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DESIGNED SUBSTRATES FOR LIVING ARCHITECTURE PERFORMANCE - IMPRIMER LA LUMIÈRE

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Abstract
'Imprimer la Lumière' examines the making of sympoetic environments that interfaces living bioluminescent bacteria colonies with spaces for human inhabitation. By employing design methodologies from architecture and textiles design, the paper asks how the experimental probing of how to design, fabricate, inoculate and feed an architecture challenges and changes the way we understand and build our physical environment. It questions how these new practices place time, growth and decay as central design drivers for a living architecture in biodesign context and asks how these can inform the emergent circular design field.

The paper presents a central conceptualisation of the "substrate" as a sympoetic interface. It examines two design strategies for these substrates. The first examines robotic 3D extrusion of hydrogel as a medium for bacterial growth. Here, we examine how the topology of the print affects and changes the growth, performance and decay of bacterial colonies. The second uses textile hanging as substrate. Here, we examine how the material composition and its functional grading through strategic embroidery can steer the light performance of the colonies. Both studies query the underlying tools and techniques for the design of bacteria propagation on substrates. The project is an interdisciplinary collaboration between architecture and textile design with special emphasis on biodesign.

1.0 INTRODUCTION

By placing living organisms at the centre of the fabrication process, biodesign [1,2] asks how the organism - whether synthetic or existing biological system and no matter its size - can connect and steer material performance. This creates a radically new departure from which materials are traditionally conceived, fabricated and appropriated in architecture and design as an inert reality [3]. It asks new questions not only of its design and crafting processes but also of its ethical and ecological roles [1,4].

'Imprimer la Lumière' uses the bioluminescent bacteria *Vibrio Fischerii* [5] as a model organism by which to probe emergent design principles for a living architecture. In 'Imprimer la Lumière', the bioluminescent bacteria is functionalised as an architectural light source. We ask how the performance of other species can be perceived as a living technology for the built environment and what happens as we start to consider the environmental needs and conditions of care that co-inhabiting a shared environment entails. The project addresses the current knowledge gap by modelling the performance of bioluminescent bacteria; capturing, characterising and predicting how their life-states, performances and propagation respond to the design-led tuning of their host-media, its form and its nutrition. Living materials are manifestly different to produce, manipulate and administer than inert materials. They are heterogeneous in that they are embedded in media, like hydrogel, that act as nourishing and oxygenating hosts. As the organism propagates, the media is depleted, changing material living conditions dynamically in time necessitating either practices of nourishing or replacing material runningly. Living materials are furthermore temporally plastic expressing changing behaviours as they react to environmental changes such as circadian rhythms, temperature, humidity and the presence of other species. Finally, they embody "different kinds of lifespans'' as practices of cryobiology (freezing and thawing of living things) and cell synchrony (artificial manipulation of cycles of cell division) allow us to change the way organisms are grown, exchanged and stored [6]. Designing with living organisms therefore necessitates the modelling of their performances as they react to environmental stimuli, their life cycles, propagation and decay as well as the temporal transformation of their media as nutrition becomes exhausted. To understand, curate and manage living materials we need to devise ways of predicting their performance as well as their propagation and lifespan as part of a creative architectural design process.

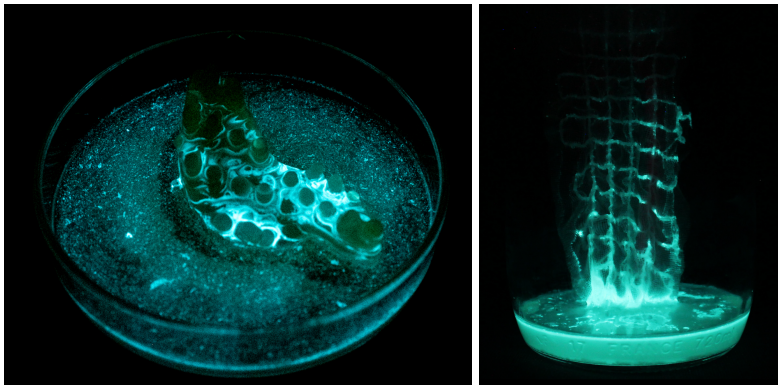

Figure 1. Probes into bioluminescent 3D robotic extruded and textile substrates for a living architecture

