A PRIORI ATTUNEMENT FOR TWO CASES OF DYNAMICAL SYSTEMS

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ABSTRACT

An application of a tuning function adopts a space metaphor in scientific methods for representing state space of non-linear dynamical systems. To achieve an interactive exploration of the systems through sounds, *attunement* is defined as *an a priori process for conditioning a playable space for an auditory display*. To demonstrate this process, two cases of dynamical systems are presented. The first case employs Chua's circuit, in which system parameters are defined as energy introduction to the system and energy governance within the system. The second case employs a swarm simulation, defined as a set of rules to dictate social agents' behaviors. Both cases exhibit complex dynamics and emergent properties. The paper synthesizes a comparative review of auditory display for the two cases while defining playable space with generalizable tuning functions. The scope of the discussion focuses on the relationship between playable space as a canonical architecture for auditory display workflow and its realization through attunement in applications of dynamical systems.

1. INTRODUCTION

When engaging a system or a data set, auditory display falls into two general categories: auditory display with sound source and auditory display with silent source. The former is an employment of a sound source into meaningful treatments in which perceived sound informs listeners about the state of a system. The techniques involve tuning and scaling the system's properties; the system's faculty to generate sound must be tuned so that the dynamical domain can be brought into perceivable ranges. The latter is an employment of a silent data set or system in a meaningful interface to an external system that is capable of producing sounds, by which resulting sound informs listeners about the structure of the data or the state of the system. These techniques involve interfacing two systems; the properties of silent data or system must be mapped to the properties of the system capable of producing sounds. This paper reflects two cases, one from each category, selected for their common ground, nonlinearity of dynamical systems. The first case is presented through a chaotic circuit; the second case is presented through a swarm simulation. Both systems exhibit self-organizing principles and emergent behaviors that are commonly observed as complex dynamics.

A dynamical system is iterative, comprised of a phase space that represents all possible states of the system and controls that afford ways of introducing changes to the system. A dynamical system is responsive to perturbations imparted to its controls or its phase space, and its output may exhibit emergent behavior.

The presented cases engage interactive explorations of the systems with auditory feedback. The differences of the two cases yield insights to architecting two different interactive systems by applying a common framework, which is a large part of the discussions in this paper. Both cases harness responsiveness and emergent properties of a dynamical system for making sounds, while the sounds' responsiveness and emergent features inform listeners about the system.

System modeling methods often adopt the concept of space as a working metaphor. For example, state space is a description of a system's input/output behaviors and a state space model is a description of how the state of a system evolves over time [1]. The plan for this paper is to present a framework for playable space (see section 2) and how it is surveyed and tuned, and present its application in two types of dynamical systems, one that natively produces sound and one that does not. The intent is to demonstrate that a well-tuned conception of a playable space is required for both types of systems, in order to enable auditory displays with respect to corresponding controls and phase space of each system. Subsequently, the examples will show that playable space is not an interface, but rather an enabling condition for the development of interfaces. The paper proposes that the concept of playable space may be formalized as a set of canonical relationships that enable the development of auditory interfaces for observing dynamical systems. This formalization, the *a proiri attunement*, is to acknowledge design criteria for auditory display in diverse dynamical systems, the criteria upholding the service to human cognition.

2. DEFINING PLAYABLE SPACE AND ITS ATTUNEMENT

How a system evolves in time depends on a model description of a dynamical system. The temporal evolution, which is a common characteristic of dynamical systems, is what makes them compatible to engage in making sounds. However, one should be reminded that time dependent data series from a dynamical system do not necessarily make sounds though they often suggest sounds to the imagination. To bring about audible sounds from the imaginary requires a *playable space*: *the canonical space made enactive by a system of references through which a listener explores the system and audits its responses*. The tuning of the playable space may unveil the expressive range of a singing quality of a system along with all other states of the system that an observer can induce by action while listening.

"Tuning" here refers to harmonious alignment of three numerically definable tuning functions: TF_1, TF_2, and TF_3. The alignment creates a feedback routing where the range (output value) of one tuning function is the domain (input value) of the next:

- TF_1 transforms a domain of a dynamical system states to a range of sounds
  - *Sound* is routed from TF_1 to TF_2
- TF_2 transforms a domain of sounds to a range of listeners actuations of changes
  - *Actuation* is routed from TF_2 to TF_3
- TF_3 transforms a domain of actuations to a range of dynamical system states
  - *System State* is routed from TF_3 to TF_1

This functional circularity forms canonical playable space, depicted in Figure 1. The feedback is harmonious when each TF_N output, the corresponding $TF_{N+1\ (modulo\ 3)}$ input share scale and boundary conditions as realized by the tuning functions. In effect attunement engages listeners through their series of actions as series of choices to resulting sounds, enlightening as to the behaviors of the dynamical system.

