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Review article

Fungal electronics

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ABSTRACT

Fungal electronics is a family of living electronic devices made of mycelium bound composites or pure mycelium. Fungal electronic devices are capable of changing their impedance and generating spikes of electrical potential in response to external control parameters. Fungal electronics can be embedded into fungal materials and wearables or used as stand alone sensing and computing devices.

1. Introduction: Why fungal electronics?

Flexible electronics, especially electronic skins and e-textiles (Soni and Dahiya, 2020; Ma et al., 2017; Zhao and Zhu, 2017; Stoppa and Chiolerio, 2014), are amongst the most rapidly growing and promising fields of novel and emergent hardware. Flexible electronic devices are made of flexible materials where electronics capable of tactile sensing (Chou et al., 2015; Yang et al., 2015; Wang et al., 2015; Pu et al., 2017) are embedded. Flexible electronic materials are capable of low level perception (Chortos et al., 2016; Park et al., 2014) and could be developed as autonomous adaptive devices (Núñez et al., 2019). Typical designs of flexible electronic devices include thin-film transistors and pressure sensors integrated in a plastic substrate (Wang et al., 2013), micro-patterned polydimethylsiloxane with carbon nanotube ultra-thin films (Wang et al., 2014; Sekitani and Someya, 2012), a large-area film synthesised by sulfurisation of a tungsten film (Guo et al., 2017), multilayered graphene (Qiao et al., 2018), platinum ribbons (Zhao and Zhu, 2017), polyethylene terephthalate based silver electrodes (Zhao et al., 2015), digitally printed hybrid electrodes for electromyographic recording (Scalisi et al., 2015) or for piezoresistive pressure sensing (Chiolerio et al., 2014), or channels filled with intrinsically conductive polymers (Chiolerio and Adamatzky, 2020).

Whilst existing designs and implementations are highly impactful, the prototypes of flexible electronics lack a capacity to self-repair and grow. Such properties are useful, and could be necessary for organic electronics used in applications such as unconventional living architecture (Adamatzky et al., 2019), soft and self-growing robots (El-Hussieny et al., 2018; Sadeghi et al., 2017; Rieffel et al., 2014; Greer et al., 2019) and development of intelligent materials from fungi (Meyer et al., 2020; Haneef et al., 2017; Jones et al., 2020; Wösten, 2019) and bacteria (Chiolerio and Adamatzky, 2021). Based on our previous experience with designing tactile, colour sensors from slime mould *Physarum polycephalum* (Adamatzky, 2013b,a; Whiting et al., 2014) and our recent results on fungal electrical activity (Adamatzky, 2018; Beasley et al., 2020b,a), as well as following previously demonstrated thigmotropic (Almeida and Brand, 2017) and phototropic response (Corrochano, 2019) in higher fungi, we overview our recent experimental results on electronic properties of mycelium bound composites.

In this article we report that fungi exhibit properties of memristors (resistors with memory), electronic oscillators, pressure, optical and chemical sensors, and electrical analog computers (Fig. 1).

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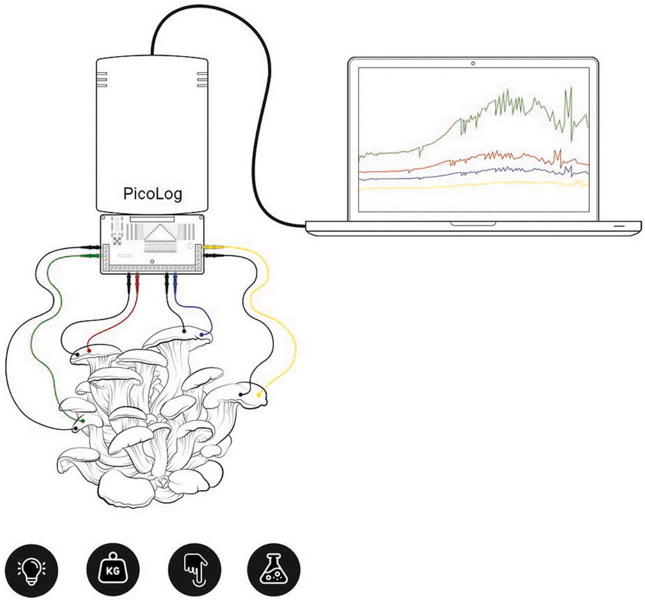

Fig. 1. A scheme off the electronic interface with fungi.

