Playing with Growth Patterns: Merging Biotechnology and Architectural Design to Sense Environmental Toxins

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This architectural research project, titled *Artificial Lucidum*, conflates principles in biotechnology with computational processes to design responsive architectural devices that augment bodies with biosensors. The biosensors, embedded within a wearable architecture, measure environmental toxins, and convey this data through an augmented reality interface. The project builds upon ongoing research that is predicated on interdisciplinary collaborations within the fields of architecture and biology.

INTRODUCTION

In the spirit of play, a series of rules were established to set up a framework for a variety of growth experiments that explore the patterns, forms, and morphologies of living organisms. *E.coli* bacteria and *Physarum polycephalum* were grown under specific conditions within various parameters, allowing for a set of criteria in which to assess their unruly, natural growth and behavior. The project adapts a bio inspired form finding method using *Physarum polycephalum*, also known as slime mold, single celled organisms that can aggregate together to produce efficient, multi-cellular spatial structures. This behavior was then studied using agent-based computational design simulations to generate the design of the architectural devices. Spaces within these devices are allocated to grow *E.coli* bacteria, which act as biosensors that detect the presence or absence of environmental toxins, such as ozone, UV-light levels, heavy metals, and sulfur dioxide. Bacterial biosensors are created by DNA cloning technology followed by bacterial transformation. DNA cloning allows producing a specific protein by expressing specific genes at high levels in *E. coli.* For example, genes coding for fluorescent proteins like the green fluorescent protein (GFP) can be used as a reporter gene under the control of inducible promoter, resulting in a bio-fluorescent effect. (Figure 1). The embedded, living *E. coli* bacteria, which have very specific nutrient needs, rapid reproduction rate, and very short life cycle, making them an ideal source of pollution assessment as part of a wearable biosensor. Using augmented reality, the environmental toxins are visualized as quantitative data through a mobile phone app interface. Through the use of these architectural devices, users can understand the invisible, ephemeral aspects of the specified pollutants that are present in their surrounding environment. The project evokes a response to designing the relationship between bodies, and the spatial atmospheric conditions that surround them. The research expands upon concepts related to autopoiesis, by exploring the potentials of feedback within architecture, and a shift from static structures, to dynamic, living systems.

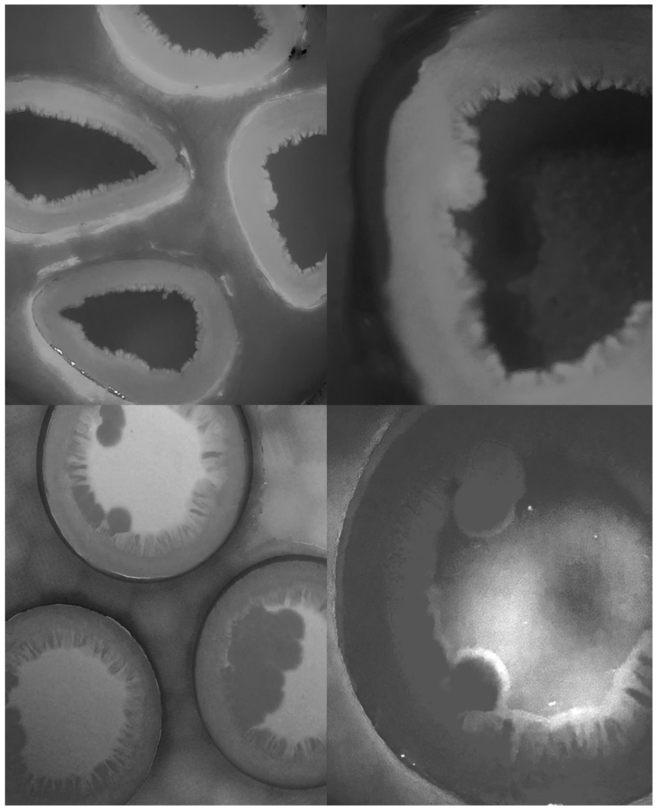

Figure 1: *E. coli* bacteria growth experiments. ©Augmented Architectures.

