dish into the microscope enclosure triggers the synchronized interaction of sound, light, and visuals, representing the state transitions of the artificial cells.

In M4L, a custom device for controlling the light bulbs is used, allowing for automation to control 12 channels within Ableton. Additionally, M4L ensures that the playback position in the Ableton arrangement view changes in sync with the detection of the Petri dish. Across all three sequences, distinct timbral characters were assigned to the three Min wave modes (pulsing, oscillation, and traveling wave) in order to render the differences between modes audibly legible. The pulsing mode was given timbres that emphasise unity and convergence, reflecting its non-directional, whole-cell behaviour. The oscillation mode was assigned timbres with the widest dynamic range, foregrounding the perceived movement between the cell poles. The traveling wave was rendered through sustained, continuous timbres, mirroring its uninterrupted circulation along the membrane. While these timbral principles are shared across all sequences, the specific sounds used for each mode differ from sequence to sequence, so that visitors encounter different sonic realisations of the same Min wave behaviour as they move through Sequences A, B, and C.

Figure 13: Microscope enclosure

Sequence A

To convey the dynamics of the Min waves in the artificial cells, the artificial cell in the observation video was colored green and the Min waves were colored white to visually highlight their movement. The video was projected in the sequence of Pulsing → Oscillation → Traveling wave, to effectively communicate the progression of the

Min wave transitions. Furthermore, the video of the "Propeller type[1]" was projected, aiming to express the dynamic movements within the artificial cell. Sequence A was designed to be straightforward and easy to follow, with clear scene transitions. Sonically, Sequence A was kept as the most neutral of the three, foregrounding the educational presentation of the mode transitions.

Seqence A	Scene1(40s)	Scene2(28s)	Scene3(44s)	Scene4(40s)
Multispeaker mapping	Pulsing	Oscilation	Traveling wave	Propeller type
Lighting	Pulsing	Oscilation	Traveling wave	Propeller type
Visual				

Figure 14: Sequence A

Sequence B

To express the transient, lifelike fragility of the Min waves and the ethereal nature of the waves inside the artificial cell, the artificial cell in the observation video was colorized in red, evoking the impression of delicate scattering sparks. The playback speed of the observational video was slowed to emphasize the graceful beauty of the wave dynamics. In the phase following the Min wave transitions, the observation video of the "Island type[2]" Min wave was projected. Sequence B was designed to have a mystical quality, ensuring smooth transitions between scenes. Sonically, Sequence B was designed to bring out the fragile beauty of the Island-type Min wave most prominently.

Seqence B	Scene1(68s)	Scene2(48s)	Scene3(48s)	Scene4(42s)
Multispeaker mapping	Pulsing	Oscillation	Traveling wave	Island type
Lighting	Pulsing	Oscillation	Traveling wave	Island type
Visual				

Figure 15: Sequence B

Sequence C

To emphasize the dynamics and strength of the Min waves inside the cell, the artificial cell in the observation video was colorized in orange, symbolizing the transmission of energy. In the phase following the Min wave transition, the playback speed gradually increased towards the end to visually convey to the viewer the heightened sense of vitality. Sequence C was designed to be rhythmic, with clear transitions between scenes. Sonically, Sequence C engages the full range of Min wave dynamics to produce the most dynamic of the three sequences.

Seqence C	Scene1(40s)	Scene2(40s)	Scene3(48s)	Scene4(42s)
Multispeaker mapping	Pulsing	Oscillation	Traveling wave	All
Lighting	Pulsing	Oscillation	Traveling wave	All
Visual				

Figure 16: Sequence C

5 Discussion

A possible application of the method introduced in this study could involve directly reflecting the characteristic dynamics of Min waves in the sound output itself. By treating the periodic movement of Min waves in artificial cells as audible waveforms, their dynamics can be incorporated into sound synthesis. For example, Min waves could function as oscillators in synthesizers. Whereas conventional synthesizers rely on sine, sawtooth, or triangle waves generated by electronic circuits or digital computation, Min-wave oscillators enable linear control while introducing nonlinear and chaotic fluctuations, producing unique and complex waveforms. The dynamics of artificial cells thus suggest further directions for synthesizer design from both functional and engineering viewpoints. Moreover, artificial cells themselves, as explored in molecular robotics, can be designed and controlled as functional systems. As synthetic biology advances and Min wave dynamics become more complex and flexible, new possibilities for their use as compositional methods may emerge. This application of scientific systems to artistic practice suggests further directions for integrating biological and bio-inspired dynamic systems into musical interfaces.

