Music with Unconventional Computing: Towards a Step Sequencer from Plasmodium of *Physarum Polycephalum*

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Abstract. The field of computer music has evolved in tandem with advances made in computer science. We are interested in how the developing field of unconventional computation may provide new pathways for music and related technologies. In this paper, we outline our initial work into harnessing the behaviour of the biological computing substrate *Physarum polycephalum* for a musical step sequencer. The plasmodium of *Physarum polycephalum* is an amorphous unicellular organism, which moves like a giant amoeba as it navigates its environment for food. Our research manipulates the organism's route-efficient propagation characteristics in order to create a growth environment for musical/sound arrangement. We experiment with this device in two different scenarios: sample triggering and MIDI note triggering using sonification techniques.

Keywords: *Physarum polycephalum* · Sonification · Unconventional computing · Computer music · Future music · Biomusic · Step sequencer · Bionic engineering

1 Introduction

Computing technology has played a pivotal part in the development of music over the last 80 years. The field of computer music was conceived during the 1950s, where a computer scientist with a musical background manipulated the architecture of the CSIRAC machine to play a selection of popular melodies [1]. Since this early interdisciplinary endeavour, 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 impact the field of music. We are interested in researching how the developing field of unconventional computation may provide new pathways for music and related technologies.

During the past 70 years, what we consider to be conventional computation (Turing computation [2] and the von Neumann architecture [3]) has advanced at a rapid frequency. Amongst computer scientists, there is a growing consensus that we will one day reach the limit of today's conventional computing

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paradigms, which is a result of our ever-growing need for faster and more efficient technology. As a result of this, research into new, unconventional, computing models is building in momentum and popularity. Defining what constitutes an unconventional computing scheme is a matter of personal orthodoxy. As an overview, words from Toffoli give a general definition of what an unconventional computing scheme is: *"a computing scheme that today is viewed as unconventional may well be so because its time hasn't come yet-or is already gone"* [4].

Research into new unconventional computing schemes develops new concept algorithms and computing architectures inspired by or physically implemented in chemical, biological and physical systems. Current unconventional computing paradigms include quantum computing, DNA computing, molecular computing and reaction-diffusion computing [5]. Researchers state that if the same level of development is mirrored in the advancement of new, unconventional, computation then the *"world of computation will be unrecognisably different from today"* [6].

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. Lately, with research into unconventional modes of computation increasing, the accessibility of prototypes has been widening. This increased accessibility has enabled computer musicians to begin exploring the potential of emerging unconventional computing paradigms [7].

Although research into unconventional computing in music is in its infancy, there are a number of projects beginning to emerge. To the extent of our knowledge, these mainly adopt sonification approaches. One early example explored using chemical computing by way of a Cellular Automata model to control a granular synthesiser [8]. Another example investigated synthesising sounds with a hybrid wetware-silicon device using in vitro neuronal networks [9].

Regarding our research, there are many unconventional computing prototypes currently being developed that could hold potential for computer music. However, many of these require expensive laboratory equipment along with specialist knowledge to allow computational prototypes to be developed. At this stage of our research we needed a more accessible medium to begin conducting our experiments. Uniquely, the biological organism *Physarum polycephalum* (hence forth known as *P.polycephalum*) requires comparatively less 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 *P.polycephalum* to begin investigating how new, biological, computing schemes may offer new pathways for music.

1.1 *P.polycephalum*

P.polycephalum (Fig. 1) is a unicellular organism of the order *Physarales*, subclass *Myxogastromycetidae*, class *Myxomycete*. From spore germination

P.polycephalum exhibits a complex thirteen-phase lifecycle, normally residing in cool, moist and dark environments. During its vegetative plasmodium phase, *P.polycephalum* exists as an amorphous single cell (visible via the human eye) with a myriad of diploid nuclei, which moves along gradients of chemical and light stimuli. The plasmodium propagates towards chemo-attractants and away from chemo-repellents, which have formed a gradient on a substrate. Propagation is achieved by extending pseudopods, which disperse forming a search front while building a route-efficient network of protoplasmic veins connecting foraging efforts and areas of colonisation (Fig. 1). Upon discovery of food, the plasmodium surrounds it with pseudopods and feeds through the process of phagocytosis, ingesting nutrients that are spread across the organism via shuttle streaming. Conversely, if matter is discovered which does not entice the appetite of the plasmodium, the area is avoided.

