On Building Practical Biocomputers for Real-World Applications: Receptacles for Culturing Slime Mould Memristors and Component Standardisation

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Abstract

Our application of bionic engineering is novel: we are interested in developing hybrid hardware-wetware systems for music. This paper introduces receptacles for culturing *Physarum polycephalum*-based memristors that are highly accessible to the creative practitioner. The myxomycete *Physarum polycephalum* is an amorphous unicellular organism that has been found to exhibit memristive properties. Such a discovery has potential to allow us to move towards engineering electrical systems that encompass *Physarum polycephalum* components. To realise this potential, it is necessary to address some of the constraints associated with harnessing living biological entities in systems for real-time application. Within the paper, we present 3D printed receptacles designed to standardise both the production of components and memristive observations. Subsequent testing showed a significant decrease in growth time, increased lifespan, and superior similarity in component-to-component responses. The results indicate that our receptacle design may provide means of implementing hybrid electrical systems for music technology.

Keywords: Unconventional Computing, *Physarum polycephalum*, Computer Music, Biological Computing, Memristor

1. Introduction

Our research is concerned with engineering unconventional and novel hybrid hardware-wetware computing systems for music and sound. 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 the lack of accessible prototypes. In our research, we have been experimenting with the biological computing substrate *Physarum polycephalum*, referred to in this paper as *P.*

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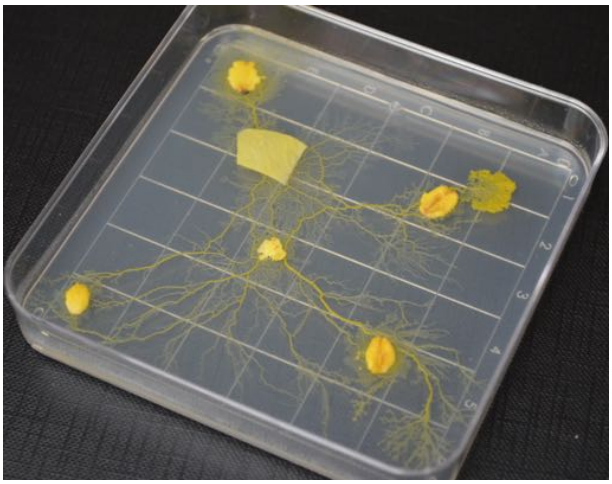

Figure 1: A culture of the plasmodium of *P. polycephalum* within a square Petri dish. The figure depicts a network of protoplasmic veins laid down by a propagating fanlike structure of pseudopods.

polycephalum, for computer music. *P. polycephalum* is an ideal candidate for research into biological computing for music due to its accessibility: unlike many other biological computing substrates, *P. polycephalum* is safe to use, cheap, requires few resources to develop prototypes, and is fairly robust. Thus, by developing systems with *P. polycephalum*, we can widen the application of unconventional computing schemes in computer music by enticing and inviting other practitioners to experiment and create artefacts with the systems we develop. It is hoped that other communities interested in unconventional computing would also benefit from our research.

P. polycephalum is a myxomycete that, in its vegetative plasmodium form, exists as an amorphous unicellular organism, which propagates on gradients of stimuli while laying down an efficient transport network of protoplasmic tubes (Figure 1). The plasmodium, although without a brain or any serving centre of control, can respond with natural parallelism to the environmental conditions that surround it. Researchers have harnessed such abilities to develop a wide range of computing and sensing schemes. Some examples include logic gate systems[1], robot control[2] and path finding[3]. See[4] for a collection and excellent guide on computing with *P. polycephalum*.

In a 2011 edition of this journal, one of the authors reported on preliminary work with *P. polycephalum* for computer music[5]. In this study, the team developed a sound synthesis framework to create a bionic instrument using recordings of *P. polycephalum's* extracellular membrane potential. We further developed this offline approach to harnessing the organism in several different musical applications: step sequencers[6], granular synthesis[7], and contemporary composition[8], to cite but three. From these research progresses, we were able to confirm that *P. polycephalum* exhibits properties that can be harnessed to implement systems for generative audio and music. However, we were conscious that we needed to move on to develop and study systems beyond offline sonification in order to progress with our research.

In 2003 Gale et al.[9] demonstrated in laboratory experiments that the protoplas-

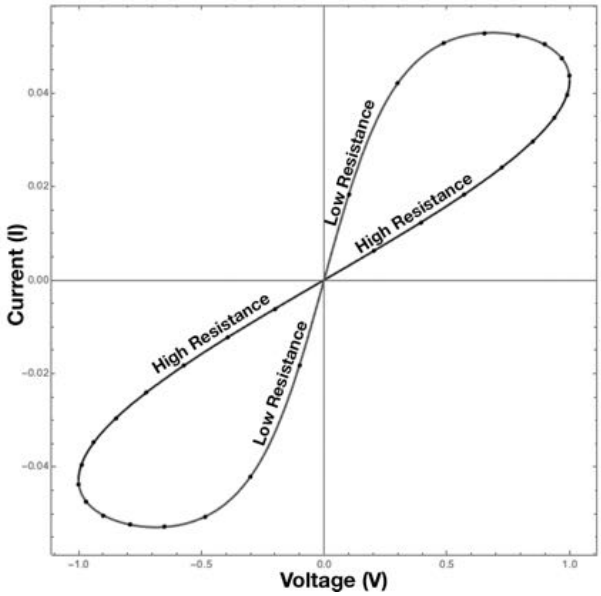

Figure 2: Example of hysteresis in an ideal memristor (arbitrary values used).