The paper presents the conceptualisation of the "substrate" as a sympoetic interface that can bring together the different environmental needs for both human and other organism. The *substrate* is here understood as a shared surface on which the bioluminescent bacterial colonies live while simultaneously providing a functionalised performance within a human environment. In our project this substrate is strategised through two differing material practices. The first set of experiments examine how robotic 3D extrusion of hydrogel can steer the forming of a three-dimensional topology for the Vibrio Fischeri colonies. Here, our work probes the overall topology of the medium, its capacity for retaining fluid states in the form of shallow basins or interior pools as well as exposure to oxygen as the two main nutrients for the bacterial colonies. Here, architectural methods for computational design and robotic fabrication are used as a platform for rethinking new design practices for living materials. The second set of experiments examines textile surfaces as a substrate. The textile is dipped in the medium and draped in order to functionalise it as a luminescent surface. Here, our experiments have examined different fibre types for supporting the living conditions for the bacterial colonies and how functional grading through embroidery with specific fibres can steer the growth of the colonies and their light performance.

2.0 DESIGNING WITH BIOLUMINESCENCE

Bioluminescence is a chemical form of light predominantly emitted by marine organisms but also some mushrooms and insects [7]. To date, bioluminescent bacteria have been described as belonging to three families of the gamma-proteobacteria but bacterial luminescence is most often seen in members of the *Vibrionaceae* family that are typically found as symbionts of deep-sea animals

and mostly refers to light in the blue-green spectrum [8]. For the 3D extrusion experiments, we work with *Vibrio Fischerii* as it is a model organism of the photobacterium genus, commonly used as a marker in biology and medicine. As such, it is well-documented and accessible. For practical reasons and because it seems to generate a higher luminescence, our textile substrates are inhabited by the *Photobacterium kishitanii*, a less studied bacteria of the same genus. Within the architecture and design communities, bioluminescence has essentially been probed as an alternative to public and domestic lighting and is largely induced by micro-algae [9–12]. Rare physical experimentations with bacterial bioluminescence in this area essentially lie in its harnessing on garments and textiles [13,14] into bioreactors for urban furniture perspectives [10].

Vibrio Fischerii are characterised by short life-spans (app 3-5 days). As any living organism, it is characterised by growth rates, the speed at which the number of organisms in a population increases as influenced by the quality of their living conditions. These impact performance directly as colonies need to reach a certain size before they start emitting light. The behaviour is therefore not linear or mechanistic but dependent on both internal and external environmentally measures that are steered by the design of the substrate. In preliminary studies we have examined the methodological principles and found that *Vibrio Fischerii* colonies live on the surface of the host-media and that enlarging the surface-to-volume ratio has a direct impact on the intensity of light emission as well as their lifespan [15]. Here, the changes of the host-media, from nutrition-or-oxygen rich to depleted, are understood as a dynamic property that corresponds to the organisms' propagation through the material. To steer these transformations and connect them to architectural functionalization (a living light source), we interface them with a simple state-based simulation to predict the light performance. This allowed us to understand the importance of topology and the amount of surface enabling contact to oxygen as well as the overarching composition of the hydrogel composite and its salinity as well as its extrusion within a 3D printing process.

3.0 SUBSTRATES FOR A LIVING ARCHITECTURE

In microbiology, substrates are generally standardised support matrices placed at the bottom of a petri dish to immobilise and feed micro-organisms for a specific purpose. Similarly, in most biodesign practices, the maintenance or act of caring for microorganisms -to which the substrate is key- relates to the completion of a specific task chosen by the designer in respect to the design intent, which ultimately results in the death of the living organism once the task is completed [4]. In both of these contexts, the design and use of *the substrate* remains centrally linked to an anthropocentric solution-driven approach that leaves little to no place for the growth and proliferation of the living organism and its colony. This tends to be increased when the growth and performance of the living organism exist outside the temporal or extensive scales of human perception making it primarily understood as a material quality [4], as an object or result rather than a being to interact and share experiences with [16].