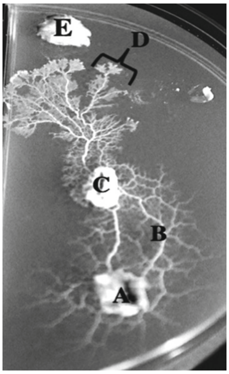

Fig. 1. A photograph of plasmodium of *P.polycephalum* showing: (A) inoculation of plasmodium into the environment, (B) protoplasmic network connecting areas of colonisation, (C) colonised food sources, and (D) extending pseudopods forming a search front along a gradient to food marked by (E).

The topology of plasmodium has been described as a network of biochemical oscillators: waves of contraction or relaxation which collide inducing shuttle streaming, distributing nutrients across the organism. This intracellular activity produces fluctuating levels of electrical potential as pressure within the cell changes. Typically this is in the range of ±50 mV, displaying oscillations at periods of approximately 50–200 s with amplitudes of ±5–10 mV [10], dependent on the organism's physiological state. When recorded in isolated zones of colonisation, patterns emerge in accordance with spatial activity and environmental conditions. Research has been put forward which highlights that such patterns can be used to accurately denote behaviour [11].

In regards to unconventional computing, *P.polycephalum* has been used for a wide variety of computations, such as execution of logic gate schemes [12], colour sensing [13] and robot manoeuvring [14] (see [15] for a collection of computing schemes harnessing *P.polycephalum* and directions for its use).

In this paper, we implement a step sequencer exploiting *P.polycephalum's* route-efficient foraging behaviour and fluctuating electrical potential. Our rationale for implementing such a device is derived from the organism's ability to solve mazes, find shortest paths and develop networks linking sources of nutrients. The idea of a *P.polycephalum* step sequencer was conceived when reviewing sets of time-lapse images with correlating electrical activities. We noticed how the organism oscillates protoplasm around a network of veins to colonised regions, and how this relates to the architecture of a musical step sequencer. We conceptualised a sequencer where *P.polycephalum* controlled step activation through propagation trajectories/colonisation, and sound event triggering with fluctuating levels of electrical activity.

2 The *P.polycephalum* Step Sequencer

A natural characteristic of plasmodium is the significant time it takes to span an environment: on average it takes several days to exhibit substantial growth. This creates an issue when harnessing its behaviour for real-time musical application. Currently, methods of exploiting *P.polycephalum's* behaviour for real-time computation is an active area of research in labs worldwide. As an interim solution, Jones has developed a computer approximation of the organism [16]. During the preliminary stages of our research into unconventional computing and music, we experimented with this approximation in sonification [17] and contemporary composition scenarios [18]. Although this approximation is useable, it is simple in its assumptions and implementation. To progress our research, it is beneficial for us to begin experimenting directly with the biological computing substrate. For us to achieve this, we record behaviour, which we then apply in our sequencer. The majority of computational prototypes with *P.polycephalum* record activities using time lapsed imagery of spatial progressions [15]. Although this gives a comprehensive record of movement, it lacks any information regarding intracellular activity and physiological states. As a result, for our experimentation we use a combination of time-lapse imagery and electrical potential data to record behaviour.

Step sequencers are software or hardware devices that loop through a defined quantity of steps at set time intervals. Each of these steps can normally exist in one of two states: active or inactive. When active, a predefined sound event will be triggered as the sequencer reaches its respective position in the loop. To implement the *P.polycephalum* step sequencer, we design an environment that represents a step sequencer's architecture. Shown in Fig. 2 is the design that we put together, which consists of six electrode zones (sequencer steps) ($S_1 \ldots S_6$) arranged in a circular fashion with a central inoculation area (C). This 360° design mimics a sequencer loop, and gives each step equal weighting in the sequence. In order to entice propagation and promote colonisation in each zone (step activation), an attractant is positioned in the centre. This is also extended to the inoculation area to create an initial central node that can propagate in any of the six directions throughout the experiment, increasing the chance of steps becoming active in a non-sequential order.