mic tube of *P. polycephalum* can act as an organic memristor. Memristors[10] are the recently discovered[11] fourth fundamental passive circuit component that relates magnetic flux linkage and charge. Unlike the other passive elements, namely the capacitor, inductor and resistor, the memristor is non-linear and possesses a memory. The I-V footprint of a memristor, when applied with an AC voltage, is a pinched hysteresis loop - a Lissajous figure formed by two perpendicular oscillations creating a high and low resistant state. In an ideal memristor, hysteresis is observed as a figure of 8 where the centre intersection is at both zero voltage and current (Figure 2). We can describe memristance using a state-dependant Ohms law, which is mathematically denoted below:

$$M = R(q) = \frac{d\varphi(q)}{dq} \tag{1}$$

where q is charge and φ is flux[10].

Computer scientists have a keen interest in experimenting with the memristor, which is due, in major part, to properties that have promise to revolutionise the way our computers work. Investigators have credited memristors as being the first to combine processing and memory abilities in a single component[12]. The discovery that *P. polycephalum* can act as a memristor is providing researchers with an unprecedented opportunity to begin developing everyday information processing systems using biological components. In regards to our research, the discovery has offered us a pathway to designing hardware-wetware systems for real-time musical application: a large step forward from the preliminary work article we published in 2011[5].

We have developed novel ways of generating musical responses by harnessing the memristor's non-linear ability to alter its resistance as a function of both its current input and history of previous inputs: an ability that is musically relatable. For a summary of our creative work with memristors see[13]. Using our research progresses, in[14] we developed a hardware-wetware system to take outside of the laboratory and immerse into real-time live performance. Our system consisted of *P. polycephalum* components that we grew in individual Petri dishes furnished with electrodes. As an overview, the system functions by a computer program transcribing a live pianist's performance into voltages that together form a complex AC waveform. This waveform passes through the *P. polycephalum*-based memristors whose subsequent current readings are measured and translated into a musical response that our system plays on the same piano via electromagnets positioned above the strings of the piano[15]. A recording of a performance using our system can be found at[16].

By immersing a system that encompasses *P. polycephalum*-based memristors into experimental real-time applications, we were able to identify some limitations that needed to be addressed to progress our work. In using the system both for rehearsals and in live concert we found that a lot of time was spent having to fit Petri dishes with the necessary electrical parts, which was tedious and fiddly. Once the plasmodium was inoculated into the prepared Petri dishes, it rarely took under 24 hours for the organism to form the required protoplasmic tube. Such time is likely due to the growth conditions not being well delineated: within the Petri dishes the organism has a number of different propagation trajectories and grows in a random fashion. Moreover, the current setup provides no protection to delicate components when the system is transported. As a result, often components become electrically disconnected when moving them from the culture cabinet to where they are required. Another limitation is each component's lifespan, which is $\approx$ two days.

In regards to the system's musical result, there is a high degree of variation from component-to-component. In the initial stages of our work, we were not concerned with component variation. Rather, we were keen to experiment with such variation as a stylistic and novel trait of using ever-changing biology entities. However, the ability to produce different results with a degree of predictable control is an important property of musical devices. Thus, to widen the usability of using *P. polycephalum*-based memristors for music, we need to standardise responses.

In this paper, we report on a method to address the limitations of encompassing *P. polycephalum*-based memristors in musical hardware-wetware. Here, rather than growing *P. polycephalum* in a petri dish and allowing it to grow in a random manner towards the food source, we have designed a receptacle to delineate the growth of the tubes. Such receptacles speed up production time, protect the organism, increase lifespan, and standardise measurement regimes and subsequent observations.

The rest of this paper is structured as follows. Firstly we present the design and fabrication of our receptacle. We also explain our rationale for our approach to the design. Next, we present the receptacle's testing and subsequent results, which is followed by discussions. The paper then finishes with conclusions.

2. Receptacles Design and Fabrication

An obvious avenue for us to go down in designing our receptacles would be to adapt techniques from microfluidics. Microfluidics is where structures such as wells, channels and tunnels are often made using a gel-like biocompatible silicon elastomer material called polydimethylsiloxane (PDMS). PDMS is durable, chemically inert, non-toxic, hydrophobic, and transparent[17]. However, the polymer is expensive and requires some expertise to create moulds and cure before it is useable. As one of the key criteria for our research with *P. polycephalum* is accessibility for computer musicians, we choose to explore using 3D printing techniques to fabricate our receptacles. In major part, commercially available 3D printers use the additive stereolithography fabrication method. These machines use rolls of inexpensive filament that are available in a variety of materials. For the work presented in this paper, we used a Lulzbot Taz 5 stereolithography printer and Autodesk's free 123Design software.

