Mycelium-based ELM Emulation Utilizing Memristive Oscillating Cellular Automata

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Abstract*—Engineered Living Materials (ELMs) represent a novel class of materials that possess intrinsic properties and capabilities inspired by living organisms. Among ELMs, fungal mycelium stands out due to its low-cost manufacturing process, ubiquity in nature, and significant environmental benefits owing to its biodegradability. Modeling mycelium's complex behaviors challenges scientists due to its intricate natural phenomena, leading to the adoption of digital twins for accurate simulations and deeper insights. Memristors, with their unique statetransition capabilities and non-volatility, emerge as promising for implementing a low-power, efficient digital twin of mycelium, demonstrating versatility across various applications beyond conventional hardware limits. This paper explores the use of memristive nanoelectronic circuits to simulate the evolution of biological mycelium hyphae, introducing a novel computational approach, Memristive Oscillating Cellular Automaton (MOCA), to model the dynamic behavior of mycelium. The MOCA design mirrors the activator and suppressor processes observed in reaction-diffusion systems, thus simulating mycelium tip growth and branching patterns. The simulation results demonstrate the successful propagation of oscillating signals across a MOCA grid, reflecting the biological pathways within mycelium.

***Keywords*—Engineered Living Materials, Mycelium, Cellular Automata, Memristor Oscillator, Memristive Digital Twin**

1. INTRODUCTION

Engineered living materials (ELMs), a new class of materials unlike the inert traditional materials, exhibit intrinsic properties and capabilities that help them to expand themselves, inspired by the living organisms found in nature. Their main working principle for their evolution is the chemical communication with their environment through nutrients and ion exchange [1]. These kind of materials can constantly evolve and are utilized in bio-materials using technologies such as coating and 3D printing, in order to be utilized in biomedical applications like the wound healing [2], and other bio-therapeutic and smart materials applications [3], [4].

Mycelium, the vegetative part of a fungus, is an extremely bright ELM prospect for next-generation materials, as it incorporates low-cost manufacturing process and is met everywhere in nature. The use of such materials, allows for the minimization of the global pollution due to their biodegradability leading to mitigation of trash buildup, contamination of the environment, and the depletion of natural resources [5], [6]. Beyond that, its utilization in bio-inspired unconventional computations has been examined [7], as it exhibits electrical characteristics similar to those that neurons produce. That proves that there is extensive use of the aforementioned biological structure in many applications that can shape a greener future.

In order for the researchers and engineers to accurately predict growth patterns, optimize conditions for mycelial ELM development, and assess potential applications, a digital twin would be advantageous. Digital twins, particularly those integrating novel electrical circuitry, emerge as an optimal solution. This is due to their inherent physical and mathematical intricacies, which enable a more profound comprehension of the underlying mechanisms of the models they represent. This approach is notably applicable to the study of mycelium [8]. The digital twin enables researchers and engineers to accurately predict growth patterns, optimize conditions for mycelial development, and assess potential applications. The idea of a digital twin of mycelium is rooted in the desire to replicate the complex, adaptive, and efficient communication networks found in natural mycelium. In terms of plausibility, this method can provide realistic results very close to the real behavior of mycelium's evolution. On top of that, there have been relevant works at the theoretical level that can analyze the phenomenon in depth [9], [10]. However, in hardware, the aforementioned topic has not been studied, thus not providing a hardware-based digital twin of mycelium.

A really promising candidate for implementing an efficient digital twin of mycelium with novel hardware is memristor. Memristors are two-terminal electrical analog components that were first theorized by L. Chua in 1971 [12], and then partially realized at HP Labs in 2008 [13]. Their primary advantage is their ability to transition between states by altering their conductance in response to applied voltage and afterwards keeping their state. As such, their non-volatility consists a key factor for emulating mycelium evolution using a compact and low-power component. Numerous unconventional applications have made use of them [14]. A few specific examples include cellular automata [15], [16], the emulation of Parkinson's Disease [17], and the recognition of characters [18], proving that they are universal components ideal to fit to a large pool of applications outperforming the conventional hardware.

In this study, the emphasis is placed on using memristive nanoelectronic circuits to simulate biological mycelium's hyphae evolution. The operation of a mycelium-based ELM is elaborated upon in Section II. Subsequently, in Section III, the notion of Memristive Oscillating Cellular Automaton (MOCA) is introduced. Section IV presents the simulation results obtained from a MOCA grid. Finally, Section V concludes the paper by summarizing the key findings and outlining potential areas for future work.

(a) (b)

Fig. 1. (a) Activator-suppressor dynamics. (b) Effect of suppressor on the ELM's growth. Adopted from [11].