EXPERIMENTS WITH LIVING ORGANISMS

Physarum polycephalum is a unicellular, multinucleate organism that relies on reactive navigation to explore its environment. The vegetative state of *P. polycephalum* (known as a plasmodium) is composed of many smaller oscillating units. Each unit oscillates at a frequency dependent upon both the local environment and its interactions with neighboring

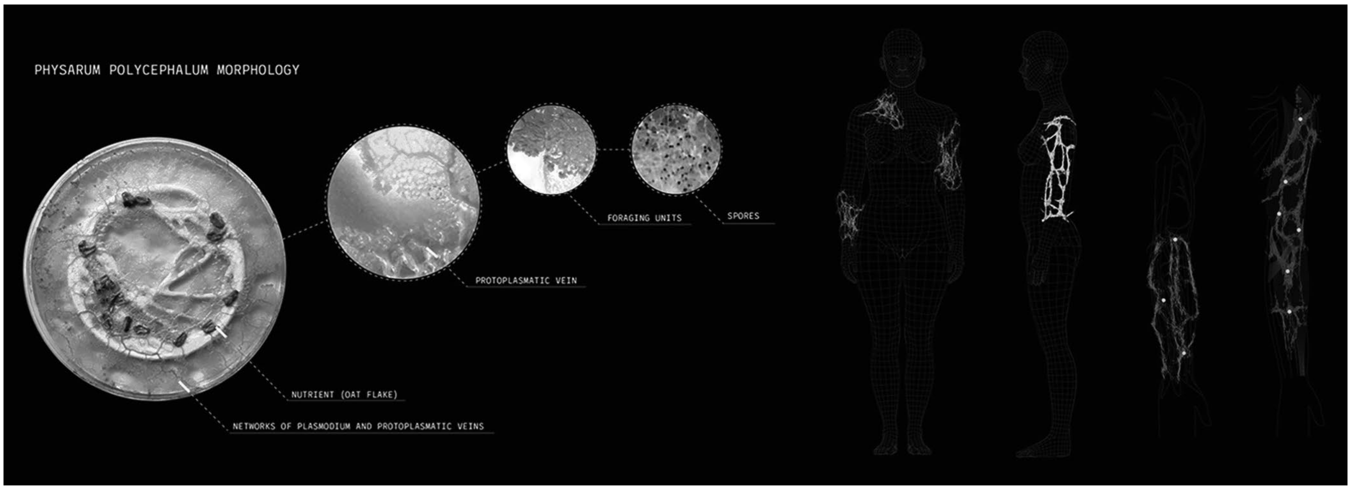

Figure 2: ***Physarum polycephalum*** growth experiments. ©Augmented Architectures.

oscillators. When the slime mold senses attractants, such as food, via specific binding to receptor molecules presented on the outer membrane surface, the oscillation frequency in the area closest to the food increases, causing cytoplasm (this is the jellylike material that makes up much of a cell inside the cell membrane) to flow toward the attractant. Additionally, binding of attractant molecules to sections of the surface membrane reduces the tension at that section, leading to a difference in internal hydrostatic pressure, such that cytoplasm flows toward the source of attractants. The collective behavior of the oscillators, each passing on information to entrain its neighbors, drives the organism's locomotion.

A group of Japanese researchers has shown that *P. polycephalum* can find the shortest route connecting two food sources when placed in a maze with two oatmeal flakes. [1]. It is also effective at dealing with more sources. In a 2010 paper, *P. polycephalum* created a network similar to the existing Tokyo train system when oatmeal flakes were dispersed to represent towns on a map of the Tokyo metropolitan area. [2].

In this project we explored the aesthetic and navigational ability of the slime mold growth behavior in different configurations of 2D and 3D printed scaffolds coated in agar and strategically placing oat flakes as nuttrieny to understand patterns of growth. The goal was to observe the single-celled organisms problem-solving behavior and the result of the membranes fusing to form a super-organism. [3]. These experiments were observed and documented, and served as an important step in understanding how these efficient networks could be formed in our design. (Figure 2). The *P. polycephalum* plasmodia were maintained in the semi dark boxes at 22 °C on large 1% agar plates embedded with 10% (wt/vol) rolled sterilized oat flakes. Original cultures were obtained from Carolina Biological Supply Company, and laboratory stocks were sub cultured onto new agar-oat plates every 3 to 4 days.