To use the plasmodium's protoplasmic tube as an organic electronic component, we need the organism to forge its tube between two electronically isolated electrodes. Thus, the tube cannot reside on an agar substrate. The organism does, however, require a high level of humidity. To achieve these requirements we designed two chambers that connected via a tube. Here, the tube is interchangeable to allow us to investigate the effect of protoplasmic tube length on memristance. The chambers have a well to accommodate 1.5ml of agar to achieve a favourable level of humidity. To delineate the growth of the protoplasmic tube, we fabricated the chambers with High Impact Polystyrene (HIPS) as the organism does not like this substance[18]. Consequently, the plasmodium will be discouraged from growing on the walls of the chamber and encouraged to propagate across the linking tube to the other chamber, laying down the desired protoplasmic tube. HIPS is a common and inexpensive 3D printing material that prints with low warping.

As the plasmodium does not like propagating over bare metals, we chose to avoid using metal electrodes in favour of more biocompatible materials. Perhaps one of the most popular biocompatible conductive polymers is poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS). In previous *P. polycephalum* memristor experiments researchers successfully used PEDOT:PSS as electrodes in demonstrating memristance[19,20]. However, like PDMS, PEDOT:PSS is expensive and requires expertise to use: spin-coating and doping in solutions to improve its conductivity. As such, we opted to use a newly developed conductive polylactic acid (PLA) 3D printing material[1]. PLA is Food and Drug Administration certified and, due to its high biocompatibility, is widely used in the medical field[21]. It is also worth noting that PLA is biodegradable, which may provide means of creating an environmentally friendly device in the future. By comparison, the conductive PLA has a volume resistivity of 0.75Ω-cm, while un-doped PEDOT:PSS has a volume resistivity of 3Ω-cm, which can be decreased to approximately $3\text{x}10^{-02}$Ω-cm when doped with glycerol[22]. Using the conductive PLA, we printed two collars that slotted into the chambers. Each collar was designed with an electrical contact point and a rim to attach the linking tube between the chambers. For

[1] http://functionalize.com/

the linking tube we used off the shelf medical grade polyvinyl chloride (PVC) tubing, which is available in a variety of inner and outer tube dimensions. As the aim is to limit the organism's growth space, we used tubing of 4mm inner diameter and 6mm outer diameter. Researchers have used similar dimensions in creating environments for measuring the electrical potential difference between two loci of plasmodium connected by a protoplasmic tube[23]. Figure 3 shows our receptacle.

Figure 3: A screenshot (top) and photograph (bottom) of our receptacle. Shown is two identical growth chambers, two lids (one with and one without an air hole), two conductive electrode collars and a 10mm base.

3. Receptacle Testing

3.1. Methods and Materials

For our research, we maintain a plasmodium farm that adopts techniques from[4]. Here, plasmodium is grown in plastic containers on a wet porous substrate and fed with

Figure 4: A photograph of our receptacles set up with different tube lengths to investigate the effect on memristance. Shown are connecting tube lengths of 2.5mm, 5mm, 15mm and 20mm.

oat flakes. We take inoculation sources from the farm after a period of circa 8 hours starvation. This process speeds up the organism's initial propagation speed.

To test the receptacle, we set up 5 samples using a 10mm length connecting tube. A 10mm tube length is derived from the original *P. polycephalum* memristor investigations. To date, there have been no definitive studies regarding protoplasmic tube length and memristance. Thus, to investigate this variable, we created and ran tests on an extra 4 samples of each of the following tube lengths: 2.5mm, 5mm, 15mm and 20mm (Figure 4). Receptacle chamber wells were filled with 1.5ml of 2% non-nutrient deionised agar. To inoculate the plasmodium into the receptacle, we place a colonised oat flake in one chamber and a fresh oat flake in the other.

For comparison, 5 control samples were also arranged using the old experimental setup (Figure 5). Here, we positioned two electrodes spaced at a distance of $\approx$10mm within 60mm Petri dishes. Each electrode consisted of a circle ($\approx$20mm in diameter) of tinned copper wire (16 stands at 0.2mm) filled with a 2% non-nutrient deionised agar ($\approx$2ml).

We monitored each sample via time-lapse imagery for the elapsed time between inoculation and forming the required protoplasmic tube. Once grown, to test the repeatability and component-to-component memristive variation, we ran I-V tests on each sample using a discretised sinusoid A.C. voltage waveform of 160 steps. As the I-V footprint of a memristor is its most characteristic property, we felt that this was the most accurate way to test our receptacles. By observing each sample's I-V morphology, we can review component-to-component memristance variation. Electrical measurements were made using a Keithley 230 Programmable Voltage Source and a Keithley 617 Programmable Electrometer. These devices were selected as they are capable of sourcing voltage and taking measurements at high resolutions. Custom software controlled each device.

