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*** Free software used to create the simulations in this paper.**
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- CAviewer (José Antonio Jiménez Amador, Genaro J. Martínez, https:// www.comunidad.escom.ipn.mx/genaro/Papers/Thesis_files/CAviewer. tar.gz)
- CATM (Sergio Eduardo Juárez Martínez, César Iván Manzano Mendoza, https://www.comunidad.escom.ipn.mx/genaro/Papers/Thesis_files/maquinaTuring.java.tar.gz)

Living wearables from slime mould and fungi

Andrew Adamatzky,[1] Anna Nikolaidou,[2] Antoni Gandia,[3] and Alessandro Chiolerio[4]

Smart wearables, augmented with soft and liquid electronics, can display sensing, responsive and adaptive capabilities, but they cannot self-grow or self-repair. Living organisms colonising a fabric could be a viable alternative. In the present article we briefly review our ideas on implementing living wearables with slime mould and fungi. The living networks of slime mould protoplasmic tubes and fungal mycelium networks can act as distributed sensorial networks, fuse sensorial inputs from wearers and environment, process information in a massive parallel manner and provide responses in benefit of the consortium human-microbe.

Most living creatures have plenty of living wearables: skin, mites, fungal and bacterial colonies colonising the skin, and critters living our hairs. Skin is out living wearable number one. The skin senses, transmit information and, more likely, is capable of distributed decision making. Limitations of the skin are that the skin is not disposable, we cannot change our skin as easy as we can change the pants or socks, sensorial and computational properties of the skins are not easily tunable, attempts to integrate soft and liquid electronics into human skins pose health risks and incompatibility issues. Also it is not acceptable in many cultures to appear in public naked, so a substantial area of our skin should be covered by fabric and thus renders useless for immediate environmental sensing. Traditionally, wearables have acted as covering tools aiming to provide comfort and protection from the elements. They have also constituted semiotic devices, machines for communication[5] and functioned as social mediators and interfaces between our bodies and society.[6] With the emergence of novel and smart materials, the functionality of wearables has been extended, offering new opportunities. Smart materials can be defined as highly engineered materials that respond intelligently to their environment.[7] They are characterized by their ability to detect and respond to stimuli from the environment (such as stress, temperature, moisture, pH, electric or magnetic fields), by a specific change of behaviour, as for instance a colour or shape or form change.[8] Smart materials are often embedded in more conventional materials and applied in a system with microelectronic components and miniaturized technologies.[9]

Smart wearables are devices that are responsive to the wearer, they can sense and process information from the user's body and environment and report results of their analysis as electrical signals.[10] In the last decade, electronics and textiles (e-textiles) have been a fundamental part of smart wearables. Integrating electronics into textile products enables the development of wearable electro-textiles for sensing / monitoring body functions, delivering communication facilities, data transfer, control of the environment, and many other applications.[11] For example, a material surface, such as a common fabric that embeds a nitinol wire (a smart material), can become sensitive and responsive (with visual or kinetic response) according to an external stimulus, like a rise in temperature. This may happen when you wear it, and the increase in body temperature causes the expansion of the fabric.[12] One of the most impacting issues regarding both electron devices and nanocomposite materials is represented by their poor capability to self-repair and grow, to self-organize and adapt to changing environmental conditions.

Although smart wearables can display sensing, responsive and adaptive capabilities, they cannot self-grow and self-repair. In addition to

Fig. 1. Live slime mould *Physarum polycephalum* growing on a doll. Experiments conducted with A. A.'s daughter, Adriana Adamatzky, in 2010.

Fig. 2. A polyurethane mannequin head colonised by slime mould *Physarum polycephalum.*

Fig. 3. Imitation of scalp innervation with *Physarum polycephalum*.

this, the materials usually used to create the electronic components of the wearables such as metals, plastics and other petroleum-based materials are derived from natural resources, which are limited and non-renewable. Electronic waste or e-waste is one of the emerging problems in developed and developing countries worldwide as it comprises a multitude of components with valuable materials, some containing toxic substances, that can have an adverse impact on human health and the environment.[13] Living organisms could be a viable alternative.

