BioComputer Music: Generating Musical Responses with *Physarum polycephalum*-based Memristors

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Abstract. This paper introduces *BioComputer Music*, an experimental one-piano duet between pianist and plasmodial slime mould *Physarum polycephalum*. This piece harnesses a system we have been developing, which we call *BioComputer*. *BioComputer* consists of an analogue circuit that encompasses components grown from the biological computing substrate *Physarum polycephalum*. Our system listens to the pianist and uses the memristive characteristics of *Physarum polycephalum* to produce a list of notes to generate a musical response with, which it plays through electromagnets placed on the strings of the piano. Such electromagnets set the strings into vibration, producing a distinctive timbre. *Physarum polycephalum* is an amorphous unicellular organism that has been discovered to exhibit memristive qualities. The memristor changes its resistance according to the amount of charge that has previously flown through. In this paper we introduce the general concepts, technology and musical composition behind the *BioComputer Music* piece. Our rationale for using *Physarum polycephalum* is also discussed.

Keywords: *Physarum polycephalum*, Memristors, Unconventional Computing for Music, Computer Music, Biomusic, Biological Engineering

1 Introduction

The field of computer music has evolved in tandem with advances made in computer science. We are interested in how the field of unconventional computation [4] 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 offer new pathways for music. For a survey of unconventional computing in music see [9].

The plasmodium of *Physarum polycephalum*, henceforth known as *P.polycephalum*, is an amorphous unicellular organism (visible to the human eye) with a myriad of diploid nuclei. The plasmodium inhabits dark, cool and moist environments and feeds on micro-particles and creatures such as bacteria and spores. It propagates along gradients of stimuli while building a route-efficient network of protoplasmic veins connecting foraging efforts and areas of colonisation (Figure 1). The visual result of the organism's network is a planar graph where colonised food sources represent nodes and protoplasmic veins represent edges. The intracellular activity of *P.polycephalum* has been described as a network of biochemical oscillators [26]: waves of contraction colliding. This contraction behaviour induces shuttle streaming, which switches direction approximately every minute.

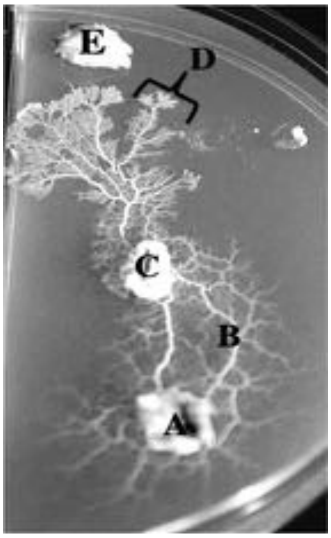

Fig. 1. A photograph of plasmodium of *P.polycephalum* showing: (A) inoculation of plasmodium into the environment, (B) protoplasmic network connecting areas of colonisation, (C) colonised food sources, and (D) extending pseudopods forming a search front along a gradient to food (E).

P.polycephalum's behaviour can be interpreted as computation [1]. Computing prototypes exploiting *P.polycephalum's* behaviour include robot control [24], logic gate schemes [3], route planning [23, 2] and numerous others [1]. We have developed several projects that harness the behaviour of *P.polycephalum* for music. These include sound synthesis [20, 7, 6, 5], a biologically inspired step sequencer [8] and contemporary composition [18].

In this paper, we give an overview of the music and technology behind the composition *BioComputer Music*. *BioComputer Music* is an innovative duet between pianist and an analogue circuit, which encompasses components grown from the plasmodium of *P.polycephalum*. This composition marks the beginning of our initial experimentation and research into building analogue hardware/wetware with *P.polycephalum* for music. The piece is to be premièred at the 2015 Peninsula Arts Contemporary Music Festival, Plymouth University, UK. This paper is structured as follows. First, we introduce the background conceptual information regarding the technology side of the composition. Then, we present the software and accompanying hardware that makes up the technology. Next, we discuss the *BioComputer Music* composition, offering our artistic motives behind the music. Finally, the paper ends with final remarks on using the presented technology to compose music with, and how we plan on progressing our work in the future.