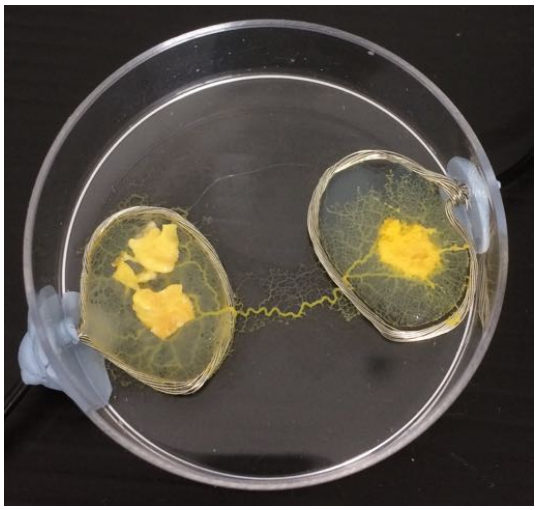

Figure 5: A photograph of the control samples' experimental setup. Shown is two electrodes comprised of a circle of wire filled with non-nutrient agar, linked by a protoplasmic tube.

Memristance is a voltage and frequency effect. The frequency of an input voltage waveform controls the size of hysteresis. That is, due to the time a system takes to respond to change across its terminals, if the frequency is too high, hysteresis lobe size will decrease. Under an increasing frequency, a memristor's I-V profile will eventually become linear. If the input voltage range is too low, the memristor's pinched hysteresis curve may become open. Thus, we tested samples under voltage ranges $\pm$ 250mV, 500mV, 5V and 10V, using voltage time steps of Δt=0.5, 1, 2 and 2.5 seconds. Once inoculated, all samples were left in a closed draw at room temperature.

3.2. Receptacle Test Results

All of the 5 10mm samples produced the required protoplasmic tube within 10 hours of inoculation (Figure 6). The fastest of these grew in under 2 hours, and the longest was 10 hours, with the average growth time across all 5 samples being 7 hours 24 minutes. All of the tube length samples made the required connection within 12 hours of inoculation. Of the 5 control samples (Figure 7), 4 produced a linking protoplasmic tube and 1 propagated off the inoculation electrode but dried out before it made the required connection. This may have been due to the destination electrode or oat flake becoming infected and thus repelling the plasmodium. The first of the control samples took 19 hours to grow while the last took 36 hours, with an average growth time across control samples being 26 hours and 15 minutes.

As the 5 10mm receptacle samples all produced the required protoplasmic tube within 10 hours, we ran I-V tests on them first at $\approx$12 hours post inoculation. Of the 5 samples, 4 presented pinched curves with the $\pm$250mV waveform using the Δt=2 and 2.5 s time steps. We only measured open curves at the $\pm$250mV range at Δt=0.5 and t=1 s. This was also the case for $\pm$500mV. With the $\pm$ 500mV, 5V and 10V ranges under time steps Δt=2 and 2.5 s, all 5 samples generated pinched curves. In regards to

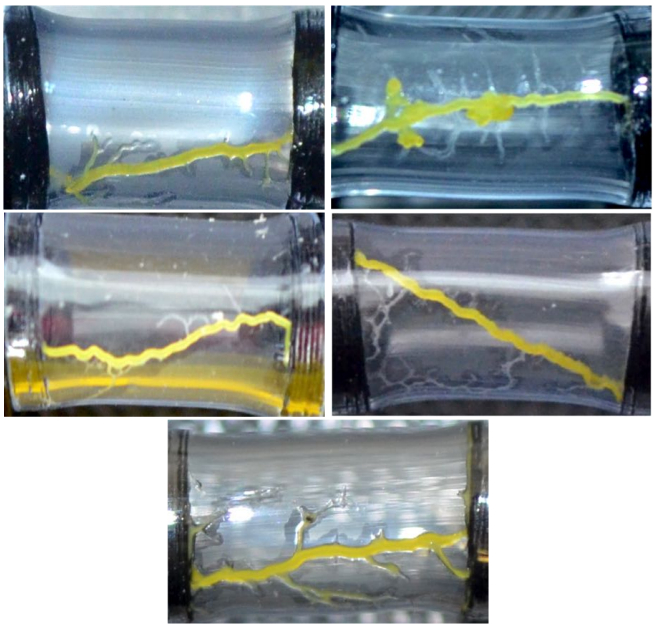

Figure 6: Photographs of each of the 5 protoplasmic tubes grown in our receptacles.

hysteresis morphology, we found there to be a strong relationship both in single sample curves measured at different time steps and voltage ranges, and sample-to-sample curves. That is, hysteresis loops had relatively consistent lobe sizes as well as pinch locations, which is depicted in the graphs in Figure 8. We did notice, however, that although hysteresis morphologies were similar sample-to-sample, there was variation in overall resistance between samples. It is possible that such variation may be a result of protoplasmic tube diameter, which we only restricted to 4mm.

With the 2.5mm samples, we only measured open curves at Δt=0.5 and 1 s under voltage ranges $\pm$ 250mV and 500mV. However, these open curves, unlike their 10mm counterparts, were very close to touching at the origin (Figure 9), which is indicative of an increase in memristance as a result of component shrinking. We produced similar results with the 5mm receptacle samples with slightly larger origin offsets. At the two longer time steps, all 2.5mm and 5mm samples produced pinched curves.

With the 15mm and 20mm receptacles, no pinched curves were measured at the two lower voltage ranges. Furthermore, at 5V and 10V, we measured pinched curves but their lobe sizes were very small. To investigate if this effect was due to the system requiring a longer time step to respond to the ΔV due to the longer tube, we took measurements with Δt=3 and 4 s. Under these longer time steps, however, the pinched curve became open.