Bacterial biosensors help to easily detect the presence or absence of environmental toxins (like sulfur dioxide, sulfur, and metal ions). Cells like microalgae or *E. coli* bacteria can act as so-called bioreceptors due to their high sensitivity to surrounding environment and rapid response to external stimulants. Bacterial biosensors are created by DNA cloning technology followed by bacterial transformation. DNA cloning allows producing a specific protein by expressing specific genes at high levels in *E. coli*. For example, genes coding for fluorescent proteins like the green fluorescent protein (GFP) can be used as a reporter gene under the control of inducible promoter. To express genes that produce reporter proteins, a full-length double-stranded cDNA (or copy DNA) is isolated. Next, the double-stranded cDNA is inserted into an expression vector, which is adapted to function in *E. coli*. To express the protein in *E. coli*, the cDNA must be transcribed from an *E. coli* promoter. A promoter is a region of DNA that initiates – or signals- the expression of the reporter gene. The promoter T7, derived from a bacteriophage, is typically used. In our project, we imagine that the binding of the environmental toxins (small molecules like sulfur dioxide, sulfur and metal ions), to the promoter regions will act as the signal to produce GFP, emitting a green light visible under UV-light.

The project theorizes on the development and us of genetically modified bacteria that yields different fluorescent colors according to the environmental toxin they are reacting to. Through the the use of bioengineered bacteria, the organisms can be designed to emit green fluorescence in the presence of high UV-light levels, magenta fluorescence in the presence of heavy metals and cyan fluorescence in the presence of sulfur dioxide. (Figure 4). Each color of bacteria was tested in petri dishes filled with different 3D printed patterns with agar. With UV-light we tested the levels of fluorescence in the different colours.

