A Physically-Distinct, Multi-Agent, Sonic Space Ecosystem

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ABSTRACT

This paper presents the work, development, and initial findings of a move in the Sonic Spaces Project away from single-computer based systems towards an interactive, musical metacreation system comprised of distributed, physically-distinct agents built from single-board computers. In addition to discussing the technical specifics of how this system was developed, the article also takes time to discuss the implications towards the perception of "agents" and "agency" by human-participants. As well as the specific role of agents in computational systems such as this one.

1. INTRODUCTION

Sonic Space no. 9; for deliberate sculptural agents is a sonic space ecosystem. This work is novel within the larger Sonic Spaces Project for its move away from a single-computer-based interactive music system comprised of agents sharing hardware, to a multi-computer-based system comprising physically distinct sculptural agents.

This change has implications for how agents are treated in the Sonic Spaces Project, the development and composition of sonic space ecosystems, as well as the resulting interaction of human-participants. This article presents the work completed towards this change, as well as some of the resulting implications.

2. SONIC SPACE ECOSYSTEMS

The Sonic Spaces Project is concerned with research and practice into so-called "sonic space ecosystems". Work in the Sonic Spaces Project is interested in researching techniques for the composition of interactive music systems that exhibit or explore properties, behavior, and relationships found in natural ecosystems. A basic metaphor used to describe these music systems is the idea of living agents or species, which need energy (sound) that they use to live and survive from. A living agent in a sonic space ecosystem listens for sonic energy it can consume, in doing so, this energy is transformed by the agent through digital signal processing, and then returned to the environment for other agents to use. The resulting output created from all of the agents, as well as human-participants, creates an emergent composition. The resulting emergent music is dependent not only on the nature of the algorithms composed for the system, but also on the external sound contributed to the system, as well as the acoustic relationship between the system and its containing environment. The implications of ecosystem relationships in music are significant, as have been discussed by [1–5].

Recognizing the diverse viewpoints that could emerge from such discussions, the Sonic Spaces Project delineates its practice in ecosystemic art by creating sonic space ecosystems. This type of interactive music system's goal is to create spaces where sound from any source (system, human, or background machinery) ultimately alters the resulting emergent music. The goal is not to create evolutionary-based art (EA) or model genetic algorithms (GA). Instead, this project aims to explore systems based in principles from the fields of general systems theory, complex systems, cyber-physical systems, and ecosystem theory. The idea of a sonic space ecosystem has been fully defined in previous work in relationship to these fields [6, p. 59]. The resulting definition is presented as;

> *Sonic Space Ecosystems* (clarified here to refer to feedback-based sonic ecosystems) are classified as both *cyber-physical systems* and *interactive music systems*, comprised of hierarchically related *elements* that together perform a *system function* that is greater than is possible by the individual elements. The primary function of this system is to create a controlled *music environment* which exhibits *emergent* qualities of *self-organization* created through *inter-reliant relationships* between internal elements in the digital system, and relationships between the digital system itself to the physical *sonic space* that it is installed within. These elements are made *aware* of their physical world through microphones that act as input transducers, allowing them to use *sonic energy* that they then transform according to their *individual function* (algorithms) as a way of surviving themselves. This transformed *sonic energy* is then returned to the *sonic space* through loudspeakers that act as output transducers as a way of *potentially affecting* the system as a whole. A *healthy system* is one that exhibits self-regulating *states* of *growth*, *decay*, or *steady states* and is capable of recovering from unexpected or extreme environmental changes. These systems are *open* and require external contributions of *sonic energy* by *human-agents/participants* or *non-living external elements* in the *environment*. This *sonic space ecosystem* then fulfills Jørgensen's requirement that "an ecosystem is a dynamic complex of *elements*, *agents*, *communities*, and the nonliving environment, interacting as a functional unit," [7, p. 20] while at the

same time fulfilling the ideas of interactive music systems.

The above definition of sonic space ecosystems serves to describe the necessary qualities of such a system, by grounding the definition in information from the previously mentioned related fields. In composing such a system, the behavior and capabilities of the system to create emergent music are considered in relationship back to this definition.

For an in-depth description and justification of this definition, the reader is encouraged to read the chapter on the "Theoretical Grounding and Definition of Sonic Space Ecosystems" from the referenced source. For the purposes of this article, only a few of these ideas within the definition will be further clarified, with emphasis placed on those concepts which are critical to a discussion of a sonic space ecosystem with physically-distinct agents.