2. MYCELIUM-BASED ELM MECHANISMS

To accurately emulate a mycelium-based ELM, it is important to incorporate the fundamental behaviors of the mycelium. On the one hand, the ELM can be understood as an outcome of microorganisms' metabolic processes, necessitating an exploration of the bidirectional interaction between the organism and its surroundings. On the other hand, it could be perceived as a substance, emphasizing the importance of its mechanical characteristics as a critical result of the model. All in all, its behaviors could be categorized into four main categories: the metabolic processes, the transport processes, the micro-structural dynamics, and the propagation. Physically, these could include hyphal extension, branching, substrate diffusion, and anastomosis [19].

Mycelium tip evolution is commonly represented through a model of biased random walk, with the beginning of branching being a random occurrence. The main dynamics that are being replicated include tip extension and branching, translocation, and communication with external stimuli such as substrate uptake and depletion. These dynamics are usually represented by reaction-diffusion systems that are able to produce fractal structures that resemble mycelium networks [20], [21]. In this work, the proposed approach comprehensively embodies these specified attributes, employing a self-organizing activator-suppressor reaction-diffusion system as its foundation [22].

Reaction-diffusion systems serve as mathematical models to elucidate the spatio-temporal variations and dynamic interactions of multiple substances, thereby facilitating the generation of intricate patterns [22] and they significantly contribute to the comprehension of biological pattern formation [23]. Furthermore, these models can also scale up to any dimension desired, as they are governed by partial differential equations that are not limited to any dimension.

To enhance the comprehension of pattern formation, it is essential to delve into the intricacies of the reaction-diffusion system utilized. This system delineates the dynamics between two substances, referred to as the activator and the suppressor, and their impact on the resultant cell formation. The activator is a substance that promotes cell development, where the presence of its concentration beyond a specific threshold may precipitate cell generation. Conversely, the suppressor functions to diminish the activator's concentration, exhibiting an antagonistic effect. The activator-suppressor interactions of the reaction-diffusion system utilized are summarized in Fig. 1.

Two modifications are required for the system to produce structures that embody the mechanics and, most importantly, the structure of the mycelium. Firstly, the activator is constrained to operate solely within a cell, while the suppressor is allowed to function universally. This arrangement effectively restricts the growth of the activator to the confines of the cell, thereby allowing the suppressor to direct and essentially shape the cell's development by suppressing the activator's undirected and unregulated expansion. In this way, the activator acts like the cell's plasma membrane by not only defining the borders of the cell, but also allowing the cell to interact with its environment in a controlled way [24].

Regarding the general mathematical foundations for the expressions of the concentration of the activator, the suppressor and also the state of the cell, these are defined as follows:

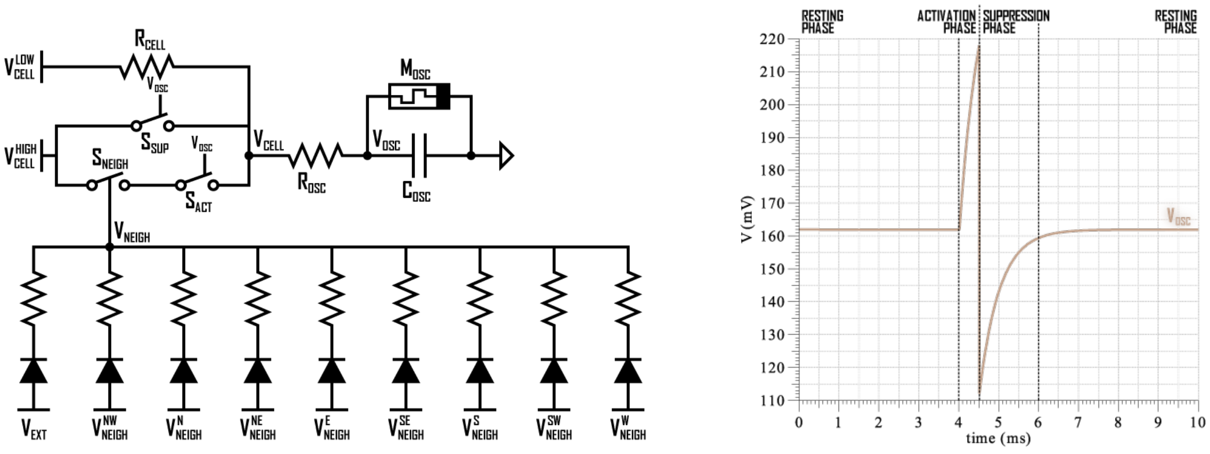
$$\frac{\partial u}{\partial t} = \nabla^2 u + \zeta(\kappa u + u^2 - \lambda u v) \,\epsilon\, \Omega c \qquad (1)$$