In 'Imprimer la lumière', we seek to understand, design and use the substrate as a shared interface in which human beings and bacteria have an equal role. In other words, we understand the substrate as the projection of an inter-species and interdependent space of co-inhabitation. Indeed, if the micro-architecture scale of our experiments does not yet shape space for humans, they work as a site of interaction, an interface through which learning on the long run how to "live and die well together in a thick present" to borrow the words of Donna Haraway [17]. Implicit in this perspective is the positioning of architecture as something that evolves through time and whose materiality integrates the different scales of experiences (in time and space) of the living beings that interact with it. The conceptualisation of the substrate in this project therefore embodies a design space of encounter between the short-term and micro scale of bacterial life cycles and the relatively longer-term temporality and intermediate scale of human beings. In terms of material choices, the substrate reflects this attempt to enable encounters across time and scale as much as the underlying practices of the interdisciplinary collaboration. In 'Imprimer la Lumiere' we examine two forms of substrate informed by architectural and textile design based practices. Both substrates embody a form of architectural vulnerability requiring a renewed sense of interaction, perception and care when they become bacterially alive.

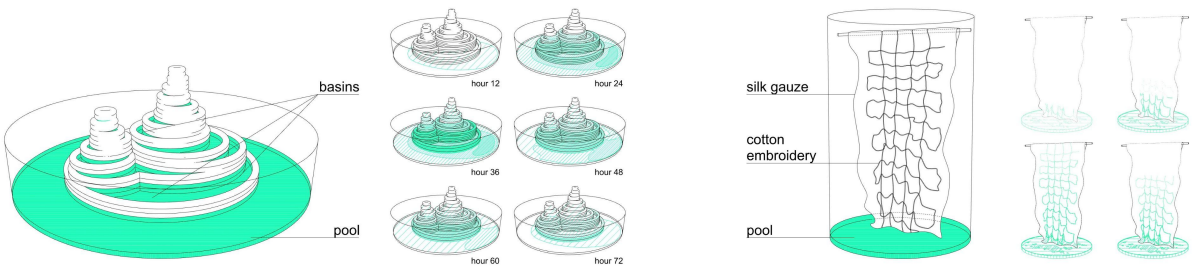

Figure 2. How to represent, instrumentalise and fabricate a living architecture

4.0 3D PRINTING HYDROGEL

This design strategy examines 3D printed hydrogel as substrate for a self-illuminating micro architecture (Fig. 3). 3D printing is explored as a means of expanding the forming processes of the medium to investigate how topology and surface treatment can drive the life cycles and therefore the light performance of the bacteria. Taking point of departure in architectural design practices, we have developed a design-integrated methodology understanding of the living conditions for bacteria and how these can be designed, 3D printed and evaluated.

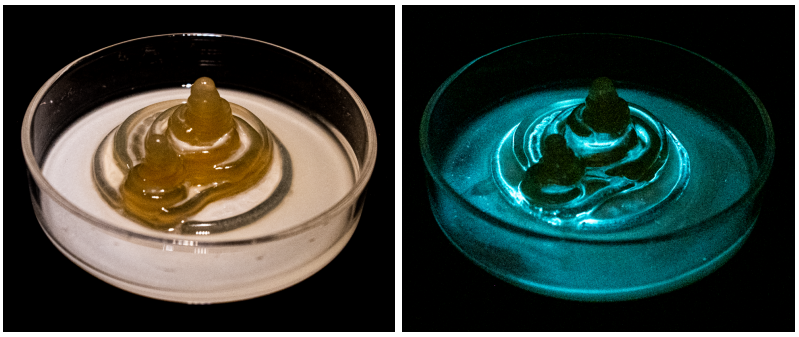

Figure 3. 3D printed hydrogel topology with nutritious broth after inoculation with bacteria and later with bioluminescence

4.1 UNDERSTANDING LIVING CONDITIONS

The first task in our experiment has been to understand the optimal living conditions for the vibrio fischeri bacteria and designing a 3d printable medium for it to live in. The design of this material is based on the standard growth medium for bacteria: agar agar, which bacteria cannot metabolize. We use it as a base for our gel to hold the nutrition, water and oxygen needed by the bacteria to live. As our bacteria are originally marine, salt is an essential additional ingredient. Vibrios require 1 to 3% NaCl for growth[18]. As *Vibrio Fischerii* grows well at temperatures between 24°C to 28°C [5] and for consistency of experiments, we are keeping them in temperature controlled incubators at 25°C. The last prerequisite for the bacterials' luminescence through luciferase is oxygen [19] provided by diffusion in the gel and surface contact of bacteria with surrounding air.