2 Background Information

First, we give an overview to some underlying concepts behind the technology used for *BioComputer Music*, the first of which is the memristor. Memristors are the fourth fundamental passive circuit component that relates magnetic flux linkage and charge. The memristor's existence was originally theorised by Leon Chua in 1971 [10] but was not physically discovered until 2008 [22]. A memristor alters its resistance as a function of the previous charge that has flown through it. The current versus voltage characteristic of a memristor, when applied with an AC voltage, is a pinched hysteresis loop - a Lissajous figure formed by two perpendicular oscillations. Hysteresis is where the output of a system is dependent on both its current input and history of previous inputs. In an ideal memristor, this figure is observed as a figure of 8 where the centre intersection is at zero volts and current (Figure 2). For an excellent introduction to memristors see [15].

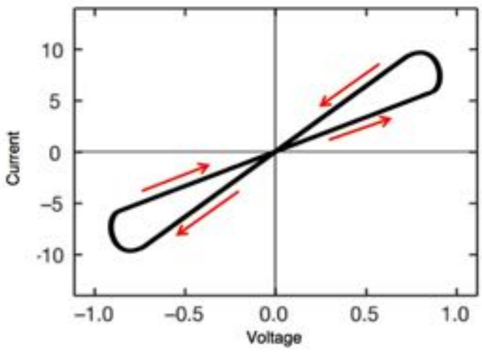

Fig. 2. Example of hysteresis in an ideal memristor (arbitrary values used).

We believe that the memristor's nonlinear ability to alter its resistance as a function of both its current input, and history of previous inputs, holds potential for music generation. Unfortunately, until recently, we have been unable to explore such potential due to the component not yet being commercially available. There has, however, been one investigation using a simulation of a memristor network under a DC voltage [12] to generate music [13]. Other labs have also been restricted in their memristor interests due to this lack of accessibility. As a result, researchers have been looking past conventional electrical engineering approaches and have found that a selection of organic systems exhibit memristive characteristics. Examples include human blood [16], human skin [14] and Aloe Vera plants [25].

In 2009, Pershin et al. [21] published a paper that described the plasmodium's adaptive learning behaviour in terms of a memristive model. Shortly after, Gale et al. [11] demonstrated in laboratory experiments that the protoplasmic tube of *P.polycephalum* showed I-V profiles consistent with memristive systems. These discoveries have conveniently allowed us to coincide our musical research interests in memristors and unconventional computing with *P.polycephalum*. Moreover, it has gifted us with an early opportunity to investigate how some of the memristor's characteristics may provide new pathways for music before they are made widely accessible.

In *BioComputer Music*, we experiment with the plasmodium's memristive characteristics: its nonlinear ability to alter its resistance as a function of the previous input current to generate musical accompaniments. Here, we have designed a system that transcribes the performance of a pianist into MIDI note information. The result of such transcription is subsequently scaled into voltages that together fabricate a discrete waveform that is passed through a *P.polycephalum* protoplasmic tube. We then measure the instantaneous resistance at each voltage step and, using mapping/sonification techniques, transcribe the evolved output to musical notes, which are played through electromagnets arranged above the piano's strings. In the following section, we give an overview of the *BioComputer Music* system.

3 The *BioComputer Music* System

The *BioComputer Music* system consists of two parts, hardware and software. First, we explain the hardware, which consists of eight protoplasmic tubes (henceforth referred to as components) grown from plasmodium, two electrical instruments, USB relay boards and twenty-four electromagnets.