Beyond the specific case of Min waves, the approach taken in this study can be described in more general terms. Compositions that work with biological dynamic systems involve decisions at several distinct levels: how the organism's activity is mapped to sound, how a processing framework is arranged around that activity, and, in some cases, how the biological substrate is cultivated in the first place. The approach taken here adds a further stage upstream of these: the design of the synthesis conditions from which the biological dynamics themselves emerge. Synthesis conditions, in this sense, function as an upstream compositional parameter space — a point at which the composer can intervene to shape what the downstream stages of mapping, processing, and cultivation will work with.

Framing compositional decisions in this way suggests several directions that follow from this framing. First, similar upstream interventions can in principle be explored with other reaction-diffusion systems, or with dynamic systems outside biology whose behaviour can be tuned through their generative conditions. Second, the coexistence of controllable statistical tendencies and the fluctuation that varies from cell to cell and moment to moment — evident here in the relationship between synthesis conditions and individual cell behaviour — can itself be treated as a compositional resource, rather than as noise to be eliminated or regularity to be

[1] When multiple Min waves are generated within a single artificial cell, those that exhibit behavior resembling a propeller are referred to as propeller-type.

[2] When multiple Min waves are generated within a single artificial cell, those that form large domains and move slowly with fluctuations are called island-type.

enforced. Third, when the composer intervenes at the level of the conditions that generate the dynamics, what is being composed is not only a particular musical outcome but the range of outcomes that such conditions can give rise to. The present work offers one concrete realisation of this approach, and the extent to which the framework can be transferred to other biological or bio-inspired dynamic systems remains an open direction for further work.

6 Conclusion

This study proposes a compositional method that leverages the dynamic characteristics of Min waves generated in artificial cells. The system reflects both controllability based on scientific analysis and the chaotic behavior inherent in reaction–diffusion waves in acoustic expression. We developed a system that tracks Min wave coordinates from observation video and uses them as oscillators for musical composition. By synthesizing artificial cells in the physical world, nonlinear movements influenced by environmental factors, unattainable through mathematical models or existing datasets, can be directly reflected in music.

A limitation of the present system is that sound and light generation are based on tracking data from pre-recorded observational videos, rather than on live microscopic observation of artificial cells. As a result, the system does not yet offer immediate real-time responsiveness. Future work aims to capture Min waves in real time via microscopy, enabling immediate sonification and greater compositional flexibility.

A second limitation concerns reproducibility. Preparing artificial cells that generate Min waves requires specialised biological protocols and laboratory equipment such as a fluorescent microscope and purified proteins. This dependence on specialised infrastructure presents a barrier to reproducibility for artists and researchers outside a biological laboratory context. Addressing this — for instance, through simpler preparation protocols, or by making observation videos publicly available for others to work with — remains an important direction for making this compositional approach more broadly accessible.

Beyond the limitations above, another direction for future work concerns the complexity of the waveforms themselves. While the present system tracks Min waves in individual artificial cells, simultaneously tracking multiple waves across several cells could enable compositional use of the more complex composite waveforms that emerge from the interactions between waves. This would extend the compositional parameter space from single-cell dynamics to the interaction dynamics between multiple artificial cells.

In conclusion, this study integrates the self-organizing phenomenon of Min waves occurring in microscopic space into a compositional algorithm and demonstrates how artificial cell dynamics can be used in music. Designing and manipulating biological phenomena as part of artistic creation contributes a framework that may inform further explorations at the intersection of art and science.

Ethical Standards

Fujiwara and Takada et al. of the Laboratory of Biomolecular Engineering at the Department of Biosciences and Informatics at Keio University, obtained ethical permission for the content of the research, including the preparation of experimental samples, and used artificial cells in accordance with relevant laws and regulations in Japan. We ensure that all procedures, including genetic modifications and the processing of experimental samples, fully comply with Japanese legal and ethical standards throughout the research process. This includes measures such as attaching polarizing film to the objective lens to suppress UV light during microscopic observation. Additionally, we have taken thorough measures to ensure the safety of visitors during the exhibition.

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A Appendix One

A.1 Archive Videos

Supplementary videos illustrating the performance and installation can be accessed via the following links:

- Archive video from the exhibition at Keio University SFC
  https://youtu.be/14zsY3kNjEE:
- Archive video from at the "ZOU-NO-HANA FUTURESCAPE PROJECT 2024"
  https://youtu.be/wo3pJzybBwc:

A.2 Sound Data

- Orbis Sound Data
  https://on.soundcloud.com/eFhcgYf6NuYvyyNu6