$$\frac{\partial v}{\partial t} = d\nabla^2 v + \zeta(\mu u^2 - v) \,\epsilon\, \Omega \qquad (2)$$

$$\frac{dc}{dt} = \zeta \nu c(a(u) - c)(c - 1) \,\epsilon\, \Omega \qquad (3)$$

Where u and v represent the concentrations of the activator and the suppressor, respectively. Eq. (1) and eq. (2) describe the manner in which the solutions for activation and suppression propagate through space, referred to as the diffusion term, while at the same time elucidate the interaction between the solutions u and v, known as the reaction term. Eq. (3) is the derivative of the state of the cell c over time calculated as an expression between u and v.

These equations can fully encapsulate the desired characteristics of a reaction-diffusion model. While hardware implementation cannot fully incorporate such mathematical calculation, the described processes should be properly incorporated for the successful simulation of the ELM's growth, shape and directionality processes.



(a) (b)

Fig. 2. (a) Memristive Oscillating Cellular Automaton circuit. (b) MOCA output oscillation and operational phases.

3. MEMRISTIVE OSCILLATING CELLULAR AUTOMATA FOR ELM EMULATION

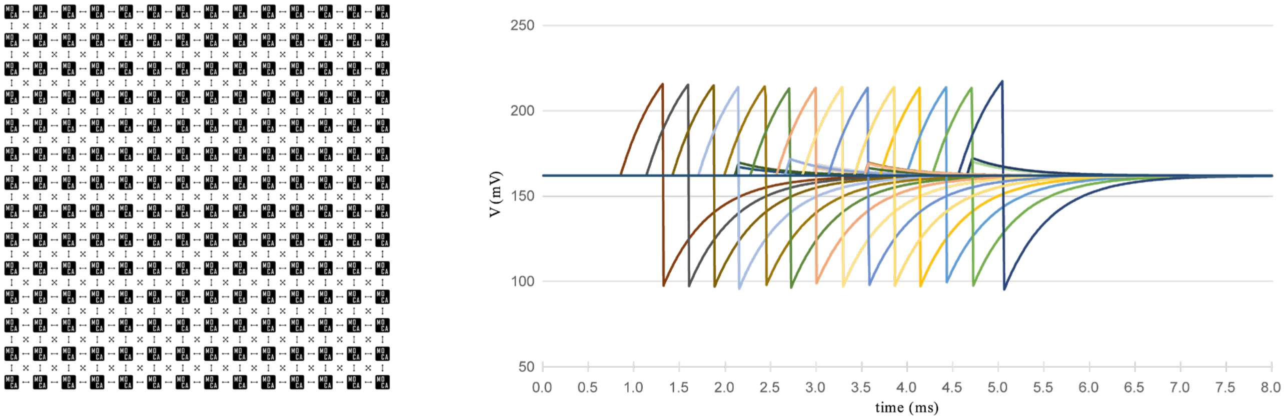
In order to incorporate the necessary biological processes and mechanisms of mycelium-based ELMs, Cellular Automata (CAs) are considered a good candidate as they are an effective computational tool for simulating physical phenomena, leveraging their inherent parallel processing capabilities to perform computations efficiently when implemented in hardware [25]. Recent advancements in unconventional nanoelectronic devices, particularly memristors, have fueled the development of novel CA-based computing approaches. These include Memristive Cellular Automata (MemCA) [26] and Memristive Cellular Nonlinear Networks (M-CNN) [27]. A recent development introduces the Wave Cellular Automata concept, incorporating wave generation circuitry to mimic wave propagation within a cellular-like architecture [28]. These wave generators interconnect to form a network, enabling the propagation of electrical wave signals with the ability to interact spatially, replicating the core concepts of CA neighborhoods and evolution.

Following these principles and in order to integrate in circuit level the reaction-diffusion dynamics in a simplified manner, a Memristive Oscillating Cellular Automata (MOCA) configuration, illustrated in Fig. 2(a), is considered to feature an output voltage (Vosc) oscillation mechanism (Fig. 2(b)) that fluctuates within specified voltage thresholds set by a unipolar memristive CBRAM device (M_{OSC}). This oscillation is achieved by connecting the cell to the voltage outputs of its immediate Moore neighborhood ($V^{NW;N;NE;E;SE;S;SW;W}$). An external voltage supply (V_{EXT}), which corresponds to external stimuli that affect hyphae evolution such as humidity, nutrients, light, etc, in parallel with the neighboring voltages, allows the definition of distinct MOCA rules by properly affecting the connecting node (V_{NEIGH}). Different values to V_{EXT} leads to different values to V_{NEIGH}, which means that the threshold of the switch S_{NEIGH} can be reached easier or harder, enabling different behaviors for each cell.