2. Fungal memristors

A memristor, also known as Resistive Switching Device (RSD), is a two or three-terminal device whose resistance depends on one or more internal state variables of the device (Adamatzky and Chua, 2013). A memristor is defined by a state-dependent Ohm's law. Its resistance depends on the entire past signal waveform of the applied voltage, or current, across the memristor. Using memristors, one can achieve circuit functionalities that it is not possible to establish with resistors, capacitors and inductors, therefore the memristor is of great pragmatic usefulness. Potential unique applications of memristors have been enabled by their physical implementation and are expected to occur in spintronic devices, ultra-dense information storage, neuromorphic circuits, human brain interfaces and programmable electronics (Chua et al., 2019; Chiolerio et al., 2017).

In experimental laboratory studies (see the setup in Figs. 2(a) and 2(b)), we demonstrated that *P. ostreatus* fruit bodies exhibit memristive properties when subject to a voltage sweep (Beasley et al., 2021a). The ideal memristor model has a crossing point at 0 V, where theoretically no current flows. Figs. 2(c) and 2(d) show the results of cyclic voltammetry of grey oyster mushrooms with electrodes positioned in the caps and/or stems. When 0 V is applied by the source meter, a reading of a nominally small voltage and current is performed.

When the sample under test is subjected to a positive voltage (quadrant 1), it can be seen there is nominally a positive current flow. Higher voltages result in a larger current flow. For an increasing voltage sweep there is a larger current flow for the corresponding voltage during a negative sweep. In quadrant 3 where there is a negative potential across the electrodes, the increasing voltage sweep yields a current with smaller magnitude than the magnitude of the current on a negative voltage sweep. Put simply, the fruit body has a resistance that is a function of the previous voltage conditions.

The living membrane is capable of generating potential across the electrodes, and hence a small current is observed. To conclude, living fungi can be used as memristors (resistors with memory) in biocomputing circuits.

3. Fungal oscillators

An electronic oscillator is a device which converts direct current to an alternating current signal. A fungal oscillator is based on endogenous oscillations of an electrical resistance of mycelium bound composites. A nearly homogeneous sheet of mycelium of *P. ostreatus*, grown on the surface of a growth substrate, exhibits trains of resistance spikes (Fig. 3(a)) (Adamatzky and Jones, 2011). The average width of spikes is c. 23 min and the average amplitude is c. 1 kΩ. The distance between neighbouring spikes in a train of spikes is c. 30 min. Typically there are 4–6 spikes in a train of spikes. Two types of electrical resistance spikes trains are found in fruit bodies: low frequency and high amplitude (28 min spike width, 1.6 kΩ amplitude, 57 min distance between spikes) and high frequency and low amplitude (10 min width, 0.6 kΩ amplitude, 44 min distance between spikes). To assess feasibility of the living fungal oscillator, we conducted a series of scoping experiments by applying direct voltage to the fungal substrate and measuring output voltage. An example of the electrical potential of a substrate colonised by fungi under 10 V applied is shown in Fig. 3(b). Voltage spikes are clearly observed. Spikes with amplitude above 1 mV, marked by '*', except the spike marked by 's' have been analysed. We can see two trains of three spikes each. Average width of the spikes is 10^3 s, average amplitude 2.5 mV, while average distance between spikes is c. $2 \cdot 10^3$ K s. To conclude, fungi can be used as a very low frequency electronic oscillators in designs of biological circuits.

4. Fungal pressure sensor

We stimulated blocks of *G. resinaceum* mycelium colonised substrate by placing a 16 kg cast iron weight on their top face (Fig. 4(a)). Electrical activity of the fungal composite block was recorded using 8 pairs of differential electrodes, as specified in Fig. 4(a). An example of electrical activity recorded on 8 channels, during the stimulation with 16 kg weight, is shown in Fig. 4(b) (Adamatzky and Gandia, 2021). In response to application of 16 kg weight the fungal blocks produced spikes with median amplitude 1.4 mV and median duration 456 s; average amplitude of ON spikes was 2.9 mV and average duration 880 s. OFF spikes were characterised by median amplitude 1 mV and median duration 216 s; average amplitude 2.1 mV and average duration 453 s. ON spikes are 1.4 higher than and twice as longer as OFF spikes. Based on this comparison of the response spikes we can claim that fungal blocks recognise when a weight was applied or removed (Adamatzky and Gandia, 2021). The results complement our studies on tactile stimulation of fungal skin (mycelium sheet with no substrate) (Adamatzky et al., 2021b): the fungal skin responds to application and removal of pressure with spikes of electrical potential. The fungal blocks can discern whether a weight was applied or removed because the blocks react to the application of weights with higher amplitude and longer duration spikes than the spikes responding to the removal of the weights. The fungal responses to stimulation show habituation. This is in accordance with previous studies on stimulation of plants, fungi, bacteria, and protists (Applewhite, 1975; Fukasawa et al., 2020; Ginsburg and Jablonka, 2021; Boussard et al., 2019; Yokochi et al., 1926). To conclude, mycelium bound composites are capable of detecting pressure, therefore fungal pressure sensors can be incorporated into living loci of fungal building materials.