Despite *Vibrio Fischerii* being a well documented model organism it is still highly sensitive to its environment. In our tests, we found that the pH level has an important role to play. To assess the acidity levels of the medium, we measured living and dead cultures with pH strips. The dead cultures all had a pH of four while the alive ones had pH levels ranging between 5 and 7. As Vibrio species are fermentative, producing acid in carbohydrate-containing media without formation of gas [18] , we concluded that the bacteria produce acid in turn polluting their environment; it is not neutralised. By adding ground chalk to our medium, the bacteria lifespan of sample cultures in nutrient broth increased drastically from 6 days to 15 days. As the bacteria produce acid, the chalk is dissolved to neutralise it. Using chalk in liquid broth cultures is simple, the chalk will stay at the bottom of the bottle ready to be dissolved. Using chalk in the gel medium is harder as the chalk sinks to the bottom of the melted gel and is therefore not evenly distributed in the prints.

4.2 DEVELOPING HYDROGEL BASED 3D PRINTING PROCESS

While dedicated bioprinters exist, these do not address architectural scale and lack an integration with architectural design environments [15]. Therefore we use as a scalable alternative: a 6 axis collaborative robot (UR5e), where our medium is extruded through a high precision micro-dispensing unit (ViscoTec ecoPen700) with self-sealing rotor-stator arrangement and a proprietary cartridge system, which allows to store and feed the 3d printing medium [20]. The benefit of this dispenser is the precise control of flow and the ability to start and stop the printer at any time. The dispenser can be sterilised and fits therefore to the required sterile lab workflows required for all parts in contact with bacteria, as this is the only way to protect bacteria from contamination (Fig. 4).
As part of the scaling up processes, further developments have been necessary to control the viscosity of our 3D printing medium during the printing process and final state. Self-regulating heating mechanisms for all parts of the printing apparatus keeps the medium above the gelation point at all times. We found furthermore, that the addition of gelatine to our medium lowers the gelation temperature of the mixture to 40°C. This reduced temperature conserves energy, enables faster gelation and smooths the surface for a more homogeneous appearance. While gelatine is theoretically not beneficial for the bacteria, our experiments showed that the growth was not notably affected by it. Finally glycerin is used in our hydrogel as a plasticizer that increases the flexibility of the intermolecular connections between the agar polymer chains [21]. When the medium for printing is perfectly tempered, we are able to make prints with significant overhang and height.

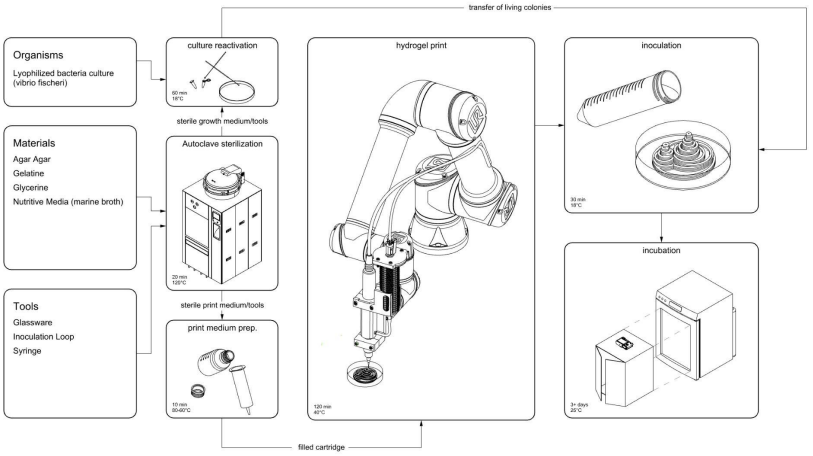

Figure 4. Fabrication process in 'Imprimer la Lumière'