Fig. 2. Step sequencer growth environment design

2.1 Methods

In order for us to record the behaviour of *P.polycephalum* we use two forms of hardware: a USB manual focus camera and high-resolution data logger. Each experiment takes place in a plastic petri dish 90 mm in diameter with the camera centred above. To guarantee an environment that promotes growth, a black enclosure is placed over the experiment limiting the light intensity level imposed on the plasmodium. To illuminate the petri dish for image capture, an array of white LEDs turn on periodically.

Electrical potential levels are recorded using an ADC-20 high-resolution data logger manufactured by Pico Technology UK. Within each petri dish, bare wire electrodes are wired in place through small holes in the base with wiring underneath secured using adhesive tack. Electrodes are arranged with one reference and six measurements: the reference resides in the centre and gives a ground potential for each of the measurement electrodes.

Each step's electrode is coated in non-nutrient agar, which keeps humidity high and promotes growth/colonisation. Due to the agar substrate being liquid based and thus a conductor, a non-conductive plastic isolates each step, allowing electrical potentials to be recorded across the environment without interference. Shown in Fig. 3 is the electrode array layout before being coated in agar and after. Attractants (oat flakes) are placed on top of each step, maintaining an equal distance from the centre to entice the propagation and facilitate colonisation. To start each experiment, a piece of plasmodium is inoculated on the centre region. Inoculation sources are extracted from a small *P.polycephalum* farm (see [15] for farming techniques), and put through a period (approximately six-seven hours) of starvation before the experiment begins. This starvation process speeds up initial propagation speed.

Once the plasmodium has been inoculated into position, we begin to record behaviour. To achieve a uniform and coherent set of data we use our own developed software system, designed to record *P.polycephalum* behaviour [19,20]. Throughout the duration of the experiment, our software takes 100 data samples from each electrode at 1-s intervals, samples are then averaged to give a single reading for each second. This level of recording detail is necessary in order to

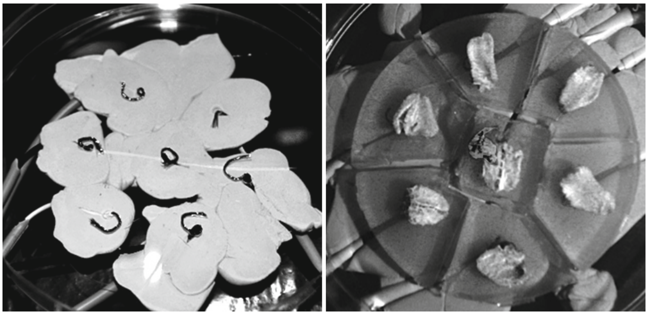

Fig. 3. Photographs showing the construction of the growth environment. Shown left is the bare wire electrode array wired into position. Right shows the completed growth environment with each electrode embedded within blocks of agar.

capture the natural gradients exhibited with various progressions, some of which are fairly prompt. Images are taken at intervals of 5 min with the LEDs turning on 5 s before and staying active for 10 s.

2.2 Results

The data collection process took just under five days to complete and was halted as the plasmodium entered its dormant Sclerotium phase. This occurred as a result of a drop in humidity as the agar substrate dried out in conjunction with a lack of nutrients as food sources within the environment became exhausted. The collection process generated an excessive quantity of electrical potential data: circa 330000 entries for each measurement electrode. Harnessing this quantity of information in our device would result in extremely long sequences of sounds. In order to circumvent this, we apply a compression algorithm. From our musical intention point of view, it is important while compressing this data that time based meaning and relevant gradients between behavioural patterns are maintained. Here, we view the data not as individual electrodes but as sets of entries for each second. First, we reduce quantity through combining blocks of 10 entries and averaging their measurements, leaving a single entry for $e_1 \ldots e_6$. We then process the subsequent data in the following manner: n entry is only withheld from removal if two measurements from $e_1 \ldots e_6$ present a change over a set threshold (b) from their counterpart within the previous entry stored (n^{-1}). This is expressed in the following where if ${}_x(\mathrm{S}) = 1$ the entry is withheld, otherwise it is lost:

$$\sum_{i=1}^{6} x(|e_i^n - e_i^{n-1}| \geq b) \geq 2 \tag{1}$$

This compression stage reduced the quantity of entries to circa 5500, while maintaining behaviour patterns and the voltage gradients between them.

Presented in Fig. 4 are graphs representing each measurement electrode's entries after compression.

It took the organism just under 12 h to propagate to a step. When the plasmodium arrives at an electrode's substrate, a fast change in voltage is registered, which in our results is an increase ranging from ±5–15 mV. Propagation to each step came equally from both the central node as well as neighbouring steps. Activities and conditions within colonised regions cause differing intracellular activity, which in turn can result in electrical impulses across the organism. Such impulses are typically registered in regions connected directly, but may spread a distance across the organism if the amplitude and conditions at other regions are favourable. This can be seen on electrodes 3, 4 and 5 in Fig. 4, marked by the rectangle. Also, regions that are propagated to simultaneously exhibit initial synchronised patterns in their electrical potential. In our experiment, this is the case for electrodes 1 and 2, as shown by the triangle in Fig. 4. The Sclerotium phase is characterised by a increase in voltage. This is marked by a circle on electrode one in Fig. 4.

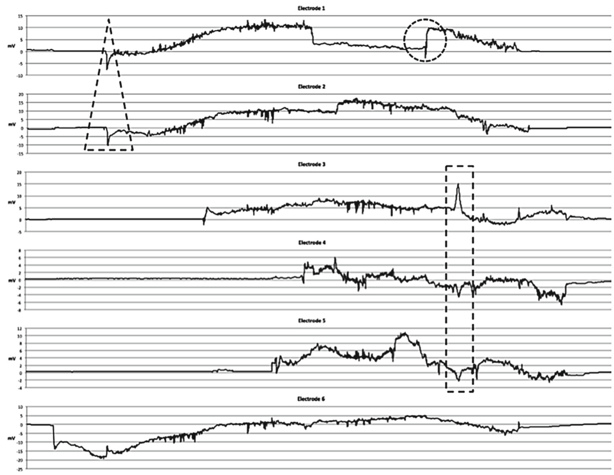

Fig. 4. Graphs of results

2.3 Step Sequencer

We programmed this device in Max with some data handling operations being dealt with in Java. First, we established a data recall system. Here, the user can define how fast they wish the electrical potential data to be recalled into the system in entries per second. Upon doing so, the system defines the frame rate for the time lapsed imagery, in order to play back the images in motion with perfect synchrony. As with any musical devices, the user interface is an integral part of its function. Within this device, the interface is built around the time lapsed imagery playback, inducing a connection between the user and the organism. Once in the system, each electrical potential entry is broken into its six individual readings and altered to become an absolute value. The system then steps through each measurement in a 360 ° order taking a reading at a user defined BPM. Steps only become active within the sequence once populated by the plasmodium. Until this time, no reading is taken. Once activated, the system looks for a level of change in electrical potential in order to retire steps from triggering sounds when the plasmodium is no longer active. This is achieved by storing readings over a short period of time and reviewing any oscillatory behaviour.

We decided to experiment with our sequencer in two different scenarios. The first looks at harnessing *P.polycephalum's* behaviour to extend the functionality of the conventional step sequencer by triggering different sounds as a function of each step's electrical potential reading. Here, the readings taken by the metronome are used to trigger one of four sound samples assigned to each step, which are associated with a voltage range. We tested this device using a set of piano samples all belonging to the key of C major. This sample set consisted of a variety of dynamic chords, notes and short phrases. These were assigned in a logical manner where samples we considered to have a higher value are triggered through elevated electrical potential readings.