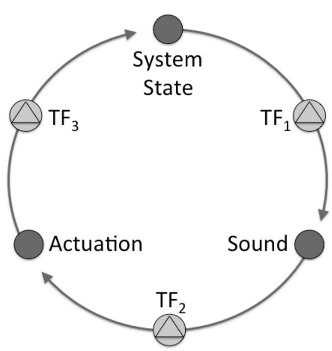

Figure 1: Canonical Playable Space comprised of three tuning functions (TF). At TF_2 an auditing agent acts upon the system. The agent may be a human listener or an autonomous listener.

Our working definition of attunement adopts the concept of space as metaphor. Attunement is a requirement *a priori* for observing complex dynamics through sounds, by conditioning spatial representation of interacting systems with tuning functions transcended from one space to another. In short, the attunement is an embodiment of the mapping in a data transfer from one process to another, when each mapping has an impact on the others. The first case example presented in section 4 employs the native sound generator, a chaotic oscillator. The second case example presented in section 5 employs the silent system, a swarm simulator. In both cases the process of realizing playable space creates conditions to support designs such as a playable interface or a procedural sound palette.

3. PRIOR WORK

Prior work for the first case: The application of the Chua oscillator to sound synthesis has been studied in [2, 3, 4, 5, 6]. In the application of continuous chaotic systems, two approaches are possible and may be considered complementary. One approach is to apply the chaotic system as one component of a simulation of physical instruments. In this approach nonlinearity in chaotic systems is used as a source for generating excitation patterns which are coupled to models of linear delay lines that describe tubes or strings of physical instruments. More recently, Bilotta et al. [7] applied Chua's circuit for making sounds by sending discrete values from x y z positional data from phase space to a discrete note generator. This approach introduces position data as an abstraction translated into sound, closer to the approach represented by the swarm simulation. The case presented here, detailed in [8] takes a different approach to apply the chaotic system as a signal generator and explore the circuit for its potential audio properties by varying the linear and nonlinear characteristics of the chaotic system itself.

Prior work for the second case: Flocking behavior and evolutionary algorithms are widely explored in areas of computer-generated graphics, having origins in Reynold's "flock of boids" [9]. Due to the efficiency of the algorithms, many applications were developed to support CG effects in commercial production including film special effects and computer game characters—notably Will Wright's *Spore* [10]. Examples in visual art include Sims [11], Sommerer and Mignonneau [12], and McCormack [13]. In [14] this author reported a table-size multiplayer application of a swarm simulation interface for sound.

4. THE CASE OF DYNAMICAL SYSTEM WITH SOUND SOURCE

This section reviews the chaotic oscillator called Chua's circuit in order to demonstrate the first case auditory display with sound source. As a sound source, Chua's circuit is an autonomous dynamical system that generates continuous signals. Chua's circuit is conceived as a paradigm to demonstrate a physical system that satisfies the working definition for chaotic systems [15, 16 17]. A dynamical system can be called a chaotic system when it displays several fundamental features unique to the presence of chaos. One of the most important features of chaotic system is characterized as a topological mixing mechanism, *stretching and folding*. In this mechanism, a unit interval is stretched apart repeatedly by exponential growth until it reaches the ergodic limit of the system; then the two initial points are folded back together. While the stretching operation tends to pull apart nearby orbits, the folding operation brings them back together within a bounded region of phase space but on a different plane. In addition to the mixing mechanism, stretching and folding, a chaotic system displays an asymptotic motion that is not an equilibrium point, periodic, or quasi-periodic, and this motion is often called chaotic motion, which create strange attractors. These tendencies produce complex sounds with multi-layered tone quality comprised of combinations from pitches to noise bands, also rhythmic patterns that disrupt continuous pitch, and at other times two or three distinct pitches.

4.1 Physical properties of the Chua's circuit

The following components are used in the Chua's circuit. These are the minimum number of electronic components that a circuit requires in order to demonstrate chaotic behavior [18]:

1) One locally active resistor,
2) Three energy storage elements,
3) A non-linear element.

