Music with Unconventional Computing: Granular Synthesis with the Biological Computing Substrate *Physarum polycephalum*

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Abstract. This paper reports on the outcomes of an approach to granular synthesis using the biological computing substrate *Physarum polycephalum*. The plasmodium of *Physarum Polycephalum* is unicellular with a myriad of diploid nuclei, which moves like a giant amoeba in its pursuit of food. The organism is amorphous, and although without a brain or any serving centre of control, can respond to the environmental conditions that surround it. In the presented approach, we harness the organism's oscillatory behaviour and protoplasmic network configuration to produce and sequence sound grains. Such an approach is an extension to one of the author's previous musical works with *Physarum polycephalum*, which he presented in [13].

Keywords: Unconventional Computing, Biological Computing, Computer Music, *Physarum polycephalum*, Bionic Engineering, Music, Granular Synthesis

1 Introduction

Computers have been programmed to produce sound from the beginning of the 1950s [10]. Since, advances in computer science have had a significant impact on both the way audio media is consumed and produced. Therefore, it is likely that future computational advancements will change the field of music. Amongst computer scientists, there is a growing consensus that we will one day reach the limit of today's conventional computing paradigms, which are derived from the Turing machine [17] and von Neumann architecture [18]. We are interested in how the advancing field of unconventional computation may provide new pathways for music and related technologies.

In computer music, there is a tradition of experimenting with emerging technologies. Until recent years, developments put forward by the field of unconventional computation have been left unexploited, which is likely due to the field's heavy theoretical nature, complexity and lack of accessible prototypes. Uniquely, the biological computing substrate *Physarum polycephalum* requires comparatively fewer resources than most other unconventional computing substrates: the organism is cheap, openly obtainable, considered safe to use and has a robustness that allows for ease of application. It is for these reasons we have selected *Physarum polycephalum* to begin investigating how new, biological, computing schemes may provide innovative pathways for music. We have developed several projects that harness *Physarum polycephalum* for creative applications. These include sound synthesis [13], a biologically inspired step sequencer [7] and an analogue circuit for music generation [6] that encompasses biological components [9]. For a survey of unconventional computing in music see [8].

Physarum polycephalum (henceforth known as *P.polycephalum*) is an amorphous unicellular organism visible to the unaided human eye. *P.polycephalum*, during its vegetative plasmodium phase, creates an optimised network of protoplasmic veins connecting food sources (Figure 1). The visual result of the organism's network is a planar graph where colonised food represent nodes and protoplasmic veins represent edges. The plasmodium feeds on micro-particles and creatures such as bacteria and spores and moves like a giant amoeba along gradients of attractants and repellents. The intracellular topology of plasmodia can be described as a network of biochemical oscillators [1]: waves of contraction or relaxation that collide inducing cytoplasmic streaming. Such intracellular activity produces fluctuating levels of electrical potential, typically in the range of $\pm$50mV, displaying oscillations at periods of approximately 50-200 seconds with amplitudes of 5-10mV [2]. If recorded in isolated zones of colonisation over the duration of it being active, patterns emerge that correlate to spatial activity and environmental conditions. Adamatzky and Jones have examined such patterns and reported that they can be used to denote the plasmodium's behaviour and physiological state [2].

P.polycephalum's behaviour can be interpreted as computation [1]. Computational prototypes exploiting the organism's behaviour include robot control [16], logic gate schemes [3], route planning [15] and numerous others [1].

In this paper, we report on an approach to granular synthesis harnessing the plasmodium of *P.polycephalum*. This work is an extension to one of the author's previous projects, which he presented in [13]. In this project, the organism's electrical readings were recorded and subsequently scaled to control the frequencies and amplitudes of a group of oscillators within an additive granular synthesis framework. The results of this project were interesting and created a reasonable auditory representation of the organism's behaviour. However, results were hampered by the quantity of data generated by recording the organism's electrical activity. Such large amounts of data were compressed to render them usable, which was to the detriment of the relationship between the sound and the behaviour of the plasmodium. In this paper, we report on the outcomes of a different approach to sound synthesis with *P.polycephalum*, where we take advantage of the organism's oscillatory behaviour by regarding it as a granular audio oscillator that we can control via various methods of stimulation.