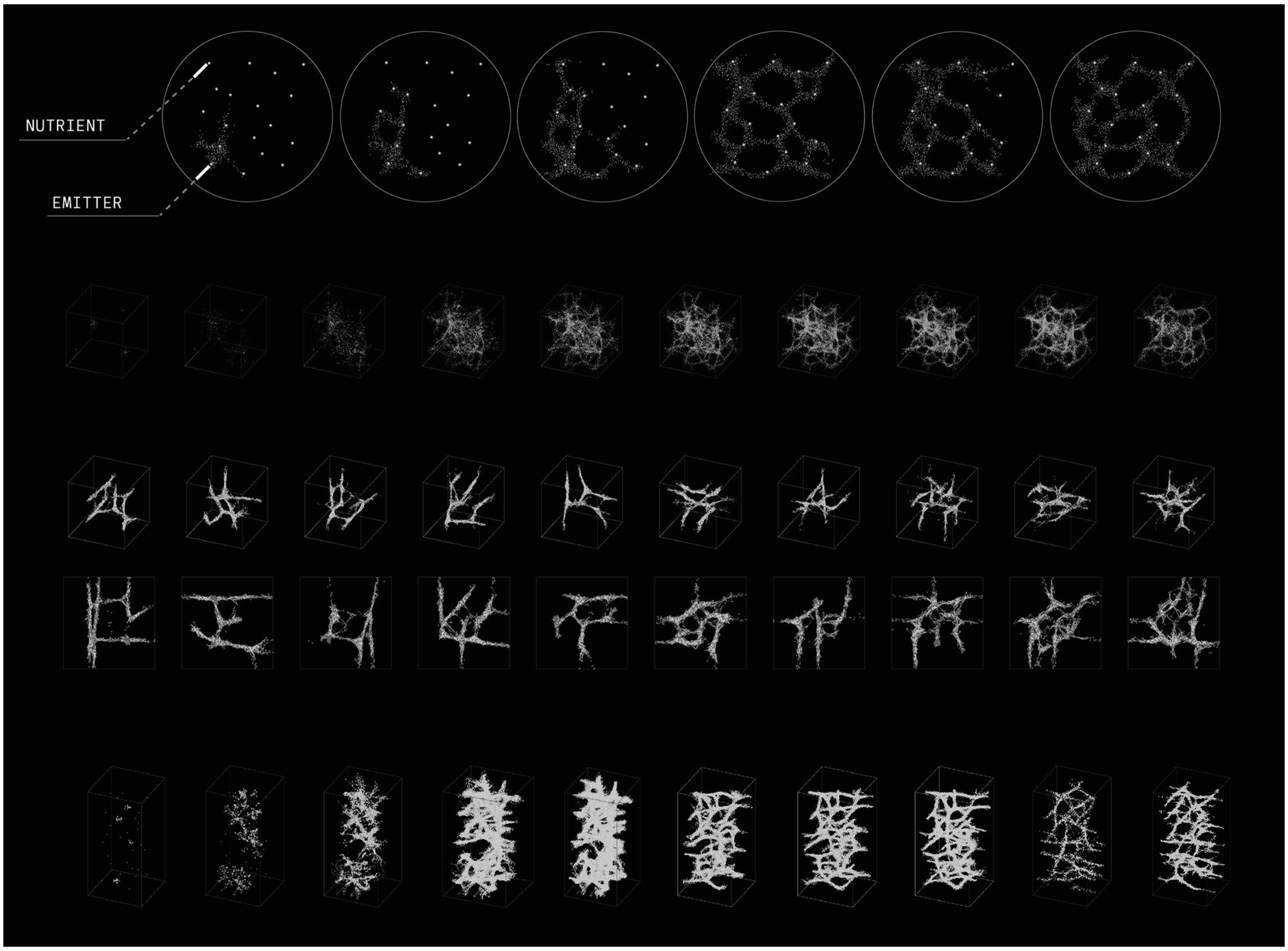

Figure 3: Computational agent-based simulations. ©Augmented Architectures.

EXPLORING GROWTH PATTERNS THROUGH COMPUTATIONAL AGENT-BASED SIMULATIONS

This project looks to biological formations to provide insight into the rules that define complex systems. The complexity of patterns generated in nature have a tendency to self-organize and arrange themselves systematically. This complexity is created out of clear principles. [4]. Building upon knowledge from the growth experiments, a series of computational models were generated to simulate the behavior of the slime mold growth patterns and self-organizing qualities based on a clear set of rules. Similar to the growth of a biological organism, which develops over time, the computational simulations were used to study and develop emergent patterns that evolve over time. These simulations are based on the stigmergic mutli-agent algorithm (Jones), which yields emergent and self organizing behavior through agents and actions. [5]. Organizations of stigmergy can be found in the collective behavior of bacteria, *P. Polycephalum*, and insects, such as ants and termites. The project utilizes an open source visual programming tool called Physarealm, which was developed for simulating *P. Polycephalum* growth patterns within the Rhino 3D visual programming editor, Grasshopper. [6]. The Physarealm tools provide various components that allow for the simulation of the growth of slime mold in three dimensions. The resulting patterns are based on rules, parameters, and constraints, which can be modified or adjusted to generate different results, including 'emitters' and 'nutrients' which serve as the source and attractors for growth. (Figure 3). This allowed for a series of versions exploring various growth patterns, allowing for both a certain amount of control over the system, as well as an unruly, unpredictable, emergent organization. The paths of the agents were also traced using 'trails' to generate curves. This allowed for a better understanding of the virtual movements in relation to time, as well as providing geometry to generate three dimensional meshes, allowing for the forms and spaces of the simulation to be studied.