The basic elements of Chua's circuit include four linear circuit elements and a nonlinear resistor N_r that is named the *Chua diode* [18]. The four linear elements consist of an inductor L, two capacitors C_1 and C_2, and a resistor R; a linear resistor R_0 is added in series to L (see Figure 2) in order to explicitly model the resistance characteristics of L. Chua's diode has a piecewise-linear driving point characteristic (DP) including a negative resistance that allows energy to be introduced into the system. The piecewise-linearity in N_r includes three segments with negative slopes; increasing the incline of the negative slopes describes increasing the amount of energy introduced into the circuit.

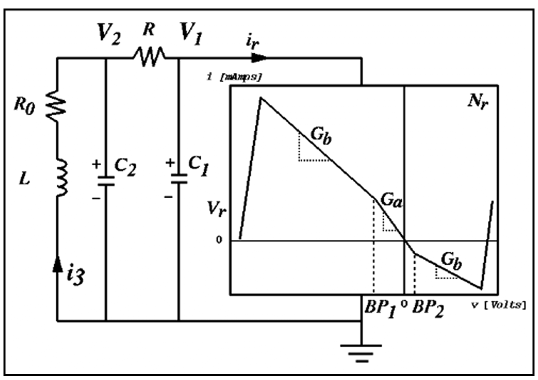

Figure 2: Chua's circuit diagram with nonlinear resistor N_r

4.2 Sounds Produced by the Chua's circuit

Chua's oscillator generates a range of signals from simple periodic to intermittent and quasi-periodic, to aperiodic and chaotic. Chaotic attractors contribute harmonic and inharmonic spectra and noise components to signals generated by a system. Signals from chaotic systems can be described in terms of stability and instability, patterns and their degrees of intermittency, transient qualities, and ambiguity of certain states, which amount to the complexity arising in our perception.

Figures 3a and 3b are Discrete Fourier Transforms of signals taken from the digital simulation of Chua's oscillator. Figure 3a shows the energy distribution of the signal relatively concentrated at a regular interval along the frequency spectra whereas figure 3b shows the energy distribution with somewhat irregular organization.

Figures 4a and 4b are the correspondent time-domain waveform representations of the signals in figures 3a and 3b. The signal in figures 3a/4a is known as a limit cycle with period one; it's acoustic characteristic can be described as a stable tone with energy peaks in the frequency spectrum that reinforce our perception of the period-one frequency. These spectral energy peaks behave like partials in a harmonic vibration such as a plucked string; when the partials occur at regular intervals of near-integer ratios as shown in figure 4a they are said to be in harmonic relation, acoustically reinforcing a fundamental frequency having a clearly detectable pitch. The signal in figures 3b/4b is complex and quasi-periodic; visually there are no spectral peaks and determine well-defined frequency regions or patterns and the change of the waveform of the signal is unpredictable over time. This signal is known as a chaotic signal. The acoustic characteristic of a chaotic signal is noise-like, as our ear cannot settle into well-defined frequency regions or relationships among energy peaks in the spectral domain. The noise-like quality of the chaotic signal is due to chaotic distribution of the energy of the signal along the frequency spectra at all times. In sum, the chaotic signal is a structured noise that is perceived as "colored noise".

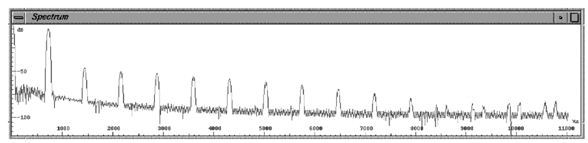

Figure 3a: Frequency spectrum from a periodic attractor

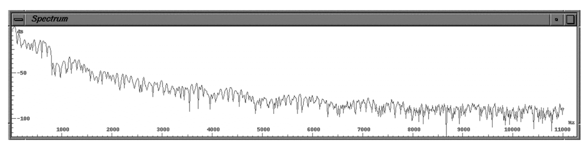

Figure 3b: Frequency spectrum from a chaotic attractor

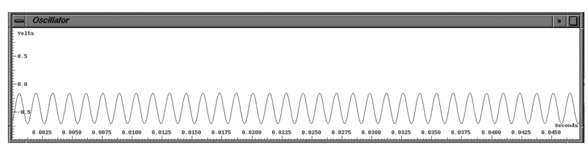

Figure 4a: Time domain signal of the spectrum figure 3a

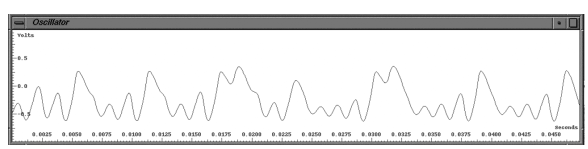

Figure 4b: Time domain signal of the spectrum figure 3b

4.3 Playable Space Tuning for the Chua's Circuit

A playable space frames a coherent scale for a listener to impart actions and experience corresponding audible changes.