5. Fungal photosensor

Fungal response to illumination was analysed using a fungal skin — a 1.5 mm thick sheet of pure mycelium of *G. resinaceum* fungi (Fig. 5(a)) (Adamatzky et al., 2021b). The response of the fungal skin to illumination is manifested in the raising of the baseline potential, as illustrated in the exemplar recordings in Fig. 5(b). The response-to-illumination spike does not subside but the electrical potential stays raised until illumination is switched off. An average amplitude of the response is 0.6 mV. The rise in potential starts immediately after the illumination is switched on. The potential saturation time is c. $3 \cdot 10^3$ s on average; the potential relaxation time is c. $3 \cdot 10^3$ s. Typically, we did not observe any spike trains after the illumination was switched

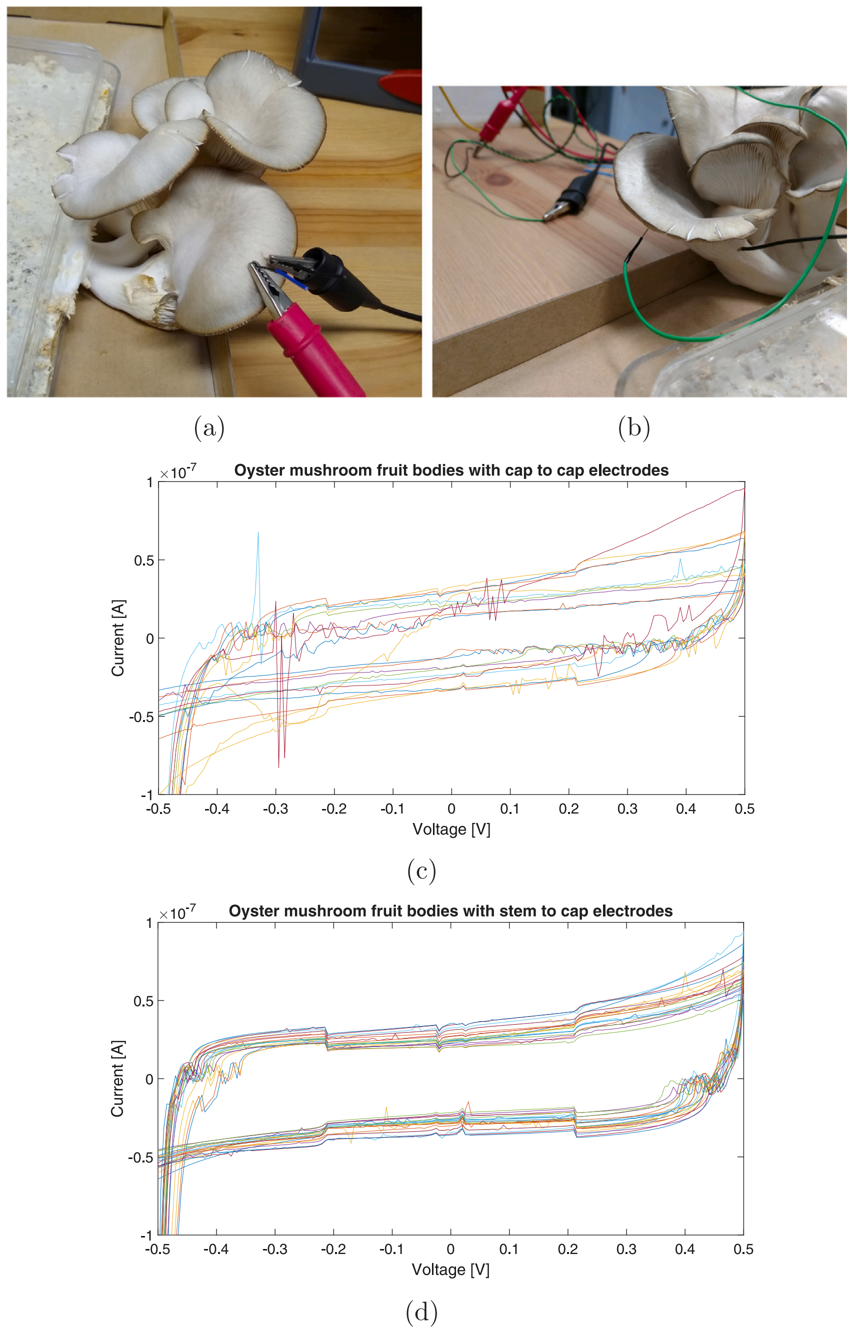

Fig. 2. Fungal memristors. (ab) Positions of electrodes in fruit bodies. (a) Electrodes inserted 10 mm apart in the fruit body cap. (b) One electrode is inserted in the cap with the other in the stem. (cd) Raw data from cyclic voltammetry performed over −0.5 V to 0.5 V. (c) Cap-to-cap electrode placement. (d) Stem-to-cap electrode placement.
Source: From Beasley et al. (2021a).

off, however, in a couple of trials we witnessed spike trains on top of the raised potential, as shown in Fig. 5(c). To conclude, living fungal materials respond to illumination by changing their electrical activity, therefore fungal materials can be incorporated in logical circuits and actuators with optical inputs.