4. 3 FOLLOWING LIFE: ANALYSIS AND REGISTRATION OF BIOLUMINESCENT BACTERIA

In order to evaluate our success in design and maintain living conditions for bacteria we had to develop a new set of instruments. Our initial attempts to detect the presence of living bacteria with optical oxygen sensing based on the dynamic quenching of an oxygen sensitive indicator dye by oxygen [15] provided only a very localised result at a specific point in time. We found that imaging is a better way to register the bacteria growth and propagation patterns across the printed object over time.

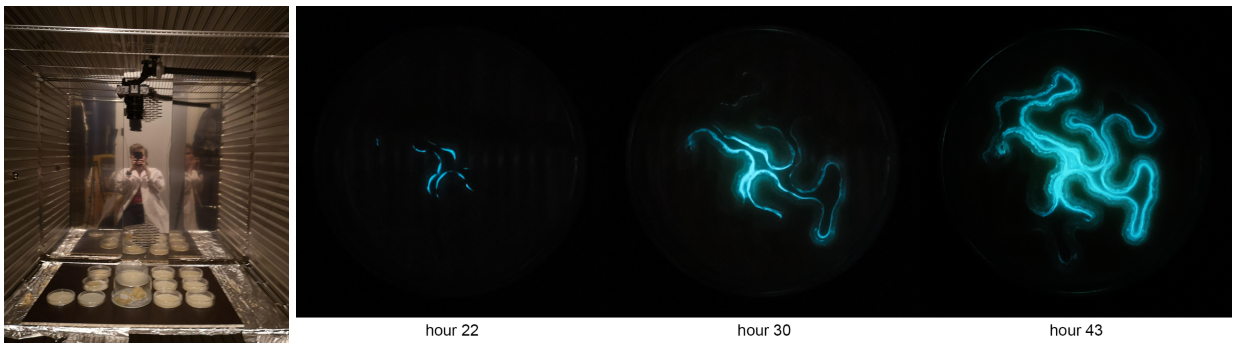

Figure 5. Bacteria culture in the incubator and bioluminescence capture in a blacked out photobox to avoid ambient reflections.

To capture the definition of bioluminescence even at low glow, we use a camera with sensitive settings (iso-3200, f/4.5, ss 10 to 30 sec). These hypersensitive image settings require a fully blacked out space. For this, we use a cardboard box lined with black fabric and a hole in the top of the box for the camera lens. This photographic-setup carries the camera and can be placed inside the incubator for continuous observation, with an image taken every 30 min (Fig. 5) . Images were taken, as long as the bacteria glowed, which has been in a range of two to seven days. For our experiments, animations made from the timelapse images provide sufficient means by which to visualise the growth, movement and peaks of propagation of the bacterial colonies and evaluate the success of the designed substrates.

4.4 DESIGN EXPERIMENTS

In 'Imprimer la Lumière', the printing medium has a hybrid role as substrate for the bacteria to live on and source of nutrition through dispersion for them. Initial experiments [15] showed that bacteria would not propagate within the interior of the printing medium, as neither the rate of oxygen diffusion nor the humidity level is high enough [15]. Furthermore, our experiments have shown that the bacteria are dependent on the humidity levels of the surface to live and propagate easily across the surface. Tests with liquid broth have shown that the bacteria can float within the fluid allowing the light to move. Attempts to simply spray nutritional broth on the substrate works on horizontal surfaces, but it dries out quite quickly.

This leads to the formulation of design criteria in which we have a high surface-volume ratio to aid access to oxygen, while at the same time developing strategies for maintaining high humidity levels through basins and pools of fluid medium poured onto the substrate after the printing process. These humidity reservoirs can be staggered vertically, creating terraced topologies that shape

the propagation of the bacterial colonies (Fig 6). Printing elevated basins required us to move from the printing of shells to printing solid volumes. This added further complexity to the 3D printing process, as the disposed material needs to conform to the exact dimension of the designed shapes. By tuning central print parameters including the extrusion rate, layer height, temperature as well as building our own software solution for slicing solids using Rhino, GH and Python, we were able to develop the volumetric hydrogel print methodologies.