This requires adjustments across three tuning functions such that each feeds the next with no discontinuities.

Playable space tuning TF_1: for Chua's circuit, the playable space tuning function TF_1 (see Section 2) is realized by the physical configuration of circuit components and determined by the voltages stored at each component. The voltages of circuit components are control states that determine the oscillation pattern that also produces the sound. To change the sound requires changing voltages of one or more circuit components to induce a transition to a new oscillatory state.

Playable space tuning TF_2: for Chua's circuit TF_2 is realized when a listener actuates a change to the voltage of one or more circuit components. Audible features determine the choice of control voltages. The potentiometer is the standard mechanism for introducing voltage change; metaphorically TF_2 invokes a listener grasping an analog radio tuner and targeting a frequency marked on the dial. TF_2 includes the acts of listening, grasping and targeting a new frequency, but does not include the response of the radio. Audible features are applied as feedback targets to define TF_2 boundaries for listener's actions navigating the regions of the circuit. In the past these boundaries have avoided sine-like oscillation produced by states known as "limit cycles" that cannot be destabilized, and "fixed point" regions where the oscillation terminates.

Playable space tuning TF_3: for Chua's circuit TF_3 is realized when adjustments of voltage control generate changes in the circuit's oscillatory states. When the control voltages of the circuit components are altered the Chua's circuit can easily become destabilized and enter undesirable, unchangeable states. When a listener adopts search criteria for any certain sound quality, desirable states are often inaccessible if voltage changes are applied to one circuit component at a time. A listener must be able to synchronously adjust five to seven control voltages while navigating the nonlinear phase space. To facilitate this high-dimensional navigation a manifold interface was developed.

4.3.1 A Manifold Interface in the context of space representation for a complex system

Phase space generally refers to all possible states of a complex system. Familiar images like paths of strange attractors are trajectories of system states evolved in time plotted in a phase space. Modeling a complex system such as Chua's circuit often formalizes the system with a set of parameters representing components that can be variable with control signals from sources external to the system. We will refer to those parameters as control parameters. Control parameters and all combinations of their numerical values in complex systems present a massive space to explore.

Varying control parameters one at a time using potentiometers to explore system states is inefficient. A *manifold interface* is used to organize efficient access to high dimensional parameter space in support of human modality [19]. A manifold is a locally Euclidean topological space, and we apply this to define a bounded sub-region of a high-dimensional space. The spatial representation of a manifold should support visual simplicity in an interface while maintaining an accuracy of its relationship to the states of the control parameters. This visual simplicity is an important factor supporting attunement, to orient observers into a human compatible exploration.

In the representation and control strategy for a complex dynamical system we distinguish the terms, control space and window space. Control space refers to all possible combinatorial space of control parameters that can impart changes to the system. N control parameters are represented as n-dimensional Euclidean space where each point in the space – an n-tuple of real numbers – corresponds to a unique set of control values of a parameterized system. To explore this space requires actuation in a Euclidean high-dimensional space. This space is not differentiable to human perception in 2D or 3D. To visualize we apply a data reduction from high-dimensional control-phase space to a 2D spatial representation. (The control space may also be reduced to a 3D volume realized with a 3D motion-sensing system.) We refer to this reduced dimensional space as a *window space*. Figure 5 illustrates a 2D window space for a path in a high-dimensional control space.