6. Fungal chemical sensor

We demonstrated that hemp pads colonised by the fungus *P. ostreatus* (Fig. 6(a)) show distinctive sets of responses to chemical stimulation (Adamatzky et al., 2021a; Dehshibi et al., 2021). We stimulated colonised hemp pads with 96% ethanol, malt extract powder (Sigma Aldrich, UK) dissolved in distilled water, dextrose (Ritchie Products Ltd, UK) and hydrocortisone (Solu-Cortef trademark, 4 mL Act-O-Vial, Pfizer, Athens, Greece). An example of the response to chemical stimulation is shown in Fig. 6(b). A response to stimulation with ethanol is characterised by a drop of electrical potential, up to 8 mV, followed by repolarisation phase, lasting for up to 15 s. Fungi respond to the application of nutrients by increasing the frequency of electrical potential spiking (Adamatzky et al., 2021a). Exposure to hydrocortisone leads to a series of electrical disturbance events propagating along the mycelium networks with further indications of suppressed electrical activity (Dehshibi et al., 2021). Fungal chemical sensors show a great potential for future applications, however substantial research should be invested in their calibration.

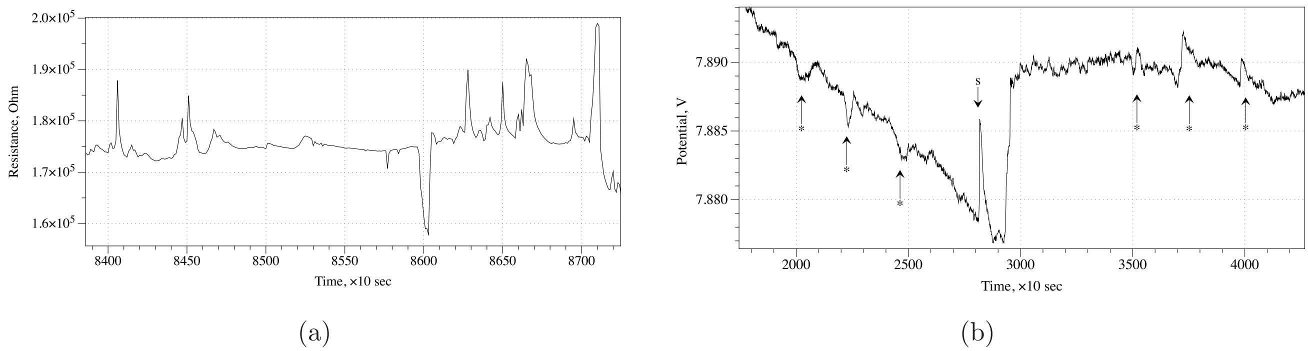

Fig. 3. (a) Examples of high amplitude and high frequency spikes. (b) Oscillation of electrical potential under 10 V DC applied, where spikes analysed are marked by '*'.
Source: From Adamatzky and Jones (2011).