2.1 Agency

One concept not mentioned in this definition, yet used in the name of the musical work this article is about, is that of "agents" or "agency". Instead the definition above for sonic space ecosystems refers to elements in the system.

Systems are said to be comprised of elements which work together to perform a function greater than is possible by any element alone. Complex systems, the type of which sonic space ecosystems are further classified as, tend to be hierarchical systems, where elements of the system are comprised of sub-elements. The relationships between these elements creates a system whose function or behavior is "greater than the sum of its constituent parts" [8]. In complex systems, the ability to describe the emergent behavior of the system through the summative properties of all elements, including sub-elements, becomes impossible due to the constitutive relationships of elements [9, p. 67]. This complexity, in sonic space ecosystems, results in emergent music which is not totally predictable yet exhibits similar types or classes of behavior between performance instances. The specifics of the emergent music are reliant not only on the algorithmic design, and digital construction of the system, but also on the; sounds and music that have come before in a performance instance; the acoustic properties of the containing environment; and, the placement of the system's hardware in the physical environment.

When describing systems, especially complex systems, in which the resulting actions of the system are not fully a-priori, it is common to refer to specific elements in the system as "agents", or to describe various elements' "agency". Since the idea of agency is one rooted in human perception and free-will, using the term within discussions of computational systems can be misleading. Recognizing this issue, the use of the terms "agent" and "agency" follows the practice of others. The use of these terms in this project "is meant as a tool for analyzing systems, not an absolute characterization that divides the world into agents and non-agents" [10, p. 36].

Within the Sonic Spaces Project, the notions of agents and agency are considered to be multi-dimensional. Long-term, one research goal of this project is to build on previous work examining the role of agency in music systems, such as [11–14], as well as the perception of agency by participants and listeners in said systems, such as [15]. However, for the time being, this project will stay at a high-level when considering agency, recognizing that from a human-perception standpoint, "routine, purpose, and judgment all constitute important dimensions of agency, [with] none by itself [capturing the] full complexity" [16]. From a computational systems standpoint, autonomous agents within the Sonic Spaces Project adapt the definitions proposed by Franklin and Graesser [17];

> An autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future.

As well as by Wooldridge [18];

> Agents are computer systems with two important capabilities. First, they are at least to some extent capable of autonomous action - of deciding for themselves what they need to do in order to satisfy their design objectives. Second, they are capable of interacting with other agents - not simply by exchanging data, but by engaging in analogues of the kind of social activity that we all engage in every day of our lives: cooperation, coordination, negotiation, and the like.

These definitions do not aim to offer an absolute, but instead to clarify the oft-used term in order for it to be useful in work describing systems with respect to the agents of the system. Perhaps, more importantly, these definitions do not restrict the use of the terms to specific instances, and allow for the containing environment, of an agent, to be another agent.

2.2 Single-Computer Systems

The Sonic Spaces Project so far has nine distinct systems, with a few of these having multiple iterations and presentational formats. All but the most recent have utilized a single-computer-based system. In this model, a single computer is connected with multiple microphones and speakers, which served as the input and output transducers for agents in a system. From a technical standpoint, these agents are small programs, or patches, which are tasked to listen to the environment, analyze incoming audio for "usable" sonic energy, consume and process that sonic energy when acceptable, and then output the sonic energy back into the environment in order to support additional "agent activities". In this model, the system has shared resources, including; computer processors, software running the piece (typically SuperCollider), audio interface, input sensors (microphones), and output actuators (speakers). The largest systems *Sonic Space no. 4* and *One Deliberate Day; Sonic Space no. 8*, each utilized 10 input microphones, and up to 12 output channels. The benefit of this model is that the agents created from the elements of the system are free to be assigned to specific locations in the environment, to 'wander' the space, or to exist where sonic energy allowed them to.

From a development and assessment standpoint, this model is ideal, as it allows for easy introspection of all elements into why an instance of a system evolves in a certain direction. This is possible, because with a single-computer-system, it is easy to collect and compare the input data, to internal representations, as well as the ultimate meta-musical choices made by the agents. Necessary changes are also easily implemented in this type of system.