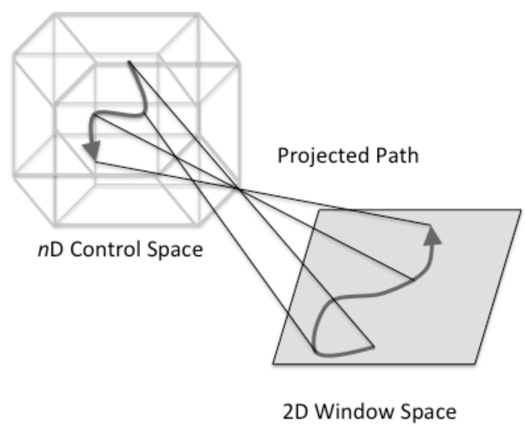

Figure 5: Manifold interface with parameter control path

A 2D or 3D window space connecting to a manifold is continuous and differentiable by defining a set of generating points. Figure 6 illustrates the bijective mapping for a 2D window space embedded in 3D space. Bijective map projects cell-coordinates from one space to another and projects back preserving the space as continuous and differentiable. For details, see [19].

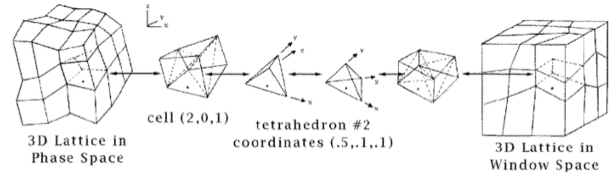

Figure 6: Bijective map between control space and window space, applied in implementation of the manifold interface [19].

To summarize the Chua's circuit playable space:

- TF_1 from dynamical system to sound
  - Realized when control voltages input to the circuit stabilize the signal in a new region of the phase space, generating an audible signal
  - Routing: A listener consults the sounds
- TF_2 from sound to listeners actions
  - Realized when a listener identifies preferred regions in the control space
  - Routing: A listener controls the circuit
- TF_3 from listeners actions to system states
  - Realized when a listener actuates potentiometers for voltage control to induce changes in the circuit's oscillatory states
  - Routing: The circuit oscillation responds to the new control voltages

Tuning function TF_3 completes the feedback routing TF_1-TF_2-TF_3 back to TF_1. Figure 7 illustrates the realization of playable space of Chua's circuit.

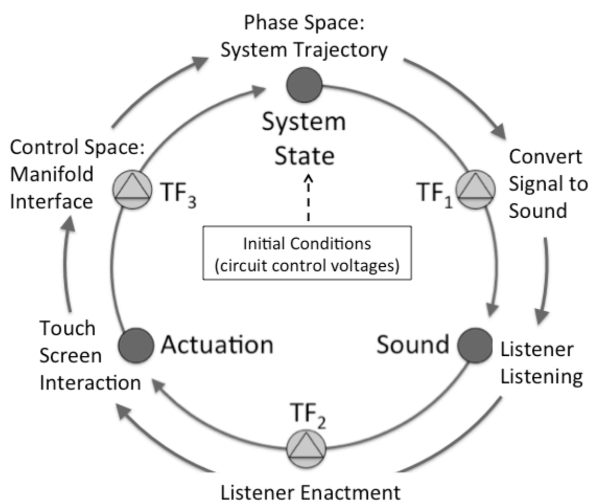

Figure 7: Schematic diagram of Playable Space of Chua's Circuit. The outer ring designates the physical system realization of the canonical inner ring structure.

5. THE CASE OF DYNAMICAL SYSTEM WITH SILENT SOURCE

A swarm simulator provides an example of auditory display with a silent dynamical system as a data source. Whereas chaotic motion is defined by a set of differential equations, swarm motion is defined by social interaction among swarm agents. Therefore a swarm simulator's internal dynamics as well as modeling methods greatly differ from Chua's circuit. While Chua's circuit had well defined physical parameters through which system energy can be manipulated, a swarm simulator is operated by a set of simple rules that dictate social behaviors of swarm agents. The auditory display with silent sources requires an external system or procedure to make sounds. There are many options for designing and choosing the external system for making sounds. For swarm auditory display, there were two choices: one option was parameter mapping from one model to another, the other option was an employment of swarm data applied to sound. We have chosen the second option and applied swarm data to procedural sound synthesis models. The first option was doable but less compatible because the large part of model definition of a swarm simulator is rule based; in sound, rules can be perceived as process not as parameters. The second option provided another example of playable space definition.

This case study uses Sayama's swarm simulation [20], based on Reynold's "boids" [9] and extended to heterogeneous swarm interaction. A number of agents (usually 100 to 300) are designated at random positions in a constrained virtual space and are set in motion at random initial velocities. The motion is not defined by simulated physics, but rather by social engagement with other agents. Each agent is given a perceptual field defined in virtual distance units, and also given parameterized responsiveness rules for interactions with other agents. An agent's rules, known as a *recipe*, determine the agent's movement with respect to other agents that are located within the agent's perceptual field at the current time step. The rules are applied across all agents at each time step, so agents reciprocally affect others' movements. Agents' individual movements and their collective movements are determined entirely by recipes, as follows.