We use eight components for our system as successive applications of voltage cause the organism to retire the grown component and forage for food elsewhere. Thus, to reduce the stress imposed on each component, our system alternates between eight. We have noticed that excessive use of any single *P.polycephalum* component causes the overall resistance to increase. Furthermore, after approximately 4 minutes of successive voltage application the component begins to dry up. As such, we alternate between components approximately once every 3 minutes. Note, we are aware that findings from [11] indicate that hysteresis loops vary heavily in magnitude from organism-to-organism and are often asymmetric (see Figure 3 for examples). It is thought that such asymmetry is due to the organism producing an internal current source, which, dependent on direction of flow, will oppose or add to driven current. In most electrical engineering situations, this would be detrimental to application. For music generation, such variation can be desirable and even sought after: composers are known to use a wide span of different processes (e.g. stochastic) to evolve their compositions. As such, we are not concerned about the stability of hysteresis at this point; rather, we are keen to investigate this quality as a stylistic trait of using *P.polycephalum*. However, methods of improving stability may be a future area of research when silicon memristors become accessible, as some level of repeatability in hysteresis will widen the application and usability of our system (e.g. performers wanting to perform a composition consistently).

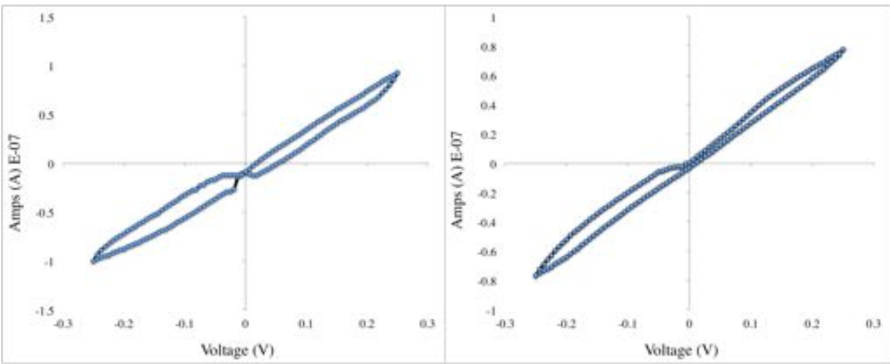

Fig. 3. Two examples of *P.polycephalum* hysteresis recorded at ICCMR labs under a fabricated AC voltage waveform of 160 steps, voltage range of ±250mV and a step dwell time of 2 seconds.

To produce the plasmodium needed to grow the components, we adopt techniques from [1]. Here, we farm the organism in plastic containers on a moist, porous substrate. The farm is fed daily with oat flakes and replanted approximately once a week. *P.polycephalum* components consist of two electrodes linked via a protoplasmic tube. Electrodes are comprised of a circle (approximately 2cm in diameter) of tinned copper wire (16 stands at 0.2mm) filled with a 2-percent non-nutrient agar. To grow the components, a colonised oat flake is taken from our farm and placed on one of the electrodes while a fresh oat flake is placed on the other. This arrangement causes the plasmodium to propagate along a chemical gradient to the fresh oat, resulting in a protoplasmic tube linking the two electrodes (Figure 4). This setup is derived from the original *P.polycephalum* memristor investigations [11]. To house eight of these components, two 120mm square Petri dishes are divided into four sections (Figure 5). During the *Bio-*

Computer Music piece, humidity is kept high for the components by fixing a moist cloth on the lid of each dish. This also limits the light intensity imposed, restricting any adverse phototaxis effects.

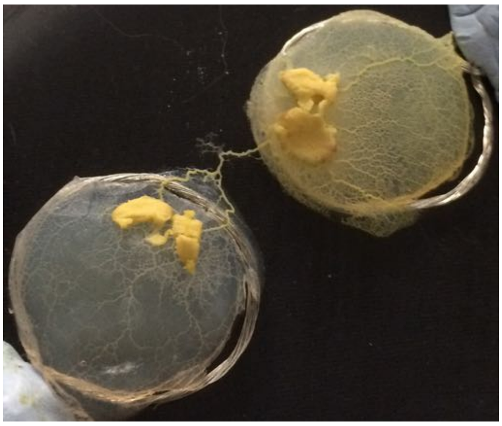

Fig. 4. A *P.polycephalum* component grown between two electrodes comprised of a circle (approximately 2cm in diameter) of tinned copper wire (16 stands at 0.2mm) filled with a 2-percent non-nutrient agar.