Granular synthesis is the rapid succession of short sound partials (typically 1-100millisecond-long-sounds) referred to as grains that together form a larger sound object. Dennis Gabor inspired this method of sound synthesis with his the-

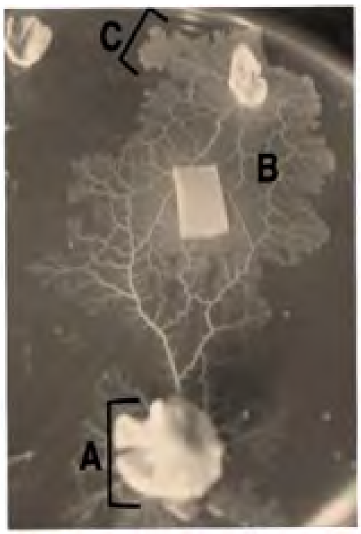

Fig. 1. A photograph of the plasmodium of *P.polycephalum* showing: (A) inoculation of plasmodium into the environment, (B) protoplasmic network connecting areas of colonisation and (C) a search front of pseudopods propagating along a gradient to food.

ory 'acoustical quanta', which proposed that complex sound events are made up of a myriad of simple sonic grains [11]. The first composer to approach granular synthesis for musical purposes was Xenakis [19] during the 1970s. Since, several different approaches to harnessing granular synthesis for music have been investigated. By way of related research into unconventional computing for granular synthesis, Miranda [14] experimented with using a cellular automata model of a reaction-diffusion computer to produce sequences of grains according to evolving chemical oscillations.

2 Methods and Materials

When conducting our research with the plasmodium of *P.polycephalum*, we adopt techniques from [1]. Here, we farm plasmodium in plastic containers on a moist, porous substrate. The farm is fed daily with oat flakes, moistened every other day and replanted onto a new substrate weekly. To inoculate plasmodium into an experimental arena, we take colonised oat flakes or heaps of pseudopods from the farm and position them as desired.

To measure the electrical activity of the plasmodium, we place bare wire electrodes coated with 2% non-nutrient agar underneath sources of food (oat flakes). Electrodes do not touch and are electrically isolated from one another by a non-conductive plastic. In each experiment, we nominate one electrode the as a reference, and, as such, position the plasmodium on top. Figure 2 shows an experimental growth environment for our granular synthesis approach. Here, four electrodes are arranged on the vertices of a square, with a reference electrode positioned in the centre. In the context of this paper, such an arrangement represents four granular oscillators. Electrodes feed into an ADC-20 high-resolution data logger by Pico Technology, which sends measurements into custom software. All experiments take place in a 90mm petri dish within a dark enclosure.

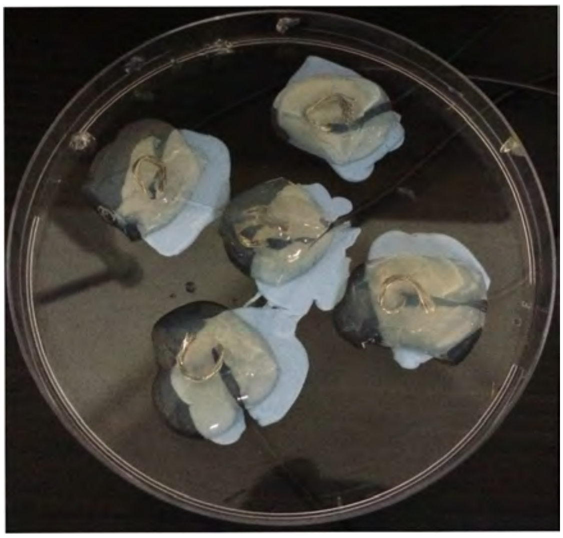

Fig. 2. A photograph of an example growth environment for the plasmodium to forage in. Shown is four measurement electrodes centred around a reference electrode.