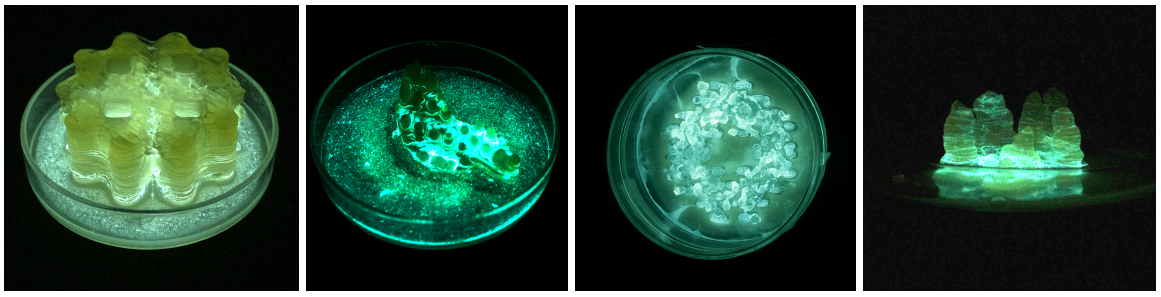

Figure 6. Bioluminescent hydrogel topologies developed by MA students in textile design, Ecole des Arts Déco, Spring 2021

4.5 RESULTS AND OBSERVATIONS

We observe that the bacteria in the pools and basins spreads easily, but the resulting glow is dim and diffuse. However, on the edges of the wet zones the glow is intensified. This zone seems to offer a good balance of humidity and oxygen. A similar intensification of bioluminescence is observed, when the pools are about to dry out and along edges on sprayed surfaces. This thin film of water provides the optimal habitat for the bacteria in design. This observation seems consistent with the habitats of bacteria in nature [22] where *Vibrio Fischerii* cells form a biofilm on the surface of the symbiotic light organ from which they later disperse [8].

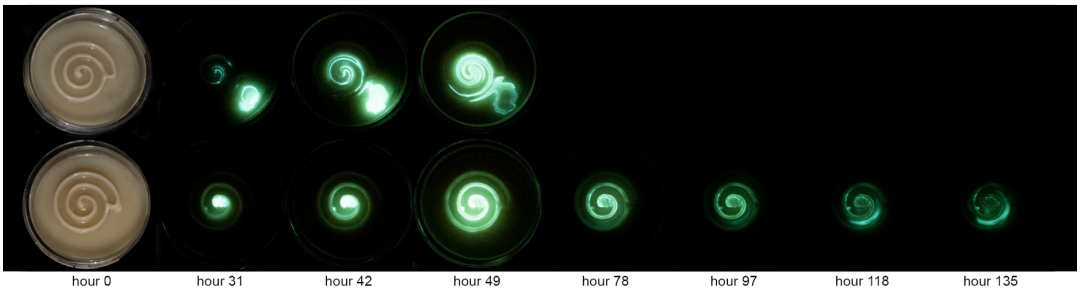

Figure 7. Bacterial growth over time: locally inoculated on a surface sprayed with nutrient broth (top) vs in a pool of it (bottom).

5.0 TEXTILE SUBSTRATES

Due to their moisture retention capacity and generous surface area, fibrous materials such as textiles provide an appropriate substrate for micro-organic life, so good that the textile industry has developed a rich tradition of antibacterial, antifungal and antimicrobial finishing treatments [23]. In this second task, we extend emergent research in the area of bioluminescent textiles [13,14] to an architectural context by questioning how textile substrates can expand the vocabulary of self-illuminating micro-architecture.