- Within an agent's perceptual range:
  - Cohesion: an agent moves toward the average position of local agents
  - Alignment: an agent moves towards the average velocity of local agents
  - Separation: an agent avoids collision with local agents
  - Whim: an agent moves randomly with a given probability
  - Pace keeping: each agent approximates its speed to its own normal speed.
- Beyond an agents' perceptual range:
  - Straying: random directional movement when the agent has no perception of others

Table 1 shows kinetic parameters for each agent *i*. The pixel was Sayama's original distance unit (since abstracted). Tendency is an agent's rate of approximation of its current speed to its own normal speed. Maxima were determined heuristically. Agents that share the same recipe (parameter values) are termed *species*. Sayama investigated heterogeneous swarms that consist of multiple species, resulting in rich emergent behaviors

Name	Min	Max	Meaning	Unit
R^i	0	300	Radius of perceptual range	pixel
V^i_n	0	20	Normal speed	pixel step^{-1}
V^i_m	0	40	Maximum speed	pixel step^{-1}
c^i_1	0	1	Strength of cohesive force	step^{-2}
c^i_2	0	1	Strength of aligning force	step^{-1}
c^i_3	0	100	Strength of separating force	pixel^2 step^{-2}
c^i_4	0	0.5	Random steering probability	- - -
c^i_5	0	1	Tendency of pace keeping	- - -

Table 1: Agent parameters for kinetic behavior [20]

5.1 Swarm Simulation Control and Phase Space

The recipe defines the control space of the simulation. Parameter values establish initial conditions for swarm agents' movements. Agents' spatial positions and their movements at each time step comprise the phase space of the simulation. The phase space of Sayama's algorithm is defined in units of spatial positions on a plane; notably in Table 1 the pixel is the spatial unit for calculating distance and movement. Agents' 2D positions represent the simulation's current state, and are typically visualized as an animated graphic of 2D geometric primitives moving on a plane.

Swarm dynamics generate emergent behaviors among agents defined by initial conditions as belonging to one or another species. Groups of agents exhibit both patterns and episodes that can vary considerably within in the phase space of a fixed set of initial conditions. Modifying the recipe values is likely to alter the emergent behaviors. Changing a recipe is typically thought of as introducing a discontinuity, creating a new species and new initial conditions and restarting the simulation.

Unlike a flocking simulation there is no leader to a swarm. Control may be introduced by a *superagent,* an agent that does not use a recipe, and moves as determined by an external source such as a player interacting with the swarm. As it moves independently the other agents respond to the superagent as a normal agent, empowering the superagent to exert influence on the swarm. "Player control" is in this way an emergent property of a simulation where a control agent moves independently of the kinetic rules of swarm agents. Acting as super agents, players' hands manipulate swarm shapes such as deformation and extrusion, separation and combination of multiple groups of agents. Performers engage a swarm's behavioral tendencies but cannot directly manipulate agents' positions or arrange swarm formations independent of agents' social relations. Figure 8 shows three players interacting with the playable swarm surface.

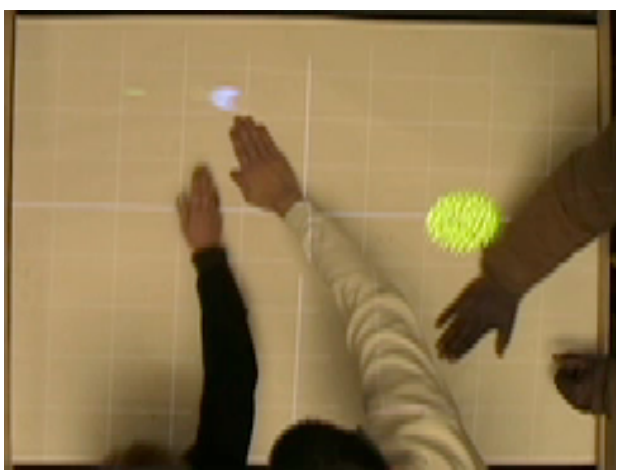

Figure 9: Three players interacting with two swarm clusters on a playable capacitive surface

To create a playable interface for engaging the swarm, a control signal from an input device is connected to the position of a virtual superagent that is only perceived when the superagent is actively controlled. The positional data of this superagent is integrated with the regular agents that determine their positions using the phase space of the swarm simulation.