The behaviour of the plasmodium can be controlled by taking advantage of the organism's innate response to various stimuli. In unconventional computing studies, substances that result in attraction or repulsion are often used as a method of data input [1]. There are a number of substances that can act as attractants (e.g. glucose and various carbohydrates) and repellents (e.g. salt and metal ions). However, once positioned in the experimental arena, these substances create chemical traces that are difficult to remove. A more dynamic method of controlling behaviour is through various lighting techniques. The plasmodium of *P.polycephalum* exhibits negative phototaxis. That is, in the presence of certain light wavelengths, the organism diverts propagation to avoid the illuminated area [12]. Studies have identified that blue and white light affect the organism's oscillatory behaviour [4]. Thus, as we are harnessing the organism's oscillatory behaviour to produce sound directly, this provides appropriate means for a composer to fine tune and create variations in the final sonic result.

3 Granular Synthesis Engine

Due to *P.polycephalum* taking several days to span an environment, we designed custom software that implements our granular synthesis approach over the duration of the organism being active. Here, we take 100 samples from each electrode every second, which are then averaged to produce a single reading per second. The software then transcribes these readings into audio buffers. At composer-defined intervals, each buffer is addressed to produce a sound grain, which are sequenced together in ascending order according to their running electrical potential average. Grain lengths are determined by scaling each electrode's potential difference value against the current average of all other electrodes, to a composer defined minimum and maximum grain length range. Each electrode's buffer is only addressed for grain creation if the organism is active in the respective area. Our software achieves this by reviewing each new measurement for oscillatory activity. Once initiated, the software automates the granular synthesis composition until the organism has exhausted all food sources and starts to fructify or progress into its dormant Sclerotium phase. Upon these conditions being met, the system halts and renders the resulting audio file. For our reference, images are taken of experiments at intervals of 5 minutes (see Figure 3 for examples). Currently, we have designed the system to accommodate up to eight electrode inputs.

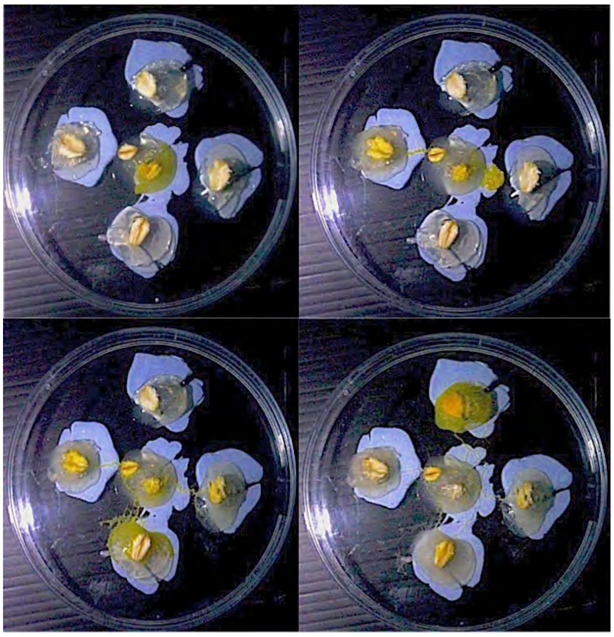

Fig. 3. Four sample images of the plasmodium's behaviour within the growth environment depicted in Figure 2.

4 Results

Considering that the growth environment depicted in Figure 2 illustrates a typical example of conditions for the plasmodium to forage in, on average it takes five days for experiments to complete. Shown in Figure 4 is a set of graphs denoting the typical electrical activity produced by the setup depicted in Figures 2 and 3. First, the plasmodium gradually propagates from the centre electrode to the measurement electrodes, which took two days to occur. When the plasmodium arrives at an electrode's site, readings show a quick rise followed by a sharp drop in potential. A clear example of this can be seen on electrode 4 in Figure 4. Colonisation happened first at electrode 3, next at electrode 1 followed by electrode 2, and, finally, then electrode 4. Propagation to each of these electrodes came equally from the central inoculation electrode as well as neighbouring electrodes. This propagation behaviour configures a protoplasmic vein network that connects each of the colonised regions together. The resulting morphology impacts the electrical activity measured by each electrode. This is because of the cellular waves of contraction and relaxation that interact and proliferate across the organism. Such activity can result in a series of impulses that can spread a distance across the organism, according to the amplitude and conditions at other colonised regions. An example of which can be seen on electrodes 1 and 2 (marked by the rectangle). The Sclerotium phase is characterised by an increase in voltage (marked by the triangle). In this example, we experimented with using light to impact oscillatory behaviour. The effect of this can be seen on electrode 4 where 3 periodic bursts of light have caused spiking and an increase in amplitude (marked by the circle).