Two eight-channel USB relay boards facilitate alternation between each component. Here, the first board regulates which component is applied with a voltage from a Keithley 230 programmable voltage source, while the second controls which component's output is being measured by a Keithley 617 programmable electrometer. We interface with each of the Keithley instruments using a Prologix GPIB USB controller.

To enable the *BioComputer Music* system to accompany the pianist, we furnished twenty-four of the piano strings with electromagnets (Figure 6). These operate by exciting the strings with an audio signal sent by our software. Currently, the system is restricted to only having up to six magnets active simultaneously. This is due to the audio interface we are using having only six outputs.

The software side of the *BioComputer Music* system is designed in Max by Cycling 74. Our software is primarily intended to act as a translator between the pianist, hardware and electromagnets. Before the *BioComputer Music* system can be used, the software needs to be informed of which strings the electromagnets are positioned on. This information notifies the software of the notes that it has available to play. Furthermore, within the software there are banks of performer-switchable pre-sets (these are made switchable via an ipad). These allow for the following parameters to be defined: active notes out of the available twenty-four, minimum and maximum note duration range, accompaniment speed factor and electromagnet excitation source. The relevance of each of these is denoted below. When in use, the software is operating in either listening or

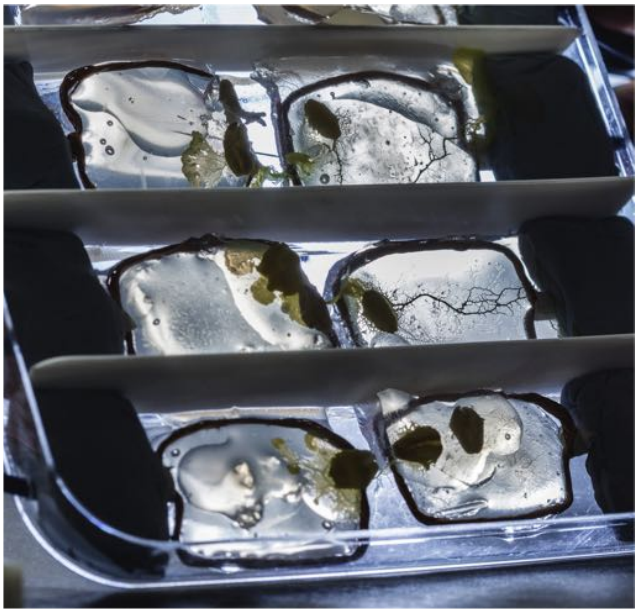

Fig. 5. Four components grown from the plasmodium of *P.polycephalum* housed in a 120mm square Petri dish.

Fig. 6. A photograph of twenty-four electromagnets furnished above the strings of a grand piano.

playing mode. When listening, the pianist is inputting into the system. Conversely, when in playing mode, the system outputs its response to the input. In this mode, the software no longer listens to the performer, but feeds back the newly generated notes into the hardware.

When listening, the software takes an audio feed from a microphone positioned above the strings of the piano. This audio signal is transcribed into MIDI note information via an FFT process, with the aid of piano-specific pitch templates. Once transcribed, the MIDI data is passed through an algorithm that serves two functions. The first is to transpose the detected pitches to the notes the performer has made available to the system. For example, if E3 is detected, but only E2 is available, the algorithm will alter the MIDI note to E2. The second function: if a pitch is detected but is not offered and there is not an equivalent available in another octave, the pitch is removed. This algorithm is necessary as allows the performer to input into the system while playing the full piano range, not just the notes furnished with electromagnets.