Back in the 2010s we proposed a concept of *extralligence* by growing living slime *Physarum polycephalum* on models of human bodies.[14] We designed, and partly implemented in laboratory conditions with slime mould *Physarum polycephalum*, an intelligent adaptive living network wearable by humans and robots. When grown on 3D bodies (living or inanimate) the living *Physarum* network provides a highly-distributed sensorial structure (light-, electro-magnetic, chemical and tactile sensitivity) with embedded dynamic architecture of massive-parallel computing processors based on geometry of proximity graphs. We have chosen an acellular slime mould *Physarum polycephalum* as amorphous living substrate because Physarum is a living, dynamical reaction diffusion pattern formation mechanism; Physarum may be considered as equivalent to a membrane bound sub excitable system (excitation stimuli provided by chemo-attractants and chemo-repellents); Physarum may be regarded as a highly efficient and living micro-manipulation and microfluidic transport device; Physarum is sensitive to illumination and AC electric fields and therefore allows for parallel and non-destructive input of information; Physarum represents results of computation by configuration of its body. In experimental laboratory studies, we showed that when inoculated on bare plastic surfaces, Physarum successfully develops an optimal network of protoplasmic tubes spanning sources of attractants while avoiding domains with over threshold concentration of repellents. When exposed to attractants and repellents, Physarum changes patterns of its electrical activity. We experimentally derived a unique one-to-one mapping between a range of selected bioactive chemicals and patterns of oscillations of the slime mould's extracellular electrical potential. This direct and rapid change demonstrates detection of these chemicals in a similar manner to a biological contactless chemical sensor. We believe results could be used in future designs of slime mould based chemical sensors and computers. We also evaluated feasibility of slime-mould based colour sensors

by illuminating Physarum with red, green, blue and white colours and analysing patterns of the slime mould's electrical potential oscillations. We defined that the slime mould recognises a colour if it reacts to illumination with the colour by a unique changes in amplitude and periods of oscillatory activity. In laboratory experiments we found that the slime mould recognises red and blue colour. The slime mould does not differentiate between green and white colours. The slime mould also recognises when red colour is switched off. We also mapped colours to diversity of the oscillations: illumination with a white colour increases diversity of amplitudes and periods of oscillations, other colours studied increase diversity either of amplitude or period.

As a proof of concept we designed an experimental laboratory implementation of a slime mould based tactile bristles, where the slime mould responds to repeated deflection of bristle by an immediate high-amplitude spike and a prolonged increase in amplitude and width of its oscillation impulses. We demonstrated that signal strength of the Physarum tactile bristle sensor averages near six for an immediate response and two for a prolonged response. Despite the sufficient sensorial abilities, the slime mould is rather fragile, highly dependent on environmental conditions and requires particular sources of nutrients. Fungi could, however, make a feasible alternative to the slime mould for the following reasons. Fungal composite materials, normally in form of solid lignocellulosic substrates colonised with the mycelium of filamentous fungi (*e.g. Ganoderma* spp., *Pleurotus* spp., *Trametes* spp.), are an emerging type of biomaterial known by being a robust, reliable and ecologically friendly replacement for conventional building materials and fabrics.[15] Fungi possess almost all the senses used by humans.[16] Fungi sense light, chemicals, gases, gravity and electric fields. Fungi show a pronounced response to changes in a substrate pH,[17] mechanical stimulation,[18] toxic metals,[19] CO2,[20] and stress hormones.[21] Fungi are known to respond to chemical and physical stimuli by changing patterns of its electrical activity[22] and electrical properties.[23] Thus, wearables made of or incorporating a cellulosic fabric colonised by fungi might act as a large distributed sensorial network.