Focusing on the CBRAM memristive device, a single-layer MIM (Metal-Insulator-Metal) structure of Ag (~ 40 nm) / SiO2 (~ 20 nm) / Pt NPs (~ 5 nm) has been taken into consideration. This device configuration exhibits rapid unipolar switching capability, a key factor in achieving the required oscillation phenomena [29]. The model utilized to represent the CBRAM device fitted in experimental data is a physics-driven model, utilizing a compact set of equations formulated in Verilog-A. This model utilizes an effective diameter (φ) as its state variable, with its time derivative determined by voltage and temperature dependent drift, diffusion, and thermo-diffusion combined effects, as established in [30].

Oscillation initiation is triggered by applying a constant DC voltage, with the persistence of oscillations over time necessitating proper configuration of resistor (Rosc) and capacitor (Cosc) values. This prevents the voltage across the memristor (Vosc) from reaching equilibrium between the oscillation thresholds. The voltage supplies V_{CELL}^{HIGH} and V_{CELL}^{LOW} deliver the necessary power through a two-branch control circuit: one maintaining the cell at idle state and another activating oscillation upon the appropriate rule conditions. An oscillation is initiated upon reaching the threshold determined by the applied rule, facilitated by a switch (S_{NEIGH}). To ensure proper MOCA operation and prevent abrupt oscillation interruption, a self-restraint switch (S_{ACT}) is incorporated in series with S_{NEIGH}. Furthermore, smooth operation is facilitated by the S_{SUP} switch, which guards against sudden oscillation halts and guarantees successful MOCA suppression, preventing rule influence on the computation time-step.

The MOCA operation can be categorized into three phases, namely resting, activation and suppression (Fig. 2(b)). In the resting phase, the oscillating unit remains idle, awaiting to be triggered. The activation phase is initiated when a stimulus surpasses the MOCA activation threshold, triggering oscillatory behavior matching the function of the activator in a reaction-diffusion system. Finally, the suppression phase follows, where the oscillation reaches its minimum voltage level before increasing and returning to its resting state, corresponding to the suppressor behavior of a reaction-diffusion system. By connecting these MOCA cells in a spatial grid, it could emulate the ELM behavior, focusing on their growth and evolution.



(a)

(b)

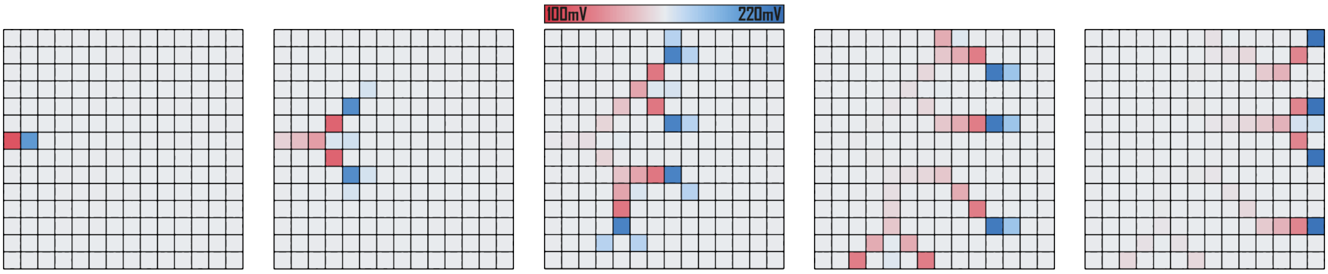
Fig. 3. (a) A 14 × 14 grid of MOCA cells with their respective neighboring connections. (b) Output oscillations from all grid's MOCA cells.