Following the pitch recognition and transposition processes, notes are transcribed into voltage values. The software does this in batches of either ten notes or ten-second's worth of notes, whichever occurs first. Initially, each note available within the active preset is assigned a voltage value in the range of 100-240mV. For this project, notes are assigned in ascending order according to pitch. Our rationale for assigning voltages this way is simplicity at this early stage of using *P.polycephalum* components for music generation. In the future, we will look to experimenting with assigning voltage values in a more meaningful fashion; for example, assigning voltages according to the number of times a note occurs. Moreover, we are researching into the organism's conductance profile under different voltage scenarios with a view to taking better musical advantage of *P.polycephalum* memristive characteristics.

Once assigned, the transcribed MIDI note data is scaled to the voltage values to create a list, which the system uses to fabricate a complex symmetrical voltage waveform with a step dwell time of 2-seconds. Here, the first quarter of the wave steps through the list in order. The second quarter steps through the list in reverse order. The second half of the wave replicates the first half but in the negative voltage domain (Figure 7). To make the waveform symmetrical, we assign the node, crest and trough of the fabricated waveform 0mV, 250mV and -250mV respectively. This creates a fabricated waveform with the voltage range of $\pm$250mV, which we chose as in our experimentation we found that it produced the best results in terms of hysteresis and did not damage the organism. Moreover, we create waveforms in this fashion as the organism produces asymmetrical hysteresis loops and we are keen to experiment with how such asymmetrical resistance can be used to produce different variations of musical notes. Once fabricated, the waveform is communicated to the Keithley 230 voltage source, which it subsequently transmits to the currently addressed *P.polycephalum* component.

Interfacing with the Keithley 617 programmable electrometer, the software measures the instantaneous resistance response at each voltage step (node, crest

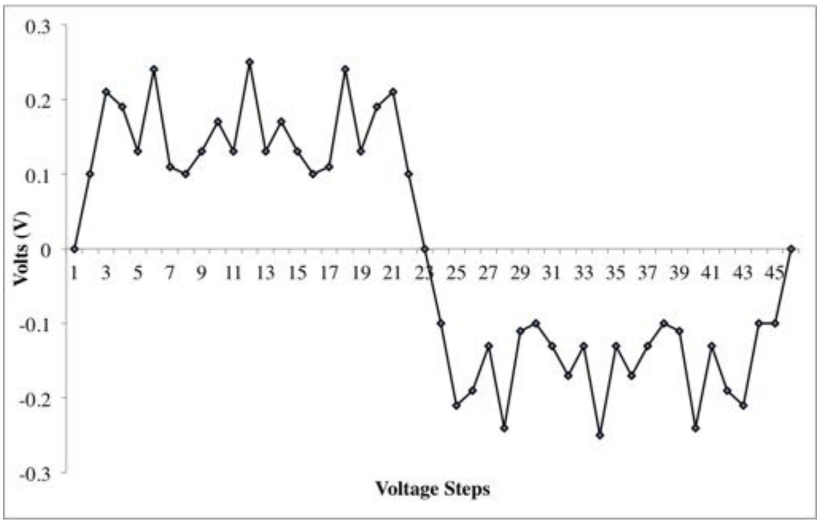

Fig. 7. An example of a voltage waveform fabricated from transcribed MIDI note data.

and trough voltages are not measured). This is calculated as in [11], where *P.polycephalum* is analysed as an active memristor. Shown in Figure 8 is a set of graphs denoting the instantaneous resistance measurements for each quarter of a fabricated waveform. Such measurements are subsequently transcribed back into MIDI note form using a mapping/scaling technique derived from the note-voltage transcription stage: available notes are arranged in ascending pitch order with higher notes being chosen by higher levels of resistance. This process is depicted in Figure 9. Each wave cycle generates four times the length of the input. The sequence of notes produced by the second and fourth quarter of the waveform are reversed; thus arranging them into the correct order.