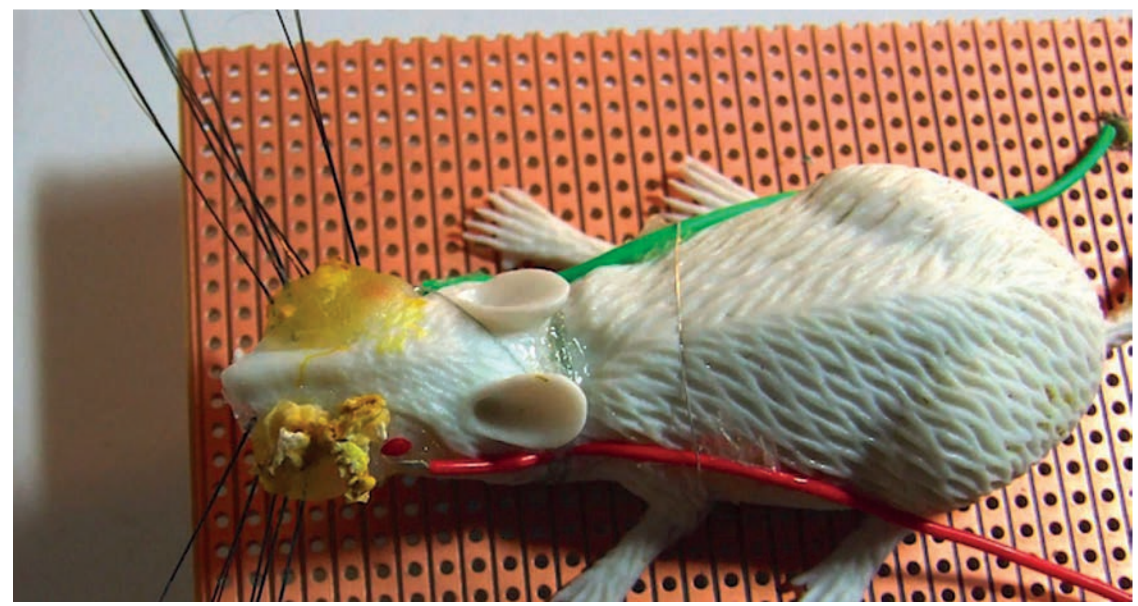

Fig. 4. Rat whiskers made of living slime mould *Physarum polycephalum*.

To evaluate feasibility of the living fungal wearables, we conducted two sets of laboratory experiments.
In the first set, to assess the sensing potential of fungal wearables, we undertook laboratory experiments on electrical response of a hemp fabric colonised by oyster fungus *Pleurotus ostreatus* to mechanical stretching and stimulation with attractants and repellents.[24] A fabric colonised by the fungus *P. ostreatus* shows distinctive sets of responses to chemical and mechanical stimulation. The response to 50 g load is in the range of 1.5 min which might indicate that rather purely electro-mechanical events take place than reactions involving propagation of calcium waves. The response to stimulation with ethanol is in a range of 7 sec. This would rather indicate physico-chemical damages to hyphae walls and corresponding electrical responses. The increase of frequency of electrical potential oscillation in a response to application of chemo-attractants or nutrients is consistent with previous studies. The increase in amplitude of spiking hours after the application of malt or dextrose might be due to the fungus ingesting the nutrients and transposing them across the wide mycelial network.
In the second set of experiments[25] we experimented with fungal skin. A fungal skin is a thin flexible sheet of a living interwoven, homogeneous, and continuous mycelium made by a filamentous fungus. The skin could be used in future living architectures of adaptive buildings and as a sensing living skin for soft self-growing/adaptive robots. In experimental laboratory studies, we demonstrated that the fungal skin is capable of recognising mechanical and optical stimulation. The skin reacts differently to loading of a weight, removal of the weight,

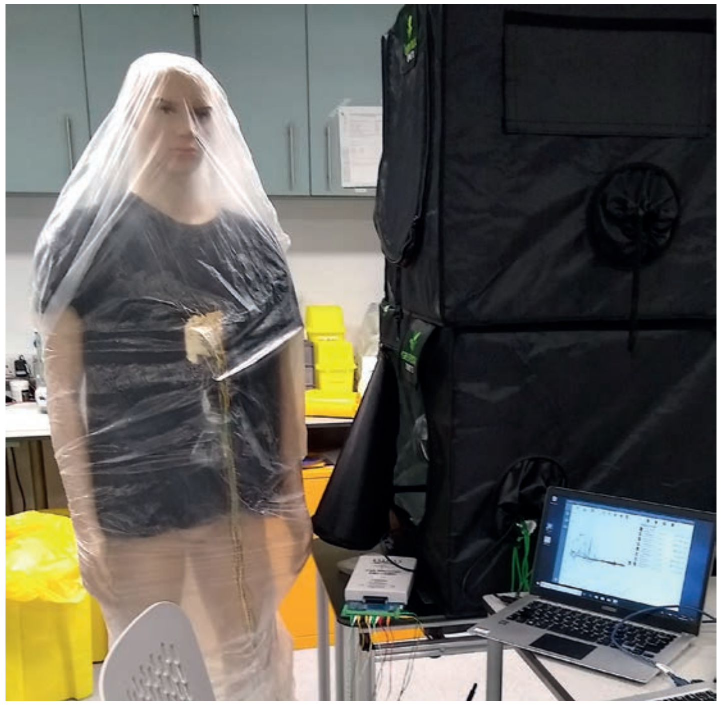

Fig. 5. A photo of experimental setup showing a hemp pad colonised with fungi, attached to a T-shirt with electrodes and recording equipment.