Of the 4 control samples, we measured a total of 2 pinched curves at $\pm$250mV, both were under a Δt=2s time step. With a $\pm$ 500mV waveform, 3 samples produced memristive curves with Δt=2s, and 2 with a Δt=2.5s. All 4 samples produced pinched curves under both 5V and 10V voltage ranges using Δt=2 and 2.5 s. At lower time steps,

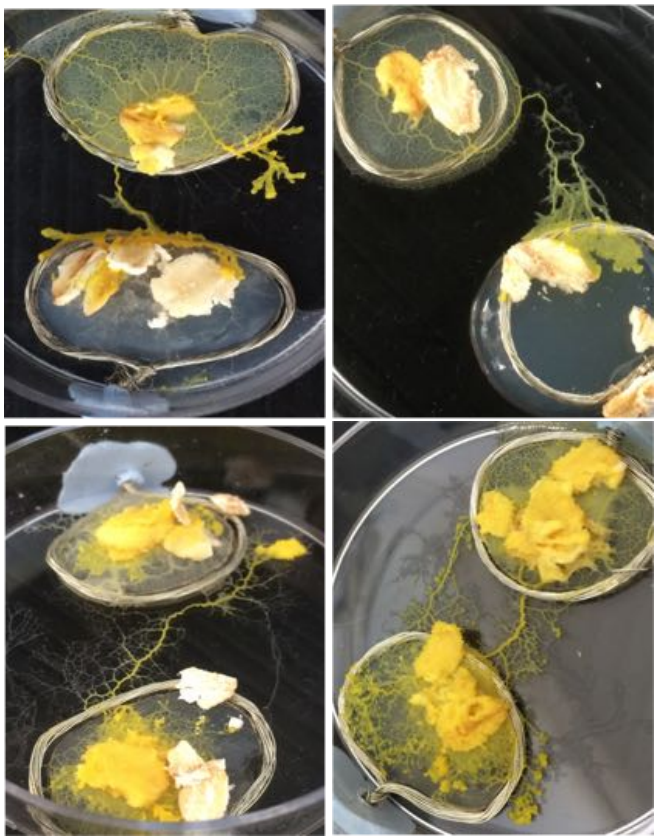

Figure 7: Photographs of each of the 4 control samples that forged the required connection between the two electrodes.

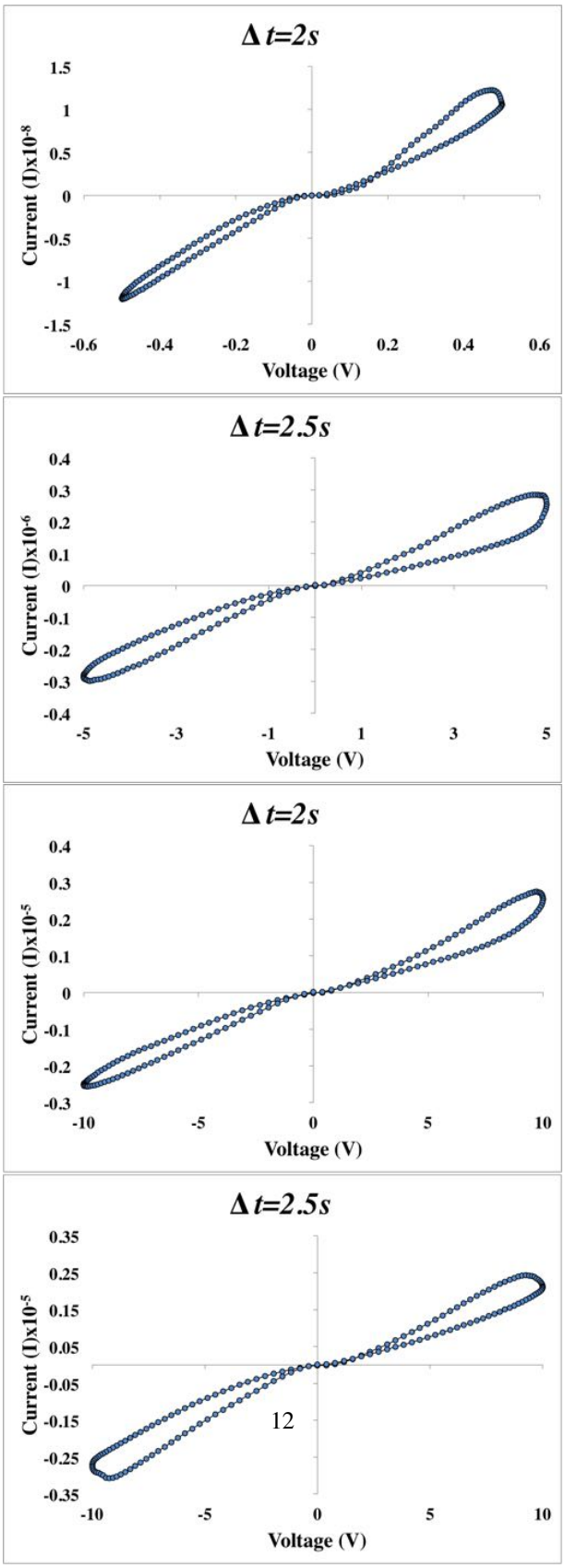

Figure 8: Four examples of pinched I-V curves measured on the 10mm receptacle samples. Notice how each curve is morphologically similar in regards to location of pinch points and lobe sizes.