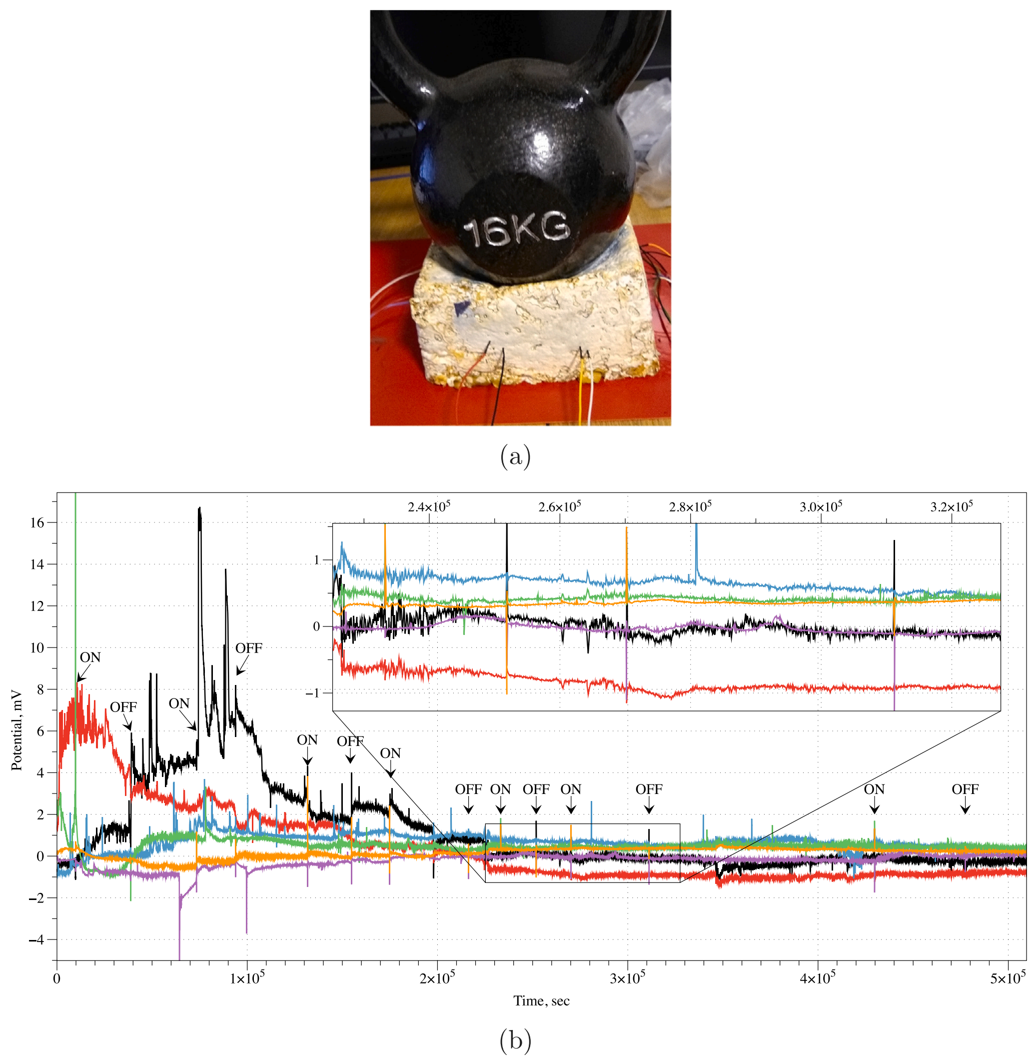

Fig. 4. (a) Experimental setup. Pairs of differential electrodes inserted in a fungal block and 16 kg kettle bell placed on top of the fungal block. Channels are from the top right clockwise (1–2), (3–5), …, (15–16). (b) The activity of the block stimulated with 16 kg load. Moments of the loads applications are labelled by 'ON' and lifting the loads by 'OFF'. Channels are colour coded as (1–2) – black, (3–4) – red, (5–6) – blue, (7–8) – green, (9–10) – magenta, (11–12)– orange, (13–14) – yellow.
Source: From Adamatzky and Gandia (2021).

7. Fungal analog computing

In numerical modelling and experimental laboratory setup we exploited principles of electrical analog computing (Beasley et al., 2021b; Roberts and Adamatzky, 2021). True and False values are represented by above threshold and below threshold voltages. Due to the non-linearity of the conductive substrate along electrical current pathways between input and output electrodes, the input voltages are transformed and thus logical mappings are implemented. Detailed descriptions of these techniques can be found in Adamatzky et al. (2020), Beasley et al. (2021b) and Roberts and Adamatzky (2021).