At this stage of implementation, due to current resource constraints, the *BioComputer Music* system only uses the *P.polycephalum* components to generate lists of notes. To apply rhythmic structure, we use a conventional second order Markov chain, which uses the transcribed MIDI data as input prior to the filtering/transposition algorithm. The output of this Markov chain is altered using the performer's speed factor parameter. To discern note durations, we use a Gaussian distribution, which operates within the performer-defined minimum and maximum range. We are currently looking into feasible methods of generating both rhythm and duration from *P.polycephalum* components and anticipate that we will have an autonomous *P.polycephalum* music generation system in the near future.

As a result of using a voltage step dwell time of 2-seconds, the system can only generate notes at 2-second intervals. It is for this reason that the note generation process is started in concurrence with the performer inputting data while in listen mode. As the system generates notes to accompany the performer, they are listed into a buffer. Upon the *BioComputer Music* system being placed

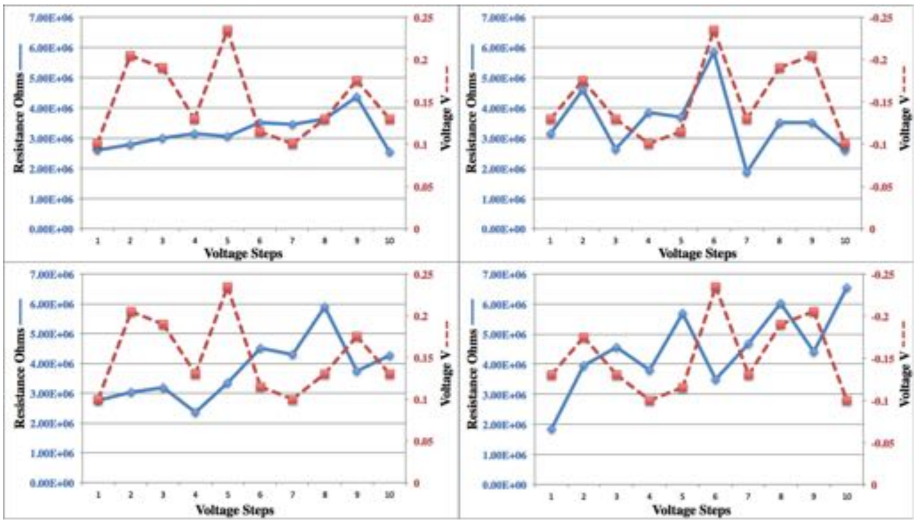

Fig. 8. Four graphs representing the *P.polycephalum* component's resistance at each voltage step. The red dashed line represents input voltage, while the blue solid line represents resistance. The voltage waveform used to create these graphs is shown is Figure 7.

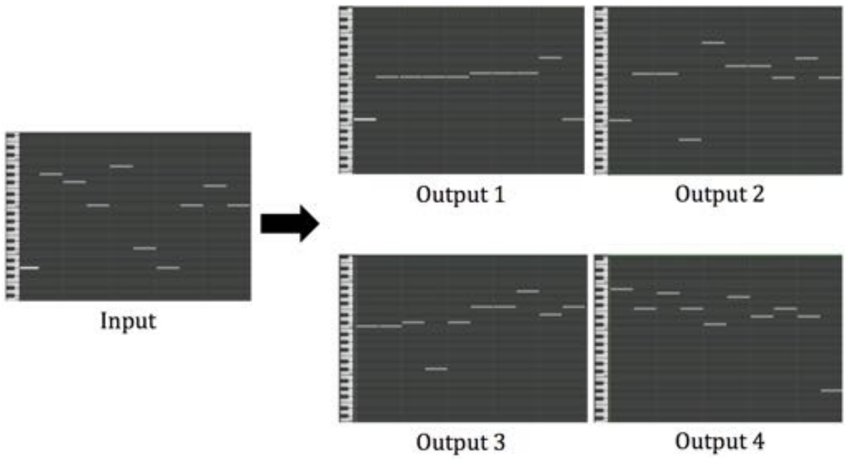

Fig. 9. An example of the *BioComputer Music* system's response to an input. Shown on the left is the input sequence of notes which are transcribed into voltages and sent through the *P.polycephalum* components. On the right, is the result of the resistance measurements for each quarter of the fabricated waveform (note that 2 and 4 have been reversed as explained). This is the musical result of the voltage and resistance depicted in Figures 7 and 8 respectively. Note, this figure is using a MIDI grid of 3 and a half octaves, only 10 notes within this range were available for the system to use; thus, the shape and distribution of notes in this figure are related to this.