2.2.1 Participant Responses

By and large, the individual system compositions of the Sonic Spaces Project have been well received and have served as productive territory for the creative practice and research goals of the project. They have been presented and performed internationally, and I have written about the project in a number of articles. However, there were a few issues that arose, which are relevant to the discussion of this single-computer-system model.

An issue with the perception of agency became evident through informal discourse and was concretely identified through both Likert scale and open-ended question surveys. Participants to the systems had a difficult time conceptualizing the sonic space ecosystems as systems comprised of agents.

Sonic space ecosystems are composed and developed following Agostino Di Scipio's idea that "sound is the interface" [1]. What is meant by this, with regard to the Sonic Spaces Project, is that the top-level elements of the system, which can be considered as agents, do not communicate with each other through any internal data interfaces. Instead, the only interface for communication for all agents, be they digital-agents or human-participant is the acoustic space of the room. All communication occurs in the containing acoustic environment, between the speakers and microphones.

These surveys showed that participants did not understand this concept and found it difficult to believe that the agents were confined to interacting within the acoustic space of the room. Another related finding from the surveys was the inability by most naïve participants to perceive notions of agency by the system (here meaning those who have not studied or practiced experimental electronic music). This latter point is included in order to acknowledge the difficulty in creating and studying systems which do not fit everyone's definition of "music", as well as to acknowledge that this issue may have influenced the former.

2.2.2 Issues of Scale

In addition to the participant issues, another problem with the single-computer-based system is scale. It is apparent that to move beyond a system with 16 inputs/outputs for a single computer would require significant investments in hardware, cables, and processing power. Not to mention that the installation, setup, and tuning time necessary for larger systems would reduce the portability of such systems. This is not to say that the technical abilities do not exist to support the development and presentation of such systems, just rather that the solution seemed inelegant.

2.3 Towards Physically-Distinct, Multi-Agent Systems

In 2014, while contemplating possible future directions for the Sonic Spaces Project, the idea of creating "mini-systems" with the quickly advancing single-board computers (SBC) such as the Beagle-Bone Black and Raspberry-PI came about. These fully functional computers, capable of running modern Unix operating systems, and already proven for their ability to run software programs such as SuperCollider [19, 20] or Pd [21], seemed ideal to explore a new-paradigm in composing sonic space ecosystems.

The processor power for these SBC's prohibited them from fully replacing the computer in a single-computer based system. However, by reducing the amount of processing that a single SBC needs, it is possible to create "mini-systems" comprised of a single agent.

Therefore, it was determined that an appropriate test iteration for the Sonic Spaces Project would be a move towards a physically-distinct, distributed, multi-agent system. This work is not the first piece to use multiple SBC's as distinct nodes in a system. This project builds from work presented in the "installation" section of the Raspberry-Pi website, as well as the work *Clouds* by Ivica Ico Bukvic [21, 29], which also created a large installation of musical agents with Raspberry-Pi's. However, the development and creative choices discussed here are significant for the larger Sonic Spaces Project, and is one of the first interactive music systems that creates emergent music based on the qualities of input sound through the use of SBC's.

3. SCULPTURE AGENT DEVELOPMENT

From the start, it was determined that each SBC would become its own agent. Development progressed with this tenant in mind. Additionally, the project was viewed from the standpoint that each agent should be capable of creating music by themselves. That is, given the appropriate type of input, the agent-system would use the sonic energy, process it, and return the altered sonic energy back to the environment.

3.1 Initial Work

During the time that I started working on physically-distinct agents, I was also heavily involved with the environmental sensing project known as Citygram. In its current phase, the Citygram project has been researching hardware and software solutions to enable the capture, analysis and distribution of environmental sound data [23]. Through this project, I was involved in the research and development of hardware and software solutions to enable the creation of remote sensing devices (RSDs) that would collect similar types of feature data and identification of novel acoustic events as sonic space ecosystem compositions.

3.1.1 Single-Board Computer

As mentioned, it was around this time that updated generations of inexpensive and powerful single-board computers came to market. A single-board computer (SBC) is a "computer that consists of a single circuit board for memory and the processor", often have I/O interface options for sensors and data peripherals, typically have a surface area equal or less to a "playing card", and are usually low-cost [24, p. 44], [25].

Eventually, I would settle on the Raspberry Pi 2 as the candidate for deployment in the project discussed here.