5.1 UNDERSTANDING LIVING CONDITIONS ON TEXTILES.

Here, we have developed similar conditions of growth as in the hydrogel probes, but adjusted it to the specificity of the selected textile substrates. We have however used a different species of bioluminescent bacteria isolated from deep sea fish: Photobacterium kishitanii, known to be brighter than Vibrio fischeri but whose living conditions are similar, therefore we have worked with the same nutrients and incubating temperature, apart from adding chalk as in this case it did not increase the lighting performance. While Vibrio Fischeri has the ability to use fermentation for metabolism without oxygen which creates acidity, Photobacterium kishtanii is aerobic and avoids the problem of death by low pH. It is considered non-motile by ATCC[1]. This means that all movement is caused by external impact such as water circulation, which our microscopic observations support

[1] (https://www.atcc.org/products/baa-1194).

Interested in steering bioluminescent movements, we therefore needed a medium which can mobilise the non-motile bacteria. For this reason, we have used a nutritional broth rather than a solid agar-based medium. As this broth is liquid, micro-movements can happen and be steered by the textile's inherent capillary effects, allowing the design of movements against gravity. In our design we utilise, that fluid rises in thin tubes or porous materials due to surface tension and adhesion forces to solid walls. For this reason, textile substrates were hung in glass containers, their extremity immersed in the nutritional broth as to prevent overflowing while still keeping the fibres hydrated by capillary effect and in order to absorb and retain the nutrients.

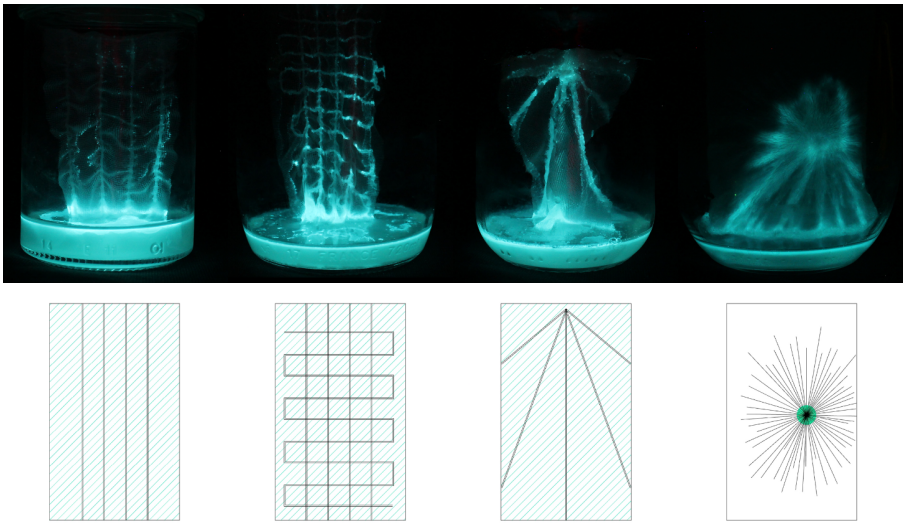

Figure 8. Probes into bioluminescent embroidered patterns and inoculation - across the whole surface or from central the node.

5.2 ESTABLISHING MAKING: FIBRES' NATURE AND TEXTILE STRUCTURES

First, we examined different fibre types for supporting the living conditions for the bacteria. Even though artificial and synthetic fibres are compatible with bacterial culture, we have favoured a selection of commercially available textiles based on organic fibres of animal and vegetal origins, including cotton, linen, silk and wool due to their good moisture absorption capacity. We predominantly used non-coloured mono-fiber textiles used for clothing. Based on woven, non-woven and knitted structures, we initially imbued a representative selection of pre-washed and sterilised textile samples with a nutritive solution. Hanging the samples with their extremity immersed in the nutritional broth proved to be an effective setup to ensure that the different textiles are equally hydrated and saturated for comparison.

Interested in the spatiality of textiles, we then studied how functional grading through embroidery with specific fibres can steer the growth of the colonies and their light performance. Thin silk gauze and synthetic tulle were used as a background, as such substrates have little to no capacity of water retention. In contrast, patterns were manually or machine-stitched respectively with highly absorbent cotton and dense polyester embroideries. We first developed basic patterns such as lines and grids to study the ability of the embroidery to absorb water and therefore of getting bioluminescent placed patterns. As expected, embroideries absorbed the nutritional broth for the bioluminescence to bloom, while the background showed minimal glow. We subsequently developed more complex patterns such as star shapes and networks to see how the bacteria grow from the inoculated midpoint.