Shown in Figure 5 is a cochleogram of the granular piece produced by our system from the setup in Figures 2 and 3, and graphs in Figure 4. In this example, the system generated 174 seconds of audio material from five days of plasmodium electrical activity. Notice the dark lines in Figure 5 and how they are morphologically related to the electrical plots displayed in Figure 4. An audio example of granular synthesis material produced by the approach presented in this paper can be found at [5].

5 Discussions

Composing with granular synthesis can be extensive and a sonically detailed process. Compositions that conform to conventional musical theory have a temporal hierarchy of structure. Part of the compositional process is managing the interaction between structures on different time scales - from individual note level to the topmost level of a complete composition. When composing with granular synthesis, there are additional levels that go below note level to grain level. At grain level, there is a massive quantity of control data required to advance to higher perspective sound levels. For example, if each grain has n quantity of parameters (these often exceed double digits), and there is q amount of grains in a second long sound object, then n multiplied by q equals the amount of

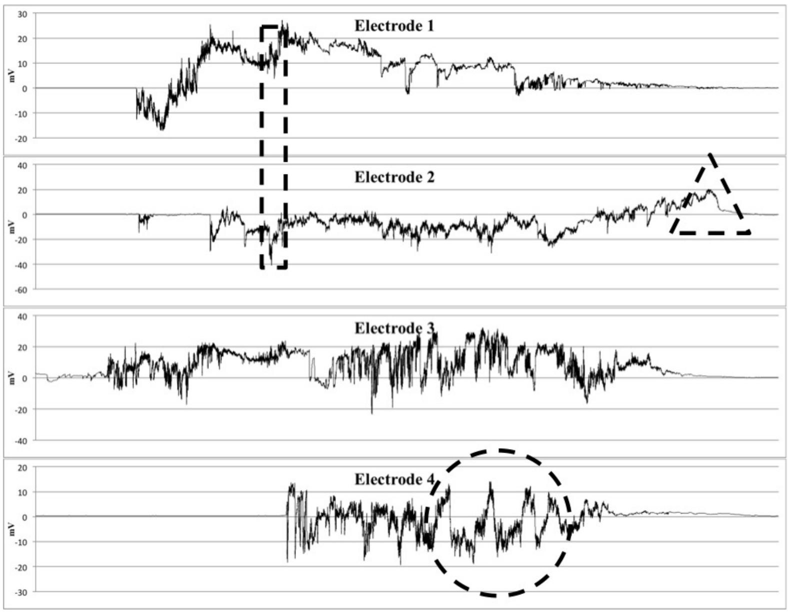

Fig. 4. Graphs depicting the electrical activity recorded on each of the electrodes within the growth environment shown in Figure 2.

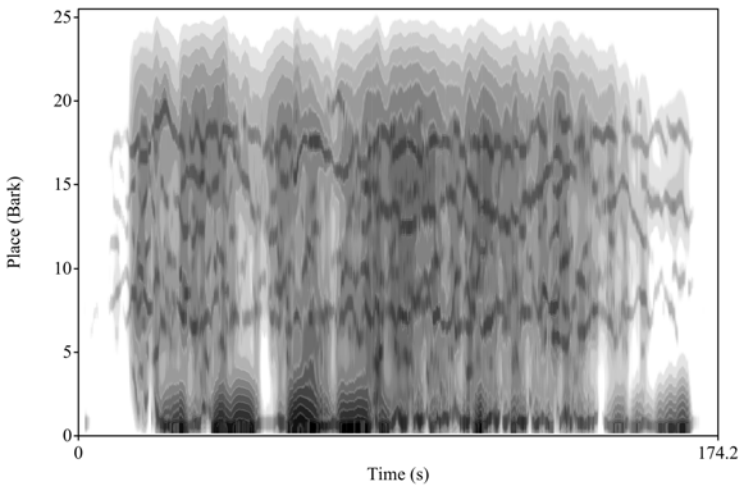

Fig. 5. A cochleogram of the granular piece produced by our system from the setup in Figures 2 and 3, and graphs in Figure 4.

data needed to produce a second of audio. As such, composers wishing to adopt granular synthesis in their works often require algorithms that produce grains in accordance with global parameters.