3.1.2 Transducers

In addition to determining a good SBC, OS, and installation procedure for SuperCollider, it was also necessary to consider the appropriate hardware and transducers for getting audio in and out of these devices. With regard to the microphone and input signal, much was borrowed from research done in the Citygram project [26]. Like Citygram, ultimately the Sonic Spaces Project would identify an USB dongle audio interface that was capable of being run through bus power via the Raspberry-Pi. Multiple interfaces were tested, the Sabrent AU-MMSA 2.1 USB interface was chosen for its low cost, driverless operation, audio quality, size, and compliance with USB 2.0.

Figure 1. Example of the JLI-61A, omnidirectional condenser electret microphone elements used.

JLI-61A omnidirectional electret condenser microphone elements were chosen for their relatively flat frequency response, cost, and size. As is seen in **Figure 1**, the element was attached to a shielded microphone cable with shrink tube used to solidify the structural integrity. The other end of the mic has a 3.5mm TRS connector, which can be run directly into the USB interface, from which it receives enough power voltage to capture audio.

For audio output, a 3" full-range driver was selected. These were chosen because of previous experience using this model during the development and composition of *Sonic Space no.'s 4 & 5.* These speakers are powered from a 15W audio amplifier.

Figure 2. Rear view of sculptural agent.

3.1.3 Housing

For the housing, 1"x12" pine wood boards were selected. In considering the design of these sculptures, inspiration was taken from bird houses and open cabinet guitar speakers. An open-back or dipole speaker design was chosen for a number of reasons. First dipole speakers radiate energy in both forward and rear directions of the speaker [27, p. 288]. This was hypothesized as creating a more dispersed sound from each agent in the sonic space. Second, open back speaker designs tend to be less susceptible to housing vibrations then sealed speaker designs. Third, this was seen as a way of further reducing energy build up in the microphone from the same physical agent. Finally, from a practical consideration, an un-sealed open back design allows for access to the component parts of the agent.

3.1.4 Power

Since these Raspberry Pi's run a headless version of Linux, they boot up into the operating system as soon as they are powered on. Also, since these sonic agents follow the principles of the Sonic Spaces Project, and only communicate through their shared sonic space, there is no need for additional data or communication. Therefore, power supplied for both the SBC and audio amplifier are installed within the sculpture. As such, starting these agents is as simple as plugging this power chord in.

3.1.5 Cost

Five of these sculptures were to be built for *Sonic Space no. 9* and there are intentions of developing a larger piece with more sculptural agents in the future. As such, cost was a major consideration in the development phase. The total cost for each agent, as of 2016, was approximately $140.

4. COMPOSING AGENTS

The software development for these agents occurred concurrently with the hardware development, so that decisions from both perspectives were made recognizing the reliance on each other. Initial creative algorithm work was completed on a Mac, which was connected to similar types of speakers and microphones as were being tested for the sculptural agents. (Compose for the hardware that will be used.) As a working system started to come together, it would be ported and loaded to the Raspberry-PI for further assessment and development.

As with other system compositions, this piece has an extensive pre-compositional phase the included considerations for system level interactions. Likewise, high-level system interactions include both planning and the development of code intended for control and management. Following these planning stages, development on the feedback-based listening, decision-making, and processing was undertaken.

Figure 4. Presentation with agents "spaced" apart.

Figure 3. Presentation with agents "clustered" together.

4.1 Conceptualize System Interactions

4.1.1 Physically Distinct Agents

The most important high-level system interaction intended for *Sonic Space no. 9*, was the presentation of a system containing multiple computers that are physically distinct and separate. Each of these individual computers, essentially becomes its own independent sonic ecosystem, capable of;

- understanding its sonic space environment,
- using sonic energy from this sonic space,
- and transforming the sonic space by contributing sonic energy.

4.1.2 Change System Communication Paradigm

Another high-level interaction that was to be explored with this system is how communication would change between individual, physically distinct, digital agents who no longer shared any of the same hardware or audio transducers. All previous systems have used shared microphone inputs for the digital agents. This is analogous to two or more agents sharing a physical ear. That being said, agents from these previous systems had a great understanding of the environment, as they often times received sonic energy information from multiple microphones placed throughout the sonic space. For *Sonic Space no. 9,* agents are placed in physically distinct locations around the room. This is intended to make it visually and sonically clear as to where they are positioned.