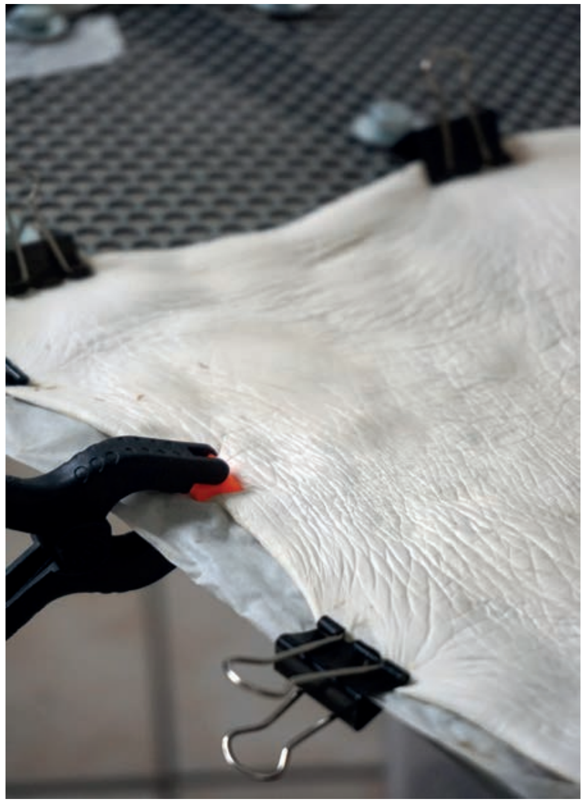

Fig. 6. The fungal skin shows animal type wrinkles.

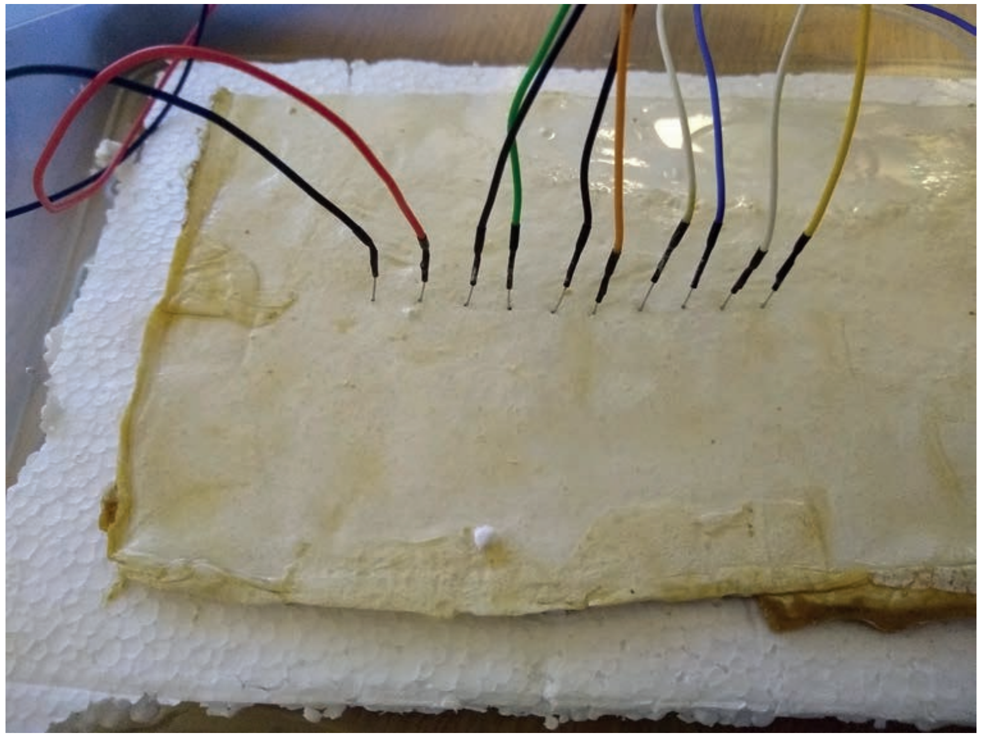

Fig. 7. Pairs of differential electrodes inserted in the fungal skin to record electrical response of the fungal skin to mechanical and optical stimulation.