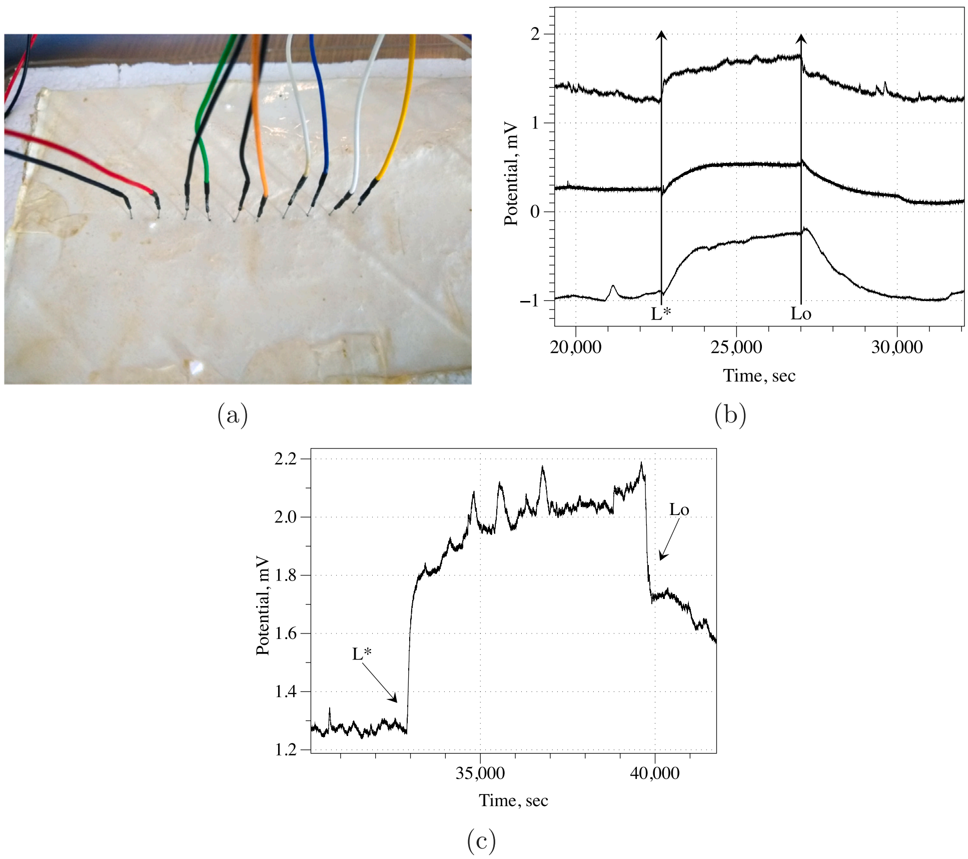

Fig. 5. Fungal response to optical stimulation. (a) A photograph of electrodes inserted into the fungal skin. (b) Exemplar response of fungal skin to illumination, recorded on three pairs of differential electrodes. 'L*' indicates illumination is applied, 'Lo' illumination is switched off. () A train of spikes on the raised potential as a response to illumination. *Source:* From Adamatzky et al. (2021b).

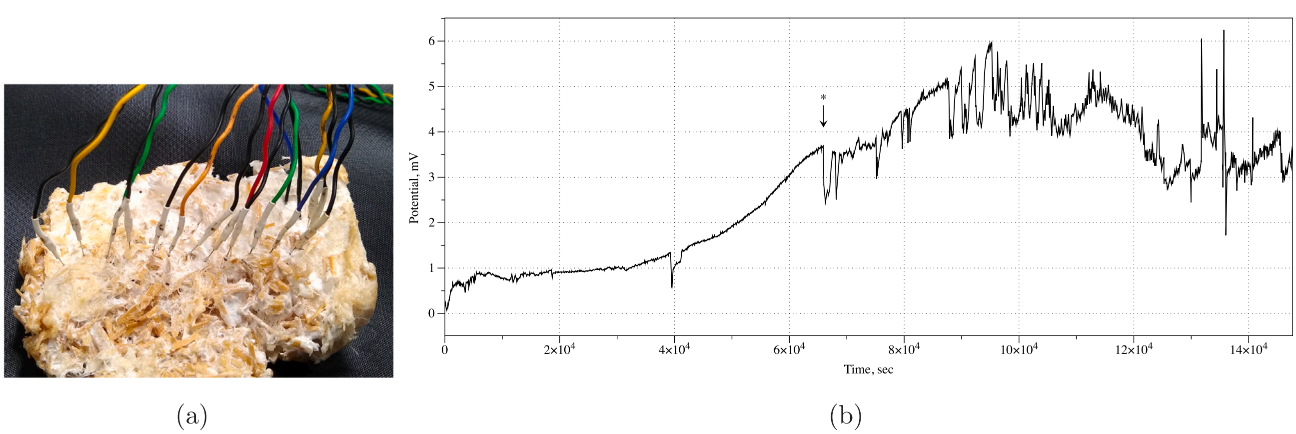

Fig. 6. (a) Experimental setup. Exemplar locations of electrodes. (b) Response to application of dextrose. The moment of application is shown by asterisk.

The z-stacks of a single colony of *Aspergillus niger* fungus strain AR9#2 (Vinck et al., 2011) were converted to a 3D graph (Fig. 7). We modelled the colony as a resistive and capacitive (RC) network. RC networks are circuits consisting of resistances and capacitors, the most fundamental passive circuit elements needed to design from a low-pass filter up to an equivalent network of a nerve cell (Freygang, 1959). The 3D graph was converted to the RC network, whose magnitudes are a function of the length of the connections.

Resistances were in the order of kOhms and capacitance in the order of pF. The positive voltage and ground nodes were randomly assigned from the sample and 1000 networks were created in each arrangement for analysis. SPICE analysis consisted of transient analysis using a two voltage pulses of 60 mV on the randomly assigned positive nodes. We modelled the fungal colony in serial RC networks and parallel RC networks. The output voltages were binarised with the threshold θ: $V > \theta$ symbolises logical True otherwise False.