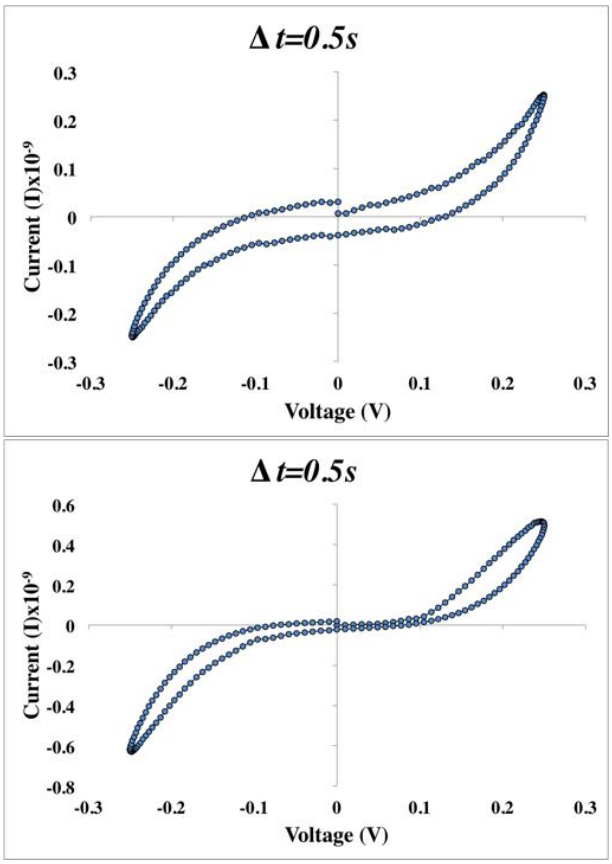

Figure 9: Two I-V graphs recorded under the lowest voltage range (250mV) and quickest time step (Δt=0.5). We recorded the top graph using a 10mm receptacle, and the bottom graph using a 2.5mm receptacle. The 2.5mm receptacle's profile was closer to touching at origin under these test conditions.

we only recorded open curves. Each control sample's I-V curves measured at different time steps and voltage ranges were morphologically similar. However, a comparison between I-V curves measured across control samples show a lot of variations both in pinch point location and hysteresis lobe size (Figure 10). In a number of the I-V tests, the control samples produced curves with multiple pinch points: a phenomenon that was not present in any of our receptacle results.

After we had run the initial I-V measurements, we monitored each sample over the proceeding days to investigate each component's lifespan. We ran measurements on each sample once a day until they presented no memristive curves. Of the 4 control samples, 2 dried up and lost their memristive curves within 2 days of initial testing while the remaining 2 continued to record pinched curves for a further 2 days. The lifespans of our 10mm receptacle samples were a lot longer than expected. Here, all samples maintained their memristance for at least 7 days, with 3 samples reaching twice that. Such a difference in lifespan is likely due to the receptacles being a small and enclosed space, which retains humidity produced by the agar for longer than the 60mm Petri dishes. Furthermore, in the case of the control samples, when food on the two islands became exhausted the organism would often discontinue the tube connecting the two electrodes in favour of foraging elsewhere (Figure 11a). Samples grown in the receptacles did not have this ability and could only span the inner circumference of the connecting tube. As the organism optimises its network over time[24], once the inside of the tube was coated the organism would optimise its connection between the two chambers creating a single tube once more. We noticed that as time went on each of the receptacle sample's protoplasmic tubes became thicker and stronger in colour. In hand with the increase in protoplasmic tube diameter, we noticed an overall decrease in resistance in the I-V measurements, with some samples measuring in the $Ax10^{-04}$ range for 10V runs against $Ax10^{-05}$ in their earlier tests. Such an observation supports our earlier thoughts on protoplasmic tube diameter affecting overall resistance.

4. Results Discussions

4.1. Memristive Effects

By comparing the graphs in Figure 8 with those in Figure 10, it is clear that the I-V measurements we made with samples grown in our receptacles have less variation across runs than the control samples. As a result of their pinch points not being at the point of origin, control samples' I-V curves were highly asymmetrical. Such curves are not the footprint of an 'ideal' memristor. One of the characteristics that classify a memristor as 'ideal' is that it does not store energy; a memristor is a passive circuit component. Therefore, the hysteresis pinch points should be at 0 voltage and current. In[25], Chua explains that if such an offset of hysteresis pinch points from the origin can be modelled by the addition of circuit elements, then the device is classified as an imperfect memristor. In the case of *P. polycephalum*-based memristors, Gale et al.[9] proposed that pinch point offset is likely due to the plasmodium producing an internal current source as a result of its intracellular shuttle streaming. Here, the organism oscillates a fluid cytosol endoplasm containing ions such as Ca^{2+} and H^{+} around its protoplasmic tubes[26,27]. Thus, the intracellular movement of ions creates a current,