The second scenario is novel and takes the form of a MIDI instrument. Here, the recorded behaviour is put through a sonification model where the user can change the parameters. Readings taken by the sequencer are used to trigger a set of nine MIDI notes that are programmed in by the user. All steps are allocated a set of four notes from the nine available, which are then each assigned to a voltage trigger range. When a note is triggered, its velocity is produced through scaling the step's current electrical potential value to the MIDI data range. In order to determine the duration of a note, the current average potential of all other steps (active and non-active) is calculated, and then compared to the triggered step's voltage to produce a potential difference value. The higher this value, the more significant the note duration will be within the sequence, with a maximum duration being four beats. The sequencer is limited to only allow six notes to sound at a time; if a note is triggered but is unavailable due to being made active by another step, the note with the closest value in the step's priority list will sound. To make this version of the sequencer versatile, we allow each step's note priority order to be changed in real-time. Furthermore, we implemented an interactive graph showing the combined electrical potential readings. This allows the user to change the current position of the data being recalled, creating means to restructure the output of the sequencer. Shown in Fig. 5 is the sequencer user interface.

3 Discussions

We explored two scenarios for the *P.polycephalum* step sequencer: sample and MIDI note triggering (for sound recordings see [21]). The output of our device in both scenarios produced a variety of interesting arrangements, which can be

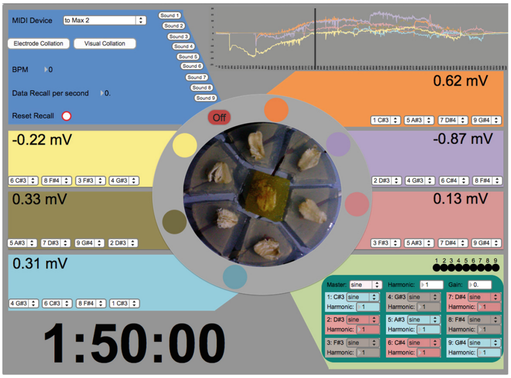

Fig. 5. The step sequencer user interface

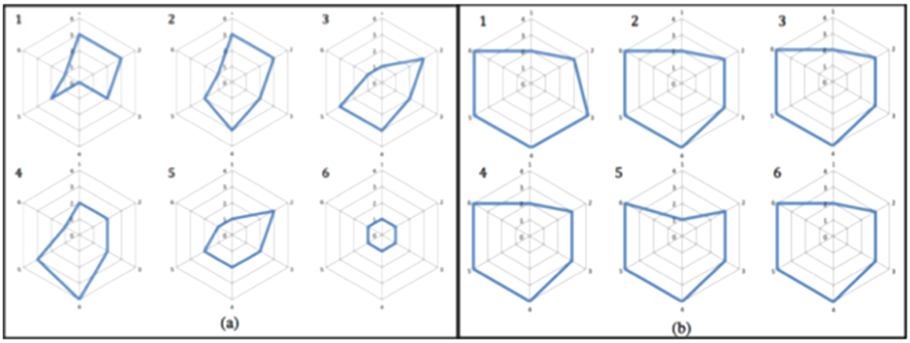

Fig. 6. Radar graphs depicting two sets of six consecutive sequencer loops. Set (a) shows the sequencer's most dynamic arrangement, while (b) shows a repetitive arrangement.

used by musicians in several different ways. In the sample-triggering scenario, we found that by allocating sounds to a relative voltage range - for example, higher velocity sounds to elevating voltages - a naturally progressive output is achieved (Fig. 6a). However, at certain points, the sample arrangement can become slightly repetitive (Fig. 6b). From a musical perspective, we believe the MIDI scenario gave more useful and interesting results. This version of the device outputs a progressive arrangement of notes, which correspond morphologically to the recorded foraging behaviour. As a sonification of behaviour, the produced output does convey auditory representation of voltage levels quite accurately. This is because each note's velocity is produced directly by the respective step's voltage - a parameter that directly relates to energy. Moreover, by producing each note's duration with a potential difference value, it is possible to compare activity on each step through listening. From a musical perspective, having note velocity controlled this way is slightly undynamic due to voltage levels also controlling which notes are triggered: each note is played with a similar velocity every time. As a compositional tool, we found this version of the sequencer useful for arranging sets of notes that we composed and applying interesting variations over time.