Note that hosting a superagent enables direct perturbation of swarm Phase Space. The superagent position bypasses the computation of agents' positions and directly asserts an independent position. When other agents perceive the supergagent their responses impart change to the social behavior of the swarm. A superagent position can persist across multiple time steps whereas all other agents must move at every time step. This lends a prolonged duration of behavioral coherence of the swarm, determined by a force external to the social simulation.

5.2 Procedural Sound Responding to a Swarm Simulation

Procedural sound synthesis is applied to generate auditory feedback from swarm states. Sound generating models are controlled by data extracted from emergent behaviors in swarm simulations. Control data mappings are defined between a set of emergent swarm states and a set of sound synthesis parameter states. States of a sound model are associated to selected states of a swarm. Thereafter other patterns that emerge in the swarm will generate corresponding sound patterns. Data selection is based on *a priori* analysis of clusters' salient features. In a baseline test we generated an independent sound to represent each agent's position data. In a separate approach we applied statistics of agents' collective patterns to an abstraction layer where swarm simulation feature data is mapped to a manifold of a sound synthesis parameter control space. The abstraction layer of the shared manifold connects the domain of a swarm's statistically recognized emergent behaviors to a range of sound transformations.

Several techniques were developed to enable reliable correspondences of sounds with highly variable behaviors of clusters. (1) Local deformations of clusters were used uniformly to modify formant characteristics of sounds[1]. This technique may be applied to many classes of sounds. It involves modifying the vowel-like qualities of "openness" and "tightness" of a sound. With this technique the effects of a player's hand deforming a cluster are immediately reflected in the local tone quality of a sound, without disrupting the composed pitch and rhythmic structure of the sound. (2) Data related to changes of cluster size and velocity is assigned to modify pitch-related and rhythm-related sound properties.

Sound sources are not associated one-to-one with clusters. The number and timing of cluster instances is highly unpredictable, dependent upon the swarm recipe and local engagement of superagents. Creating a sound source for each cluster would be capricious and inefficient from the standpoint of sound source modeling and organization. A methodology was developed to manage a limited number of voices – four for example – to correspond to an unknown number of clusters. For example, when there are less than four clusters the four voices share cluster data. For the first four clusters, voices are reassigned to data from the new clusters that form.

[1] A formant is a resonance that amplifies a frequency band that is invariant with respect to the fundamental frequency of the sound. Formants are signatures of natural sound sources due to resonant properties of physical materials.

However the number of clusters is unpredictable and will often exceed the number of voices. Beyond four clusters, the data of the largest four clusters is applied to the four voices.

Sound source localization and spatialization are added downstream. The positions of swarm clusters on the play area determine the localized positions of sound sources in a simulated acoustic environment. The simulated auditory field is larger than the physical play area, with proportional dimensions. Distance cues are introduced as clusters approach the periphery of the play area.

5.3 Playable Space Tuning for a Swarm Simulation

The playable space in Sayama's swarm simulation is depicted in Figure 9. :

- Tuning function $TF_{1:}$ from dynamical system to sound
  - o Realized when swarm data controls sounds generated by procedural sound synthesis
  - o Routing: Listener attends to sounds while watching a graphical display of swarm agents
- Tuning function TF_2 from sound to listener's actions
  - o Realized when a listener decides to touch the swarm agents on the graphical display
  - o Routing: Touching the screen creates a superagent at the touch point
- Tuning function $TF_{3:}$ from listener's actions to dynamical system states
  - o Realized when the swarm agents respond to the superagent(s) controlled by the listener
  - o Routing: All agent positions are updated

The introduction of a procedural sound engine creates a broad range of potential auditory representations of simulated swarm behaviors. The capacity to design wide varieties of sounds is desirable, and the tuning function process can provide a systematic measure of the pathway from data to new sounds to listeners and interactions that generate new data.

Playable space tuning $TF_{1:}$ for the swarm simulation TF_1 requires feature analysis of emergent behaviors. The simulation data does not represent individual agents as collective features. While sounds can be controlled by data from individual agents or from statistical summary, targeted analysis is required to detect features such as agent cluster's size and shape, birth and death. Data of these features can be applied to a large variety of sound generators. As presented in section 5.2, a targeted sound design solution for sound source management is required, to avoid auditory artifacts and uneven representation of the dynamic density of agents' positions and variable number of clusters.