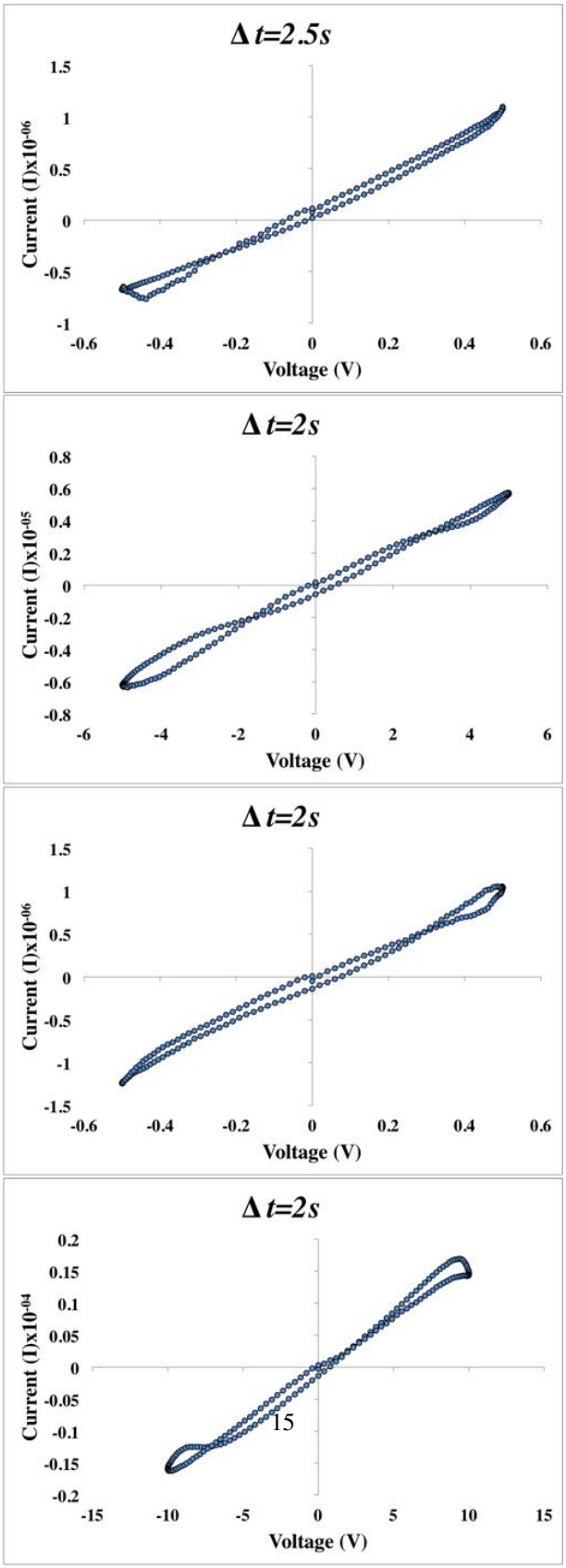

Figure 10: Four pinched I-V curves measured on the our control samples. Results with these samples presented a high degree of variation sample-to-sample. Furthermore, in several cases, the memristive curves had several pinch points.

(a) One of the control samples pictured in Figure 7 4 days after initial testing.

(b) One of the receptacle samples pictured in Figure 6 10 days after initial testing.

Figure 11: Photographs of a control (11a) and receptacle (11b) sample during our lifespan testing. 11a shows a control sample that has spanned its environment (shown by the white tube outlines) in search for food and eventually dried out. 11b is one of our control samples, which has spanned all the available space and then optimised it tube connection once more. The colour of this sample has intensified from a light yellow to a strong gold and the diameter is thicker than those depicted in Figure 6.

which, dependent on the direction of flow, will oppose or add to the driven current causing the pinch point offset. In[9], the team modelled *P. polycephalum*-based memristors as a two port 'black box' that contains a battery and memristor.

I-V profiles measured on our control samples are interesting (Figure 10) because several of them had seemingly randomly placed pinch points and multiple pinches. In theory, the shuttle streaming process described above could explain this phenomenon, where changes in streaming direction result in an extra pinch. Shuttle streaming switches polarity at intervals ranging from a few seconds to a few minutes with an average interval of approximately 1.3 minutes[28]. However, this does not explain why our receptacle tests were more reminiscent of an 'ideal' memristor's footprint (Figure 2), where pinch points were always singular and almost consistently at 0 voltage and current (Figure 8).

We have postulated another theory, which is as follows. Researchers have proposed that voltage-gated ion channels control the current in *P. polycephalum*[29], which is common in biological systems. Potassium voltage-gated ion channels have been proven to play a role in memristance in plants[30]. Furthermore, researchers have suggested that the HodgkinHuxley Axon[31] (a model that describes the initiation and propagation of action potential in neurons) comprises a potassium ion-channel memristor and a sodium ion-channel memristor[32,33]. Thus, it may be the case that our test voltage waveform is activating one or more of these channels, causing the plasmodium to take in or expel ions. This process could be how the plasmodium switches between high and low resistance states.