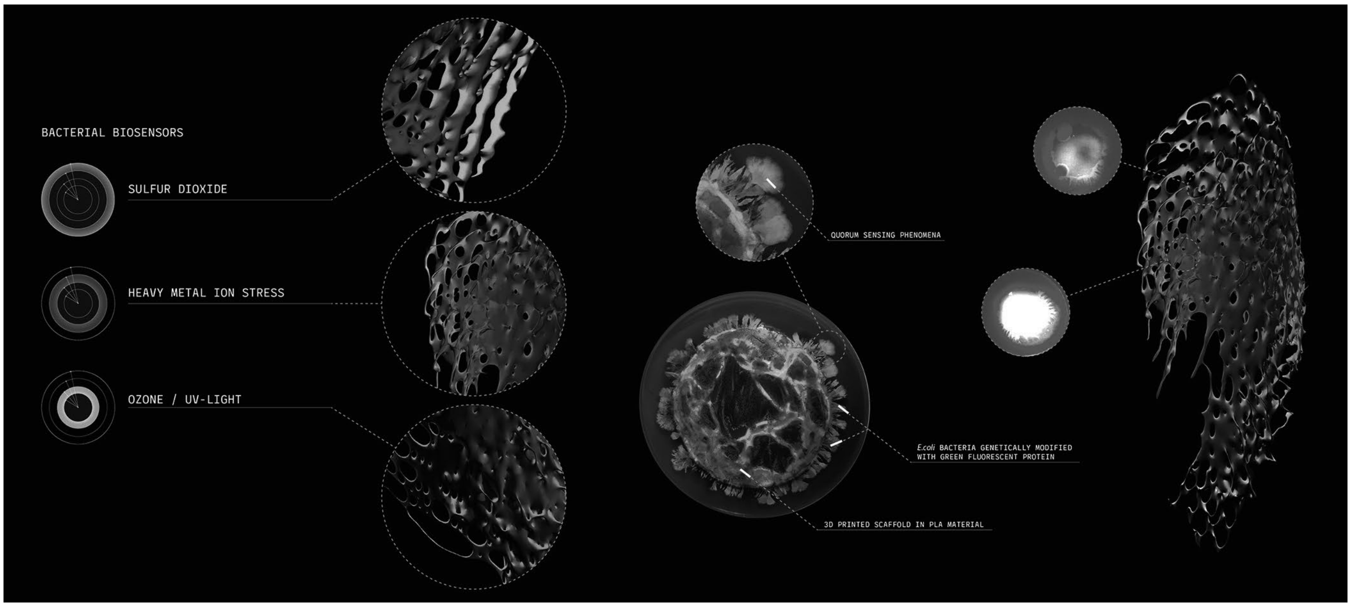

Figure 4: Diagram of the bacteria biosensors emitting various bioflourescent colors based on environmental toxins. ©Augmented Architectures.

DESIGN APPLICATION AND DIGITAL FABRICATION

The agent-based simulations served as a bio inspired process to generate the forms and structures of devices that can be worn on the body, and serve as architectures that provide a liminal space between the body and the environment. The optimization of geometry provided by the simulations yields a structural scaffold that incorporates material efficiencies through porous surfaces that can contain the bio-sensors, bio florescent bacteria. The development of the porous surfaces from the curve geometries generated by the agent based simulations was achieved through the use of computational techniques that incorporate Metaballs and marching cubes (MC) algorithms. These algorithms are utilized through tools available with the visual programming add-on for Grasshopper, Cocoon. The curves produced through the agent-based simulations are 'charged' with Metaballs, which are then wrapped with the MC algorithm to create a mesh surface. The standard MC constructs the faceted isosurface by processing data sets in a sequential, cube-by-cube manner. [7]. This provides continuous closed mesh surfaces which are then fabricated using rapid prototyping technologies, resulting in the materializing the computational agent-based simulations, into physical artifacts. The 3D printed devices are designed to fit on various parts of the human body, by strategically locating the emitter and attractor points of the agent-based simulations, in relation to the muscular and circulatory systems of the body. The bespoke devices are intended to serve as wearable body architectures that augment the body, by providing the user with data pertaining to environmental toxins. There are a total of three devices strategically located on three different parts of the human body, the wrist, the arm, and the shoulder. (See Figure 5). The geometry of the 3D printed wearable devices contain various sinuous geometries, apertures, and pockets that allow for the placement of the *E. coli* bacteria biosensors. As environmental toxins within the atmosphere increase, the *E. coli* bacteria glows to indicate the levels of sulfur dioxide, UV-light levels, and heavy metals. This serves as a responsive, architectural interface that provides information about invisible, ephemeral phenomena, enhancing the user's sensing capabilities.

CONCLUSION

This design research project investigates the opportunities for the design of architectural devices that incorporate bio-sensing and computational processes to visualize environmental phenomena. Some of the current limitations include the reliance of UV-light in order for the *E. coli* bacteria to fluoresce. Next steps in the research include genetically modifying the bacteria to bio-illuminate, which will eliminate the need for external light sources to visualize the changes in the bacteria, and visualize the data. Additionally, genetically modifying the *E. coli* bacteria to produce particular odors, introduces an olfactory approach to modifying spaces as a means of indicating changes to environmental conditions, and alerting the users of environmental toxicity levels. Bacterial odor generators, which can produce odors such as wintergreen and banana, are examples of synthetic biology and the possibilities for their applications. [7]. The project aims to create architectures that respond to environmental phenomena, but also serve as informative, intelligent systems that provide users with data. This allows for architectures that augment bodies through enhanced senses, and an awareness of the ephemeral and invisible, spatial and atmospheric conditions of their surroundings.

Figure 5: Protoype of the wearable biosensor body architectures. ©Augmented Architectures.

ENDNOTES

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