Neuromorphic fungi

Andrew Adamatzky*

Unconventional Computing Lab, UWE Bristol, UK

*Corresponding author, e-mail: andrew.adamatzky@uwe.ac.uk

ABSTRACT:

We overview electrical properties of fungi and demonstrate — in computer models and experimental laboratory studies — that fungi can perceive and process information in a way similar to neural networks. We present fungal neuromorphic electronics — a family of living electronic devices made of mycelium bound composites or pure mycelium. Fungal neuromorphic devices are capable of changing their impedance and generating spikes of electrical potential in response to external control parameters. Fungal neuromorphic circuits can be embedded into fungal materials and wearables or used as stand alone sensing and computing device. The talk comprise of three parts: fungal electronics, fungal computing and fungal language.

In **fungal electronics** we discuss the following devices. A **memristor** (resistor with memory or resistive switching device) is a two or three-terminal device whose resistance depends on one or more internal state variables of the device. Memristors are leading elements in neuromorphic circuits, human brain interfaces and programmable electronics. Experiments have shown that *P. ostreatus* fruit bodies exhibit memristive properties when subject to a voltage sweep. An **electronic oscillator** is a device that converts direct current (voltage) input into an alternating current (voltage) signal output. A fungal oscillator is built on the endogenous fluctuations in the electrical resistance of mycelium bound composites. **Tactile sensing** of fungal neuromorphic devices is demonstrated in experiments with fungal blocks which can tell whether weight was applied or removed because they respond to weight application with higher amplitude and longer duration spikes than spikes responding to weight removal. **Optical fungal sensors** are based on the living fungal materials responding to illumination by changing their electrical activity; the fungal materials can be incorporated in logical circuits and actuators with optical inputs. **Fungal chemical sensors** are demonstrated to efficiently differentiate between chemical stimuli by producing unique pattern of electrical activity.

Fungal computing can be to two types: electrical analog and voltage spikes based. In numerical modelling and experimental laboratory setup we exploited principles of **electrical analog computing**. The logical values are represented by above threshold and below threshold voltages. Due to the non-linearity of the substrate along electrical current pathways between input and output electrodes, the input voltages are transformed and thus logical mappings are implemented. A fungal colony maintains its integrity via flow of cytoplasm along mycelium network. This flow, together with possible coordination of mycelium tips propagation, is controlled by associated waves of electrical potential. These excitation waves can be employed to implement a **voltage spikes based computation** in the mycelium networks. We numerically model propagation of excitation in a single colony of *A. niger*. Boolean values are encoded by spikes of extracellular potential. We represent binary inputs by electrical impulses on a pair of selected electrodes and we record responses of the colony from sixteen electrodes. We derive sets of two-inputs-on-output logical gates implementable.

A **fungal language** is introduced in the following context. Fungi exhibit oscillations of extracellular electrical potential recorded via differential electrodes inserted into a substrate colonised by mycelium or directly into sporocarps. We analysed electrical activity of *O. nidiformis*, *F. velutipes*, *S. commune* and caterpillar fungi *C. militari*. We found that spikes are often clustered into trains. Assuming that spikes of electrical activity are used by fungi to communicate and process information in mycelium networks, we group spikes into words and provide a linguistic and information complexity analysis of the fungal spiking activity. We demonstrate that distributions of fungal word lengths match that of human languages. We also construct algorithmic and Liz-Zempel complexity hierarchies of fungal sentences. Advances towards uncovering syntax of fungal language are offered and analysed.

KEYWORDS:

Fungi; electrical activity; action potential; spike trains; memristors; sensors; fungal intelligence; fungal language