There are 16 possible logical gates realisable for two inputs and one output. The gates implying input 0 and evoking a response 1, i.e. $f(0,0) = 1$, are not realisable because the simulated fungal circuit is passive. The remaining 8 gates are AND, OR, AND-NOT (x AND NOT y and NOT x AND y), SELECT (SELECT x and SELECT y) and XOR. In the model of serial RC networks, we found gates AND, SELECT and AND-NOT; no OR gates have been found. The number n of the gates discovered decreases by a power law with increase of θ. The frequency of AND gates oscillates, as shown in the zoom insert in Fig. 8a, most likely due to its insignificant presence in the samples. The oscillations reach near zero base when θ

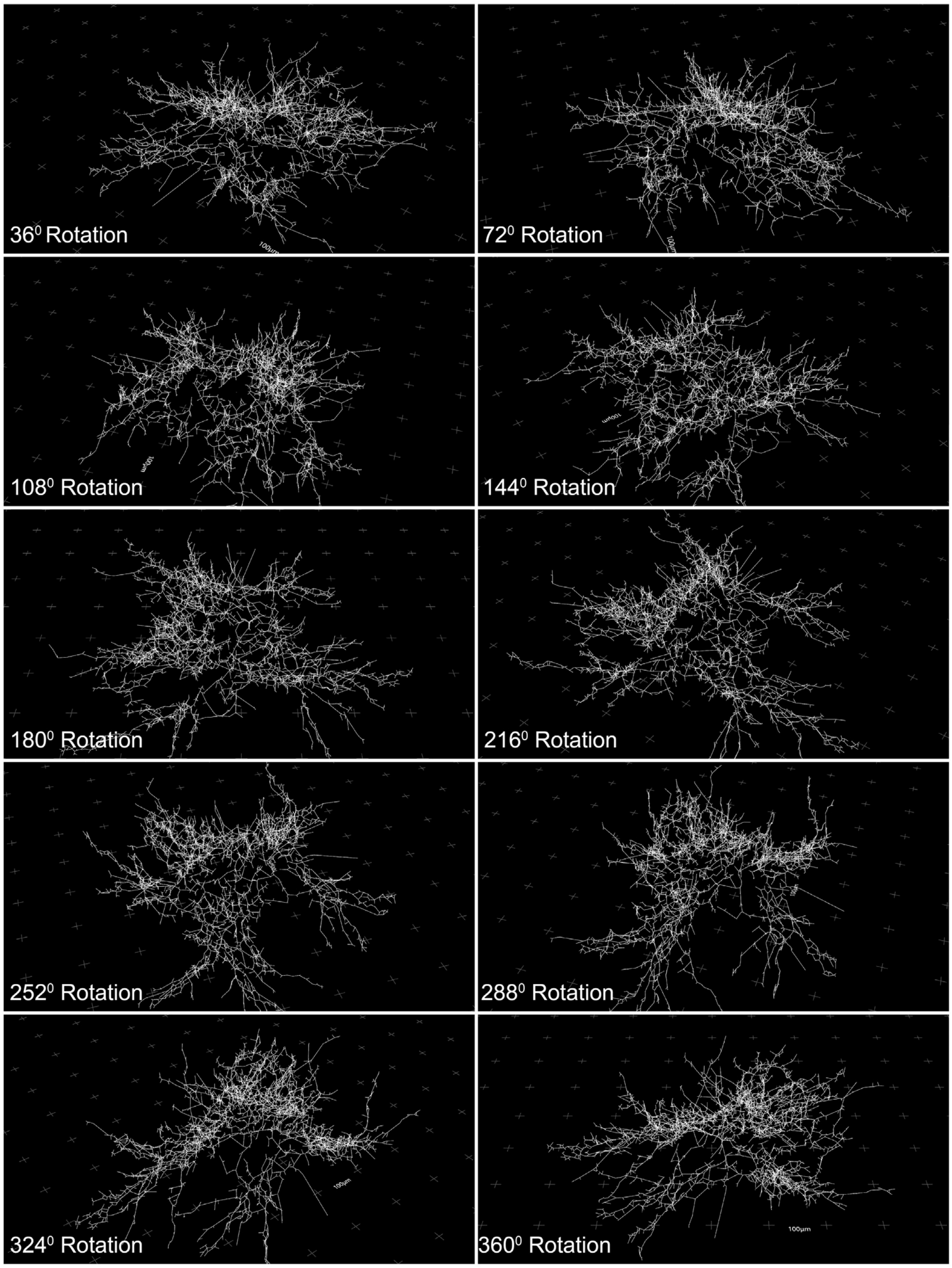

Fig. 7. Perspective views of the 3D Graph. Each frame shows the graph after a 36° rotation around the z-axis with origin located approximately in the centre of the colony, on the x–y plane indicated with registration marks.

exceeds 0.001. In the model of parallel RC networks we only found the gates AND, SELECT and OR. The number of OR gates decreases quadratically and becomes nil when $\theta > 0.03$. The number of AND gates increases near linearly with increase of θ. The number of SELECT gates reaches its maximum at $\theta = 0.023$, and then starts to decreases with the further increase of θ. To conclude, mycelium bound composites can act as computing media and implement a wide range of Boolean circuits, thus opening a new perspective in biological analog and hybrid computing.