The approach presented in this paper is useful for the composer wishing to use granular synthesis. This is because the approach automates the production of grains, and, by controlling the plasmodium's behaviour, the composer has a level of control over the sonic result. Moreover, by creating different arrangements of electrodes within an experimental arena, we can achieve a variety of audio densities and output lengths.

Currently, our approach takes several days to generate a few minutes of audio, which can make its employment tedious. In [13], we experimented with using a model of the organism to overcome this time constraint. Although this approximation is useable, it is simple in its assumptions and implementation and offers limited methods of interacting with behaviour. As such, to advance this paper's approach, we are experimenting with the plasmodium's vibrant intracellular activity. Here, we are looking into tracking the organism's shuttle streaming of biological components through a microscope camera (Figure 6).

6 Conclusion

This paper has presented an approach to granular synthesis using the biological computing substrate *P.polycephalum*. At this early stage in our research, we are spending a lot of time investigating and experimenting with how the application of *P.polycephalum* may be used to go beyond our standard offering in computer music. In the context of this paper, we are not concerned with the computational properties of *P.polycephalum*; rather, we are interested in building a sound/music-orientated understanding of its behaviour. For music, *P.polycephalum* is interesting because its behaviour can be controlled to produce variations of electrical activity (e.g., by using attractors or directing light on the organism), which consequently creates variations on the resulting audio. Methods of controlling and interacting with *P.polycephalum's* behaviour is incipient and an active area of research in laboratories worldwide. We are currently experimenting with musical ways that we can use *P.polycephalum's* behaviour in real-time.

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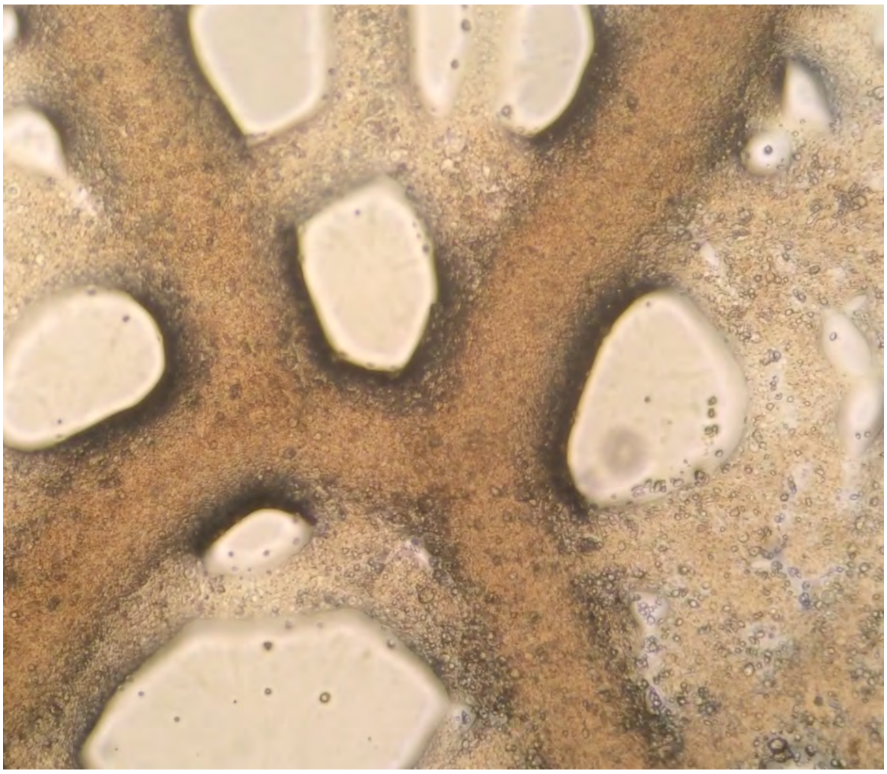

Fig. 6. A photograph of a protoplasmic vein junction under a microscope. We are currently investigating the feasibility of tracking the movement of intracellular components to control the parameters of audio synthesis frameworks.

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