Playable space $TF_{2:}$ for the swarm simulation TF_2 requires a system configuration for introducing direct manipulation of swarm agents. This is accomplished with a multi-touch surface that also displays the graphic presentation of the swarm, so the visualization becomes an interface to perturb the swarm phase space. This approach also assumes that high fidelity and responsive sound layers can be generated in real-time and presented in a playable configuration that integrates the swarm display and interface. An implementation with a touch-screen tablet computer is reported in [21].

Playable space TF_3: for the swarm simulation TF_3 is implemented by enabling the listener's touch on a display surface to introduce perturbations of the phase space of the swarm simulation. A swarm superagent (see 5.1) introduced at each interaction touch point enables all agents in the simulation to respond to the listener's actions and also to reflect other agents' responses. Listeners cannot directly manipulate agents' movements or positions, but rather can lead groups of agents to perform actions such as dividing a cluster, gathering and merging clusters, or guiding agents toward or away from other agents.

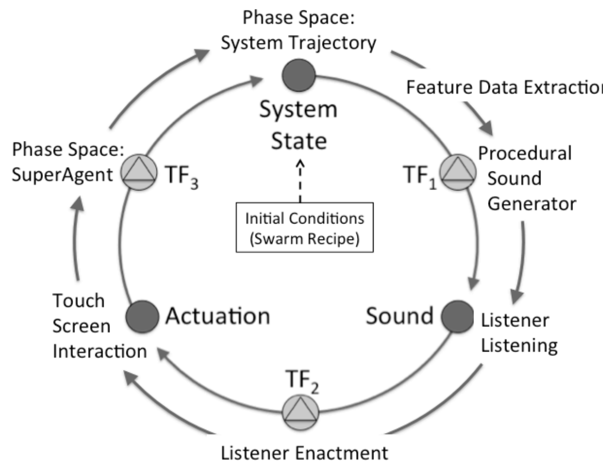

Figure 9: Schematic diagram of Playable Space of a Swarm Simulation. The outer ring designates a simulation-based realization of the canonical inner ring structure.

6. SUMMARY AND CLOSING REMARKS

An ultimate goal for auditory display is stipulated as to inform a listener the states of affairs in the system under exploration through sounds. A listener's engagement must be facilitated in ways the sounds convey a meaningful transformation with respect to the state changes in the system and to all interfacing pathways. Tuning function has been identified as a requirement to construct a coherent play space in system architecture for an interactive exploration. This is referred as *a priori* attunement. Two cases of auditory display are presented. Both cases involved nonlinear dynamical systems that exhibit complex and emergent behaviors. The specification of tuning functions enables a view across diverse dynamical systems for normalizing interactive listening scenarios. This approach enables a comparative view of the two systems presented above while featuring significant differences.

Canonical playable space provides a framework for analyzing and implementing auditory displays in diverse dynamical systems. Attunement may adopt notable differences in realizations of dynamical systems. Figures 7 and 9 illustrate contrasting realizations of tuning functions TF_1 and $TF_{3,}$ while the realizations of TF_2 are nearly identical. TF_1 shows two realizations' contrasting mechanisms of sound production. Equally contrasting are the realizations of TF_3 paths enabling listeners' actuation of system changes. In Chua's circuit TF_3 is realized in the control space of a dynamical system. In the swarm simulation TF_3 is realized in the phase space of a dynamical system. This significant difference leads to different approaches to attunement. In the first case the listener navigates a manifold of control space parameters for an interactive exploration, inducing fine-grained variations of patterns and episodes in attractors. In the second case the listener plays with the emergent behaviors of clusters of agents, interacting directly with phase space to perturb system states.

Playable space is not an interface. It provides space an enabling structure to support auditory interface design, implementation, and analysis. *A priori* attunement defines auditory display workflow by focusing on a space configuration for transcending tuning functions through interfacing pathways, and to identify the optimal sites for tuning data flow and auditory feedback within larger system architectures. As a result of studying two cases, one can argue that a listener's play experiences are conditioned by the fundamental properties of signal generators as well as the interpretation of play space in an interface. A tuning function model can be used to systematically define engagement pathways, from systems under exploration to sounds, to bring about a listener's acute attention to audit dynamical properties.

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