8. Discussion

Practical implementations of the electronic properties of fungi would be in sensorial and computing circuits embedded into mycelium bound composites. For example, an approach of exploiting reservoir computing for sensing (Athanasiou and Konkoli, 2018), where the information about the environment is encoded in the state of the reservoir memristive computing medium, can be employed to prototype sensing-memristive devices from living fungi.

A very low frequency of fungal electronic oscillators does not preclude us from considering inclusion of the oscillators in fully living or hybrid analog circuits embedded into fungal architectures (Adamatzky et al., 2019) and future specialised circuits and processors made from living fungi functionalised with nanoparticles, as have been illustrated in prototypes of hybrid electronic devices with slime mould (Whiting et al., 2016; Walter et al., 2016; Ntinas et al., 2017; Adamatzky, 2015; Berzina et al., 2015). Potential devices made of living fungi

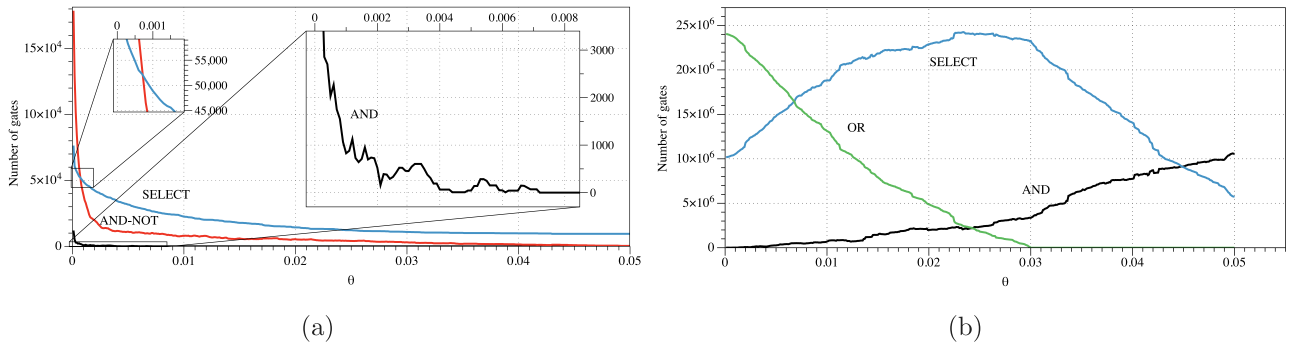

Fig. 8. Occurrences of the gates from the groups AND, black, OR, green, AND-NOT, red, and SELECT, blue, for $\theta \in [0.0001, 0.05]$, with θ increment 0.0001, in (a) fungal colony modelled with serial RC networks, (b) fungal colony modelled with parallel RC networks.

might include environmental sensors integrated in building structures (Adamatzky et al., 2019) and wearables (Adamatzky et al., 2021a), patches monitoring chemical parameters of human body (Dehshibi et al., 2021).

Further studies will be also concerned to uncover biophysical mechanisms of the electrical properties of the mycelium bound composites discovered in our experiments. Let us discuss few of the phenomena.

Memristive properties of living creatures, their organs and fluids have been demonstrated in skin, blood, plants, slime mould, tubulin microtubules, see details in Beasley et al. (2021a). A mechanism of the memristance is likely in the relocation of ions and temporary physical changes of the cell membranes.

One of the feasible explanations of the resistance oscillations could be in the translocation of water and metabolites taking place in the mycelium. This translocation is periodic, and more likely guided by calcium waves. Increase in a liquid in the mycelium loci leads to reduced resistance. When the translocated mass of metabolites leaves the area, the resistance increases. Electrical response of mycelium bound composites to mechanical pressure could be caused by polarisation of the cell membranes caused by mechanical deformation and blockade of calcium waves pathways due to mechanical constriction of mycelium strands. Electrical responses of fungi to illumination are due photosensitive nature of the fungi, with research showing fungi can be more photosensitive than green plants (Carlile, 1965; Furuya, 1986). Fungi are most receptive towards the UV end of the spectrum but exhibit photoresponses across the entire light spectrum. Briefly exposing fungi to light can interrupt their current growth cycle, triggering other responses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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