4. SIMULATION RESULTS ON MYCELIUM TIP GROWTH AND BRANCHING

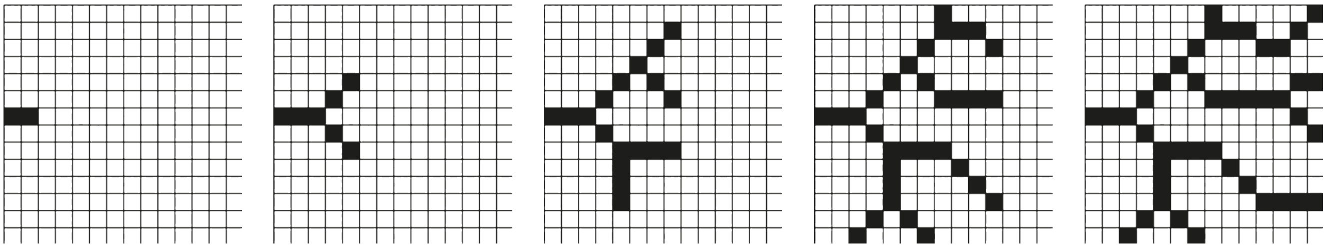
In order to simulate mycelium's hyphae propagation, a 14 × 14 grid of MOCA cells has been utilized, as depicted in Fig. 3(a). All cells are connected through their Moore neighboring ones via their oscillation output VOSC node. The voltage outputs' of all cells are illustrated in Fig. 3(b) showcasing a domino effect of oscillation propagation in neighboring cells. In detail, when a cell is triggered, it enters its activation phase and its output voltage increases. This affects its neighboring cells, leading to the activation of some of them after some time. After the activation phase, the cell enters its suppression phase, lowering its output voltage and leading to restraining its neighbors activation. The impact of suppression phase can be clearly spotted at 2.2ms, 3.6ms and 4.7ms, where different cells attempts to initiate their activation, but the suppression effect of one of their neighbors restricts them and they return back to the resting phase.

To further clarify the triggering mechanisms within the cellular grid, snapshots of all cells output voltage are presented in Figs. 4(a-e) under different simulation times. The tip of the ELM is illustrated in deep blue when the cell is at the peak of its activation phase. The evolution begins on the left side of the grid (Fig. 4(a)) and the tip is growing progressively. In Fig. 4(b), the tip branching can be observed where two different tips are developed and propagated in the grid. The tip growth and branching continues in Fig. 4(c), while some of the branches are reaching the end of the grid in Fig. 4(d). It is important to highlight that suppressed cells are colored red, restricting their neighbors evolution, like in the lower side of Fig. 4(d). The last activated cells can be observed in Fig. 4(e).

Following the operation of the MOCA grid, the evolution of the mycelium hyphae after specific times is illustrated in Figs. 4(f-j) with black color. The tip growth (Fig. 4(f)) and branching (Fig. 4(g)) are evident. In Fig. 4(h), the grid already includes 4 branches, while in Fig. 4(i) includes 5 of them, proving that the evolution continues gradually. The complete evolution of the mycelium hyphae in the MOCA grid can be observed in Fig. 4(j), where the main mechanisms of growth and branching can be clearly spotted across the grid.



(a) 1.4ms (b) 2.3ms (c) 3.2ms (d) 4.1ms (e) 5ms



(f) 1.4ms (g) 2.3ms (h) 3.2ms (i) 4.1ms (j) 5ms

Fig. 4. (a-e) Output voltages across the grid of MOCA cells in different simulation times. Blue corresponds to the activation phase, while red to the suppression phase. (f-j) Mycelium evolution after specific simulation times. Black cells correspond to the ones that have been already activated.

5. CONCLUSIONS AND FUTURE WORK

In this work, a novel methodology for simulating ELMs is presented, focusing particularly on fungal mycelium as a promising candidate for developing next-generation materials. The core concept lies in modeling mycelium behavior, advocating for the use of digital twins to offer a comprehensive understanding of its complex dynamics. A novel approach is introduced through the implementation of Memristive Oscillating Cellular Automaton (MOCA), utilizing memristive nanoelectronic circuits to simulate the evolution of biological mycelium hyphae. The MOCA design incorporates a unipolar memristor device and exhibits three distinct operational phases: resting, activation, and suppression. These phases incorporate the reaction-diffusion dynamics observed in biological systems, enabling the simulation of mycelium growth and branching patterns.

The simulation results demonstrate the successful propagation of activation signals across the MOCA grid, mimicking the tip growth and branching observed in fungal mycelium, showcasing the potential of this method in understanding the intricate behaviors of ELMs. The domino effect of neighboring cell activation reflects the biological communication pathways within the mycelium. Furthermore, the suppression phase effectively restricts uncontrolled growth, ensuring realistic behavior based on reaction–diffusion systems.

This work paves the way for further advancements in the field of ELMs by offering a novel modeling approach using nanoelectronic memristive circuits that bridges the gap between traditional materials and living systems. Future work includes expanding the MOCA grid size in order to simulate larger and more complex structures of mycelium networks. Lastly, the incorporation of environmental stimuli will be attempted introducing external voltage variations within the MOCA grid to represent the influence of environmental factors such as humidity, nutrients, and light on mycelium growth.

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