5.3 FOLLOWING LIFE & DESIGN PERSPECTIVES

We have kept track of the bioluminescent textile experiments with the same image-based registering system described in section 4.3. The textile experiments were brightest the day following inoculation and the glow was almost nonexistent the day after. The direction of growth is dominated by gravity. This could be because we inoculate with drops which run downwards. However, we have also noticed moderate movement upwards, possibly due to water micro-circulation. In terms of maintenance, we noticed that the glow could be revitalised by dropping high concentrated nutritional broth, and we assume results could be improved if we inoculate more precisely with micro volumes.

Our observations show that the textile's bioluminescent performance is highly dependent on its absorption rate. The contexture and thickness of the samples are more important than the fibre source. An exception is silk which performs lower than the rest even with thick qualities. The most successful results were observed with qualities such as cotton piqué, swandown cotton and wool's plain weave, which suggest the relevance of fluffy textile substrates, presumably providing a better oxygenation for the bacterial colonies than denser contextures and a richer water content than lightweight textiles such as gossamers or net fabrics.

This is consistent with the embroidered samples observations, where bioluminescence was more successful with looser yarns (with little twisting) and stitches with a relatively foamy texture.

Design criteria need to be further tuned for achieving a textile network of hydrated fibres spreading nutrition by diffusion to extend the bacterial colonies' lifespan and therefore the bioluminescence's observation period. However, these textile probes demonstrate that embroidery offers a complementary strategy to hydrogel 3D printing for bioluminescence's steering, allowing the design of particularly precise placed patterns occurring in the vertical plan.

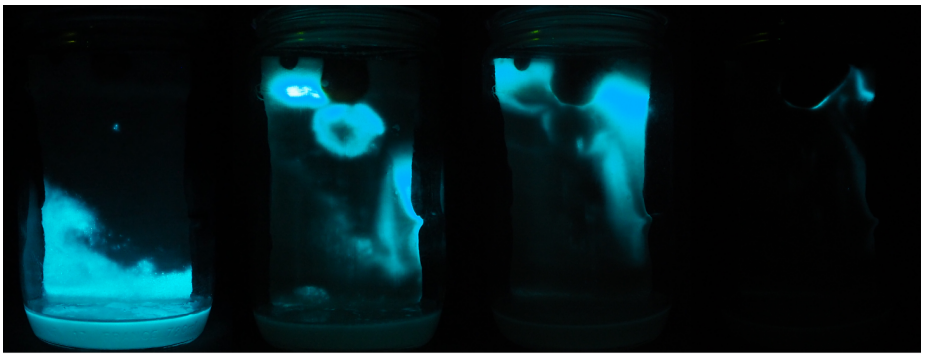

Figure 9. Bioluminescent capillarity observed on different textured cotton yarn. One and two days after inoculation

6.0 CONCLUSION

Imprimer la lumière is a design-led research project based on a biodigital approach sitting at the intersection of architecture and textile design practices. It examines the making of sympoetic environments that interfaces living bioluminescent bacteria colonies with spaces for human inhabitation. The paper explores two strategies for the design of bacterially-informed substrates for micro-architectures, allowing to steer a bioluminescent performance through time and space. Based on the robotic extrusion of an agar-based hydrogel, the first material strand demonstrates dynamic bioluminescent patterns and various lighting effects through the design of bespoke 3D printed topologies based on load-bearing principles. The second one probes the potential of embroidered textile hanging substrates to trigger static and localised light-emitting patterns based on capillarity and moisture absorption principles. Together, they probe tools and techniques for the steering of bioluminescent bacterial propagation across various substrates' transiences while shaping the preliminary basis of a bioluminescent architectural effects' vocabulary. All in all, this design-led research reflects on the integration of time, growth and decay as essential design drivers for the conception and materialisation of a living architecture apprehended as an inter-species and interdependent space of co-inhabitation.

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