Currently, our device works offline, using behavioural data gathered from an experimental process beforehand. Such an experimental process creates a large obstacle that limits the extended usability of the sequencer. Using the same set of behavioural data will result in a similar output each time. This constraint could be avoided by gathering more behavioural data, but this process takes several days and would be tedious. Moreover, this constraint poses a detrimental obstacle to overcome if the device was ever to be used during a live performance. To address this problem, we are proposing to engineer a live, wetware version of the sequencer, harnessing the organism's vibrant intracellular activity.

3.1 Future Work

P.polycephalum oscillates protoplasm around its network of veins through the process of shuttle streaming. Shuttle streaming is the intracellular movement of protoplasm back-and-forth. Under a microscope, this streaming activity is visible and can be seen moving at rates in excess of 1 mm/s [22]. Recently, researchers have been exploring how this behaviour may be used for various computational purposes, one example being logic gate schemes [12]. Cifarelli et al. have demonstrated that it is possible to load the organism with micro-particles, which are picked up and moved around with shuttle streaming [23]. We are interested in exploring how we could use the movement of such micro-particles to trigger sounds as they pass through certain areas of the organism. We intend to load the organism with micro-particles and place high magnification cameras over various parts of its network. Such cameras will feed into a system that is programmed to recognise when a micro-particle passes. In relation to a step sequencer, each camera will represent a step in the sequence where a sound event is triggered upon a particle's passing.

The ability to interact, control and repeat the behaviour of a composition tool is important to musicians. In our current device, these are all possible due to the device working off-line and using the same set of behavioural data. In the case of our proposed wetware sequencer, controlling the behaviour of *P.polycephalum* in real-time is still an active area of research in laboratories worldwide. In regards to controlling certain aspects of the shuttle streaming process, researchers have found that through gentle tactile stimulation of the protoplasmic vein, a person can change the direction and pause movement (see [24] for a video demonstration). It is possible that this stimulation method could be an approach for a composer to interact and play the wetware sequencer.

4 Conclusion

In this paper, we reported on our initial work into engineering a musical step sequencer with the biological organism *P.polycephalum*. *P.polycephalum* is currently gaining a lot of research interest in the field of unconventional computing. We have selected it as the biological computing substrate for our investigations into how new, non-classic, computational paradigms may provide new pathways for music and related technologies. It is a good candidate for such research due to its ease of application and open accessibility.

At this early stage in our research, we are spending a lot of time investigating and experimenting with what type of musical application *P.polycephalum* may be used in to go beyond our standard offering. The step sequencer presented here is an early example. The *P.polycephalum* step sequencer in the sample-triggering scenario adds a new dimension to our conventional sequencer devices by naturally progressing the arrangement of sound events. However, a similar result could be achieved through conventional automation and computer programming. The MIDI note scenario is slightly different; this harnesses a selection of sonification techniques and parameter mappings, creating an auditory representation of the recorded behaviour.

The limitations of working with *P.polycephalum* for music have become apparent from our experimentation. The time the organism takes to display behaviour is extensive, causing a large obstacle to overcome when designing musical systems. We have outlined our plans to develop a live wetware version of the sequencer, which will exploit the organism's unique intracellular movement. The implementation of such a device would be a large step forward for unconventional computing in music, being one of the first musical wetware devices.

To conclude, the intersection of music and unconventional computing is very much in its infancy. To begin understanding how this branch of computer science may be used in music, we need to immerse its application across the field. This process will widen our appreciation and lead to advances as the computing paradigm lends itself to certain applications.

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