and switching illumination on and off. These are the first experimental evidences that fungal materials can be used not only as mechanical skeletons in architecture and robotics but also as intelligent skins capable of recognition of external stimuli and sensorial fusion.
Living wearables offer a new spectrum of performance possibilities such as reactiveness, adaptiveness, and sensing capabilities. They are harmless to the environment, biodegradable and they can even nurture the cultivation of new materials in their end of life. The living material provides a unique opportunity for the wearables to be programmable by guiding the growth, controlling the nutrients and setting up the conditions in which the wearable can be created. Their ability to self-repair and self-grow makes them one of the most promising. Future studies can be focused on better understanding of electrical communication and stimulation in fungi and other microbes (advancements in biocomputation), development of biological sensors able to report slight changes in physico-environmental conditions and biochemical traces, biological sentient clothing that responds to the environment, self-sustaining and self-healing clothing and parchments grown *in situ*, exoskins and exoskeletons that symbiotically interact with the user, cross-over synergistic interactions between biological entities and electronic circuits or machines (advancements in biorobotics and biomechanoids).

[1] Professor in Unconventional Computing, UWE, Bristol, UK.
[2] Senior Lecturer in Architecture, UWE, Bristol, UK.
[3] Leading Researcher at MOGU, Italy.
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Brain Lego
Toy Computing with Lego Bricks

Stefan Höltgen[1]

"HIRNLEGOHIRNLEGOHIRNLEGOLEGOLEGO
HIRNLEGOLEGOLEHIRNLEGOLEGOLEGO
HIRNLEGOLEGOLEGOHIRNLEGOLEGOLEGO"
(*Einstürzende Neubauten*, Hirnlego, 1989)

"I have always had a predominantly visual approach to my environment. This is also probably why I never pursued music. This perhaps one-sided talent was also evident in the construction of my computer models; here, too, I preferred mechanical and electromechanical constructions and left the electronics to others who were better qualified."[2]
In this quote, computer pioneer Konrad Zuse describes his tinkering with construction kits he played with as a boy and a teenager from his viewpoint as an engineer. He used those kits in the 1920s to build all sorts of things with them: (award winning) models of cranes and excavators, spare parts for his bike, and mechanical household aids. Later on, when his computers were already working electronically, he used the thought pattern for a new system of self-reproducing machines.[3]

This mechanical thinking of computer functions has a long tradition reaching back into the Middle Ages: from Ramon Llullu's book *Ars Magna* published in 1305 where a theological 'converter' for Muslims to become Christians is drafted, to Leibniz' *Machina arithmeticae dyadicae* from 1679 (a mechanism to calculate with binary numbers) — both remained "paper machines" — through to the mechanical and electromechanical logical machines of the 19th and 20th centuries,[4] culminating in Claude Shannon's switching algebra from 1937. All of these drafts were based on the idea to make calculation and computation not only logically but also mechanically constructible.
From our present-day perspective, some of these drafts appear more like toys than serious calculators; toys that merely show the principles of computation but are not very suitable for actual usage. This view also has to do with the fact that those prototypes show their material and epistemological toy characteristics: they are often built from construction kits (for children and youth) or from everyday objects — according to the "Baukastenprinzip" ("kit principle"),[5] using heuristic design procedures, trial and error, and learning by doing.
The invitation to *think while tinkering* ("thinkering")[6] seems to be a basic principle of both logic and kit toying because both make it possible to comprehend/handle complex phenomena. This logic (the two-valued sentential logic, inaugurated in the 3rd century B.C. from Aristotle) is the timeless and non-spatial basis of all our thinking. It provides the transcendental basic structure of truth-apt propositions which are the foundation of our everyday thinking, actions, science, playing, … This reality is formalized in logics: propositions become tokens that can hold a truth value (true/false — no third option) and can be combined with junctors (and, or, if-then, not, …) to complex sentences.
A sentence like "*Tonight I'll go to the movies or I will read a book*" can be formalized as *p*