In the case of the receptacles, we have delineated component morphology, which is likely to have created memristors with more consistent internal and external components. These components are also more prone to be in good contact with the electrodes. The control samples, however, were left to span a larger environment freely, resulting in vastly different components. Therefore, control samples are likely to have differing quantities of biological components, with different spatial configurations, some of which will not be in good connection with the electrodes. That is, control samples, due to their freedom of movement, will have created complex networks of protoplasmic tubes between the electrodes (as depicted in Figure 7). Subsequently, the applied voltage may undergo varying magnitudes of resistance to reach biological components located in different parts of the organism. As a result, our test voltages may be activating multiple ion channels at varying magnitudes. Our theory is supported by the fact that all I-V curves measured on the same control sample were qualitatively similar, whereas sample-to-sample comparison shows a great deal of variation (Figure 10).

4.2. Tube Length

Results from our tube length tests were indicative of memristance increasing as a function of device shrinkage. Such a phenomenon may be due to the protoplasmic tube's field increasing as its length decreased and the testing voltage stayed the same. We also observed the dissipation of memristive effects as the tube length increased. It is possible that the longer tube lengths require a higher voltage to produce pinched curves. Although tubes at these lengths are not practical as memristors both in terms of space and the likely energy needed to use them, being able to grow longer tubes using our receptacles has other useful applications. In[34] and[35], researchers explored using

Figure 12: A photograph taken during the rehearsal of the piece *BioComputer Rhythms*.

the protoplasmic tube as wires that are capable of passing both digital and analogue voltages. Investigators of both these studies expressed the issue of being able to grow protoplasmic tubes at lengths between two designated terminals. The receptacles we have designed may provide a possible solution to such an issue.

4.3. Music: BioComputer Rhythms

As our research is committed to taking *P. polycephalum*-based memristor technology out of the laboratory into the real-world, we rendered the outcomes of the work reported above into a new interactive music system, which was featured in a public concert of a major festival of contemporary classical music in Plymouth, UK[2].

BioComputer Rhythms is an experimental one piano duet between pianist and a hybrid hardware-wetware musical system. The technology functions by encoding the pianist's performance into voltages for *P. polycephalum* memristors to process. Each of the components' subsequent responses is decoded back into music which is then played back on the performers piano and various percussion instruments through electromagnets that set the strings and the percussion into vibration (Figure 12). We direct the reader to [36] for a detailed description of the technology and performance. A video documentary can also be found at [37].

[2] https://www.plymouth.ac.uk/whats-on/peninsula-arts-contemporary-music-festival-2016

Figure 13: We have begun fabricating plug and play USB 'PhyBoxes' that the receptacles presented in this paper clip into. Our PhyBoxes encompass four *P. polycephalum*-based memristors, which are each independently addressable via a USB connection. Depicted in this Figure are two PhyBoxes and a custom-made humidity pump.

5. Future Work

With the presented receptacles, we have begun establishing consistent, robust, and more rigorous methods of implementing *P. polycephalum*-based memristors. Results from our receptacle testing are more uniform and repeatable than previous experimentation [13]. Having achieved a more stable component, we can now look to investigate the mechanisms behind the organism's memristive abilities. By gaining a better understanding of the parameters behind the organism's memristance, it may be possible to gain dynamic control over it. For example, *P. polycephalum* is responsive to certain wavelengths of light, temperature, pH, various chemicals, and pressure. In regards to our musical intentions, I-V curves measured with our receptacles are very similar sample-to-sample. Thus, by integrating the receptacles into our musical systems, the musicians will have superior control and repeatability against the previous implementation. However, if we can gain more control over *P. polycephalum*-based memristors, a user could program the components to respond in different ways. For example, they could be programmed for different styles of music or different instrumentation.

As we have reduced both the setup time for growing the components and setup complexity, we have widened the accessibility to computer musicians. To further build on these successes, we have begun developing USB plug and play boxes - which we have named PhyBoxes - that the receptacles clip into (Figure 13). To augment the Phyboxes and further extend component lifespan, we are currently investigating controlling temperature and humidity with a custom-made humidity pump. With such a device, we are hoping to be able to maintain a stable microenvironment when the Phyboxes are exposed to harsher conditions. For example, if a performer was to use the PhyBoxes in a cold/hot performance environment. Once complete, we will be able to create 'do it yourself' kits for computer musicians who are keen to experiment with using either memristors or aspects of biological computing in their works.

6. Conclusions

Currently, scientists worldwide are conducting much research into harnessing *P. polycephalum* for sensing and computation. Progresses to date in regards to *P. polycephalum*-based memristors[9,19,20] have certainly laid the foundations for further development. However, results from these experiments have varied, causing scientists to come to different conclusions in regards to the biological function behind the plasmodium's memristive abilities. Furthermore, current work with the organic component is empirical, and, therefore, it would be unfeasible to encompass it into a stable system. In this paper, we have presented and tested a 3D printed receptacle for growing *P. polycephalum*-based memristors. The purpose of our receptacle was to overcome some of the constraints of harnessing *P. polycephalum*-based memristors for real-time musical applications. While our domain application is computer music, the outcomes of this research contributes to the field of unconventional computing more generally. The results of our receptacle's testing have demonstrated that our design has significantly decreased growth time, increased lifespan, standardised component responses, and created a protected microenvironment to encapsulate the organism.

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