The interesting question about this change however, is how it changes the interaction between digital agents? This system makes it clear that agents are listening and responding from physically-distinct positions.

4.2 Consider High-Level System Characteristics

As with other systems, and specifically, *Sonic Space no. 8*, it was important to consider the diversity of sounds, create a structure that supported emergent musical form, and create varying levels of interaction. During pre-compositional work these needs were defined and implemented through high-level system characteristics.

4.2.1 Two Species

Another choice made early in the development process for this work was to compose two species of agents. During the building of the sculptures, three were stained a natural wood color, and two were stained a darker wood color. This decision about staining was made to support a desire for two separate species.

This means that there are groups of agents running the same code, but that all of the agents are not running the same code. This choice was made to create a diversity of system states and types of sounds.

At the same time, just as an orchestra has a section of violins, and *Sonic Space no.'s 6* & *7* have the same species respectively, the interplay between the same type of agent is interesting. This was something I was particularly interested in experiencing for this piece.

4.2.2 Define Digital Agents and Sonic Representations

As mentioned, each physical sculpture is viewed as an agent in this sonic ecosystem. Therefore, it is important that these agents be interesting by themselves and capable of a diversity of states individually. This means that each physical agent is capable of multiple types of sonic energy creation; dependent on the position in the cycle of the day, previous types of energy in the system, and choices made by the agent.

4.3 Develop Agent Structure

Since each agent, is itself a 'self-contained' version of the sonic space ecosystem, the development of agent structure overlaps heavily with system structure. The following conversation therefore discusses agent structure, but the reader should be aware that this same structure exists for every sculpture.

4.3.1 Self-Reliance

The agents were developed to run on Raspberry Pi boards, independently of any external information. The hardware system was programmed in a way that once power is supplied, the Linux OS boots up, and then immediately starts the sonic ecosystem. This allows each agent to exists as its own entity, without requiring additional information, data, or interventions from external sources or people. (This also fulfils the rules of agents in cyber-physical systems.)

4.3.2 Ensure Agent Listening

A structural need for these agents, which resulted from the defining of high-level characteristics for the system, was to ensure that agents listen. This is important in creating a diversity of sounds and form. It is also immediately clear in a feedback-based sonic ecosystem, where the microphone and speaker are close together and physically connected to the same structure, that an agent has the potential to simply feedback on itself only. The nature of the central-computer system allows this to occur, as there are many agents listening through the same microphones, and potentially playing out of the same speakers. In this type of system there are some protections in place to address this, but since the agents are incapable of hearing *only* themselves in such a system, it has never been fully addressed.

For this change in system paradigm however, there are two strategies used for reducing self-driven feedback. First is a simple amplitude-based ducking system. Second, frequency-domain based spectral subtraction is used to remove some of the energy from the speaker of the agent back into its own microphone. Together these two processes reduce self-driven feedback of any one agent. These techniques are also a form of self-regulation for cybernetic type systems and is apt for use in this situation.

5. DISCUSSION

Sonic Space no. 9; for deliberate sculptural agents is the first composition in the Sonic Spaces Project to leverage the distributed, physically-distinct, multi-agent paradigm presented in this paper. In initial evaluations of the work at three public presentations, including two professional conferences, questionnaire responses have shown positive improvement with respect to human-participants understanding of, and perception of, distinct agents and agency.

The work on this project has been documented through images, audio recordings, and video, which are all available from the *Sonic Space no. 9* project page (*REDACTED*). This documentation serves as a compliment and support to the information presented in this article. The recordings of this work demonstrate the ability of this system to create unique emergent music, as a result of incoming sound.

The information presented in this article presents the current state of this project, as well as steps taken to creating such a system. This system has also proven its ability to address the questions raised, while creating meaningful emergent music, as a result of sonic interaction.

There are still topics and specific research experiments to be executed with regard to this work. Especially as it relates to issues of agency, and the use of physically-distinct autonomous agents in musical metacreation systems. The development of a new system, *Sonic Space no. 10*, that builds from the work presented here, is currently in its initial phases. This work will aim to further explore the perceptions of agency within the system, as well as scale up the system to contain many more agents. Ideally, participants to this next system will walk through a grove of agents listening, responding, and making music together.

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