into playing mode, the buffer's contents is translated into commands and sent to the electromagnet hardware. If the system is placed into play mode but is yet to process the entire input, it will continue to generate notes while in playing mode until it has processed the entire input. However, if the buffer's contents is exhausted prior to processing the entire input, the system will calculate the time needed to finish and will fill the time-lapse by repeating previously generated sequences. Conversely, if the system finishes processing the input, it will begin to process the notes it has already generated.

The electromagnets function by exciting their respective piano string using an audio signal sent from our software. This signal is defined in the performer pre-sets and can take the form of a combination of wavetable oscillators each automatically set at the respective string's harmonics or a sound sample loaded into a buffer. For detailed information regarding the electromagnet side of the *BioComputer Music* system, please refer to [17].

As a summary, the musical result of the *BioComputer Music* system in its current implementation is as follows. If a repetitive sequence of notes is input, then the fabricated waveform may become increasingly directional, resulting in decreased changes in resistance. Moreover, if only a single note is input, after the initial change in resistance, the organism over time will essentially become an ordinary resistor. Thus, the resistance measurement will remain the same, resulting in the same note playing with no variation. Conversely, under an extremely dynamic input, changes of resistance are likely to be higher, resulting in a wide span of notes being output.

4 The *BioComputer Music* Composition

A recording of a rehearsal of the *BioComputer Music* piece can be found at [19]. For the composition of *BioComputer Music* we explored the notion of interactivity between a composer/performer and the *BioComputer* system. We wanted to compose a piece that sounded as if the performer asks questions to *BioComputer*, which in turn answers them. This is a very traditional musical form, which originated from ecclesiastical music where the leader of a ceremony sings a prayer in alternation with a chorus. However, we wanted to be surprised by *BioComputer's* responses, which will vary from performance to performance, but within a certain boundary of constraints (composer pre-sets). Therefore, the piece consists of materials notated on a musical score for the pianist to play when the system is in listening mode. Once a section is played, the performer switches the system into playing mode and *BioComputer* system plays its response for a given period of time until the performer switches it back to listening mode and plays another section of the music, and so on. There are occasions where the pianist plays alongside the *BioComputer* system, but the latter does not listen to this because it would be in player mode.

An excerpt of the score is shown in Figure 10. In section 10, at the top stave, the symbol Bioset 8 is instructing the performer to switch the *BioComputer* system to player mode. While it is in player mode the performer plays three chords. At the bottom stave, the passage before section 11 is played on the piano while *BioComputer* is in listening mode. This section will then be processed by the system; that is, it will serve as seeds for *BioComputer* to produce a response as soon as the performer switches it to player mode, indicated by the symbol Bioset 9.

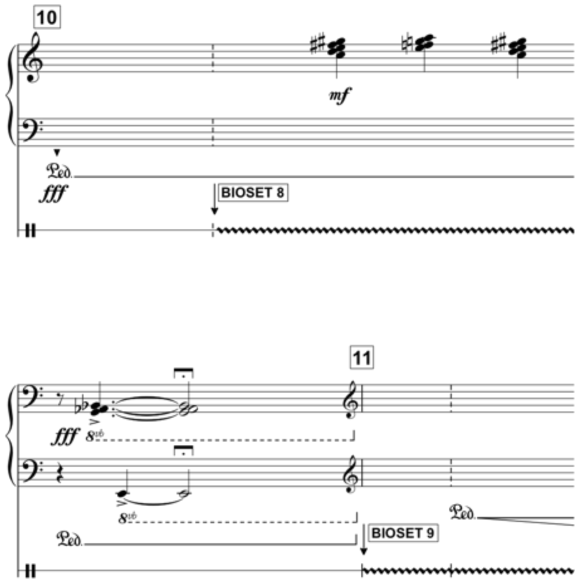

Fig. 10. An excerpt of the musical score for the composition *BioComputer Music*.

5 Final Remarks

To the best of our knowledge, *BioComputer Music* is the first musical composition that harnesses biological circuit components to generate music. *BioComputer Music* is an exciting new development for music not only in terms of technological novelty, but also in terms of approaches to creativity. In tandem with the scientific research, we also have been looking into how such new technology might lead to new approaches to musical composition. In terms of compositional practice, the *BioComputer* system has enabled us to revisit a few concepts that we have explored in previous compositions, but from a different perspective. One of them is the notion of musical interaction with a non-deterministic machine. We used to spend a great deal of time programming digital computers with artificial intelligence to interact with a performer in interesting ways. By interesting ways we mean in ways that are surprising and engaging, but not completely by accident. *BioComputer* makes this task much easier to achieve: it is a nonlinear machine in its own right and displays an intriguing level of intrinsic intelligence, which does not require much programming. It is ideal to develop the sorts of musical systems that we are interested in composing for.

In regards to our research into music with unconventional computing, the *BioComputer* system marks the beginning of a new avenue. Until now, in our research with *P.polycephalum* we have been using behavioural data that takes several days to gather. The outcomes of these studies are interesting in their own right, but our ultimate goal is to be able to harness *P.polycephalum* for near real-time musical applications. *BioComputer Music* is a large step towards reaching our goal. Although the system behind the piece is our first implementation, the musical result is both engaging and interesting. Of course, there are several areas we need to develop. Foremost, we intend to review our method of transcribing notes into voltages. Here, we are researching and experimenting with the most meaningful and interesting way of taking advantage of the *P.polycephalum* component's nonlinear conductance profile. Also, we are working towards developing feasible methods of generating note duration and rhythmic structure with *P.polycephalum* components. Shown in Figure 11 is a new prototype we are developing, where an additional two Petri dishes are used to generate note duration and rhythmic structure.

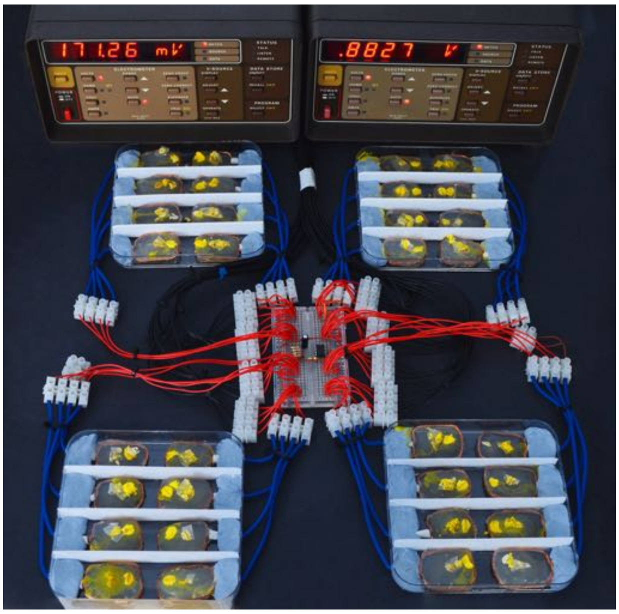

Fig. 11. We are already designing future versions of the *BioComputer Music* system. Shown in this picture is a new prototype where an additional two Petri dishes are used to generate note duration and rhythmic structure.

As we move on to work with living matter in computing technology, essentially we will be harnessing the intelligence of such organisms to compose music with. Undoubtedly, new forms of music making will emerge from Unconventional Computing. *BioComputer Music* is only a glimpse of what is to come.

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