Bacterial Hygromorphs

Experiments into the Integration of Soft Technologies into Building Skins

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1 Spore coated polyimide strips inside the dry chamber.

ABSTRACT

The last few years have seen an increase in the interest to bring living systems into the process of design. Work with living systems, nonetheless, presents several challenges. Aspects such as access to specialists' labs, samples of living systems, and knowledge to conduct experiments in controlled settings become barriers which prevent designers from developing a direct, material engagement with the material. In this paper, we propose a design methodology which combines development of experiments in laboratory settings with the use of what we call *material proxies*, which refer to materials that operate in analogue to some of the behaviors observed in the target organism. We will propose that combining material proxies with basic scientific experimentation constitutes a form of direct material engagement, which encourages richer exploration of the design domain.

We will develop this argument by reporting on our experience in designing and delivering the primer component of a themed design studio, structured around bacterial spores as hygroscopic components of building facades. The six-week design project asked students to consider the behavior of bacterial spores, and to imagine a number of systems in which they could be employed as actuators of a membrane system that responded to fluctuations in humidity. The module is interesting in that it negotiates some of the challenges often faced by designers who want to develop a material engagement with living systems, and to produce informed speculations about their potential in architectural design.

INTRODUCTION

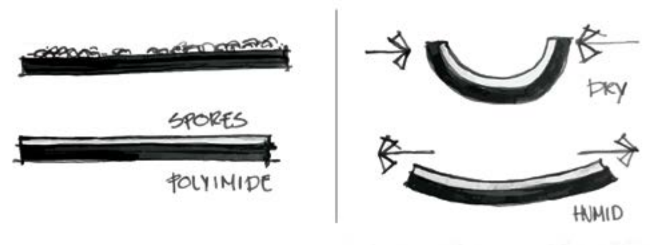
*I*n this paper we preset some initial student-led experiments into the use of a new class of hydromorphic material. Traditionally, research on hygromorphic material has focused on wood, programming hydromorphic behaviors through the patterning and combination of laminates and composites. However, recent advances in materials science has led to the development of hygromorphic materials based on bacterial spores attached to passive (hygromorphically unresponsive) layers (Chen et al. 2014; Chen et al. 2015).

These new materials work in a similar way to wood-based hygromorphs, but have distinctive characteristics. Wood laminates, for example, can be made robust and are relatively easily integrated with more traditional forms of construction and manufacture. They can, however, be slow to respond and less efficient (weight for weight) compared to bacterial-based hygromorphs. They also lack sensitivity to small changes in, for example, ambient humidity. Bacterial-spore-based hygromorphs (as they are described throughout this paper) are, in contrast, highly responsive and highly sensitive to even small changes in ambient humidity. They are, however, difficult to scale, with current demonstrators based on a weak passive layer of 8 micrometer polyimide material. They also offer the potential for enhanced programmability in terms of the patterning of the bacteria active layer, in addition to the molecular characteristics of the bacteria. The effects of the hydromorphic response may also be amplified by combining it with other materials, mechanisms, and technologies.

Whilst bacterial spores are a dormant form of the bacteria, they develop from live cells and contain the capacity for life—spores retain the genetic material to germinate into vegetative cells and multiply as environmental conditions becomes favorable. In this context, design exploration with living systems inevitably presents us with challenges. Aspects such as access to specialist labs and samples of bacteria, in addition to the specialized experimental knowledge needed to manipulate them, become barriers that prevent designers from developing a direct, material engagement with such systems. In this paper, we develop a design project that combines the work in laboratory settings with more traditional craft-based material engagements mediated by what we describe as proxies. We show that while there are challenges in engaging with living or near-living technologies, bacteria-based hygromorphs offer insight into a compelling and accessible architectural technology.

BACKGROUND

Hygroscopic materials can be used to produce low-complexity actuators which are operated by changes in moisture content in



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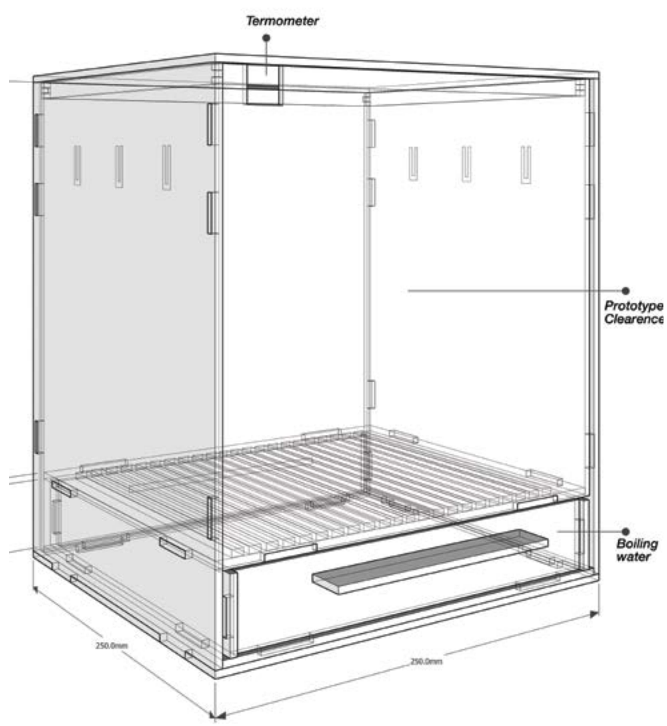

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2 2A and 2B. Diagram showing programmability of bacterial spores by means of inoculation.

3 Concertina-like behavior achieved by alternative placing of spores.

4 Axonometric diagram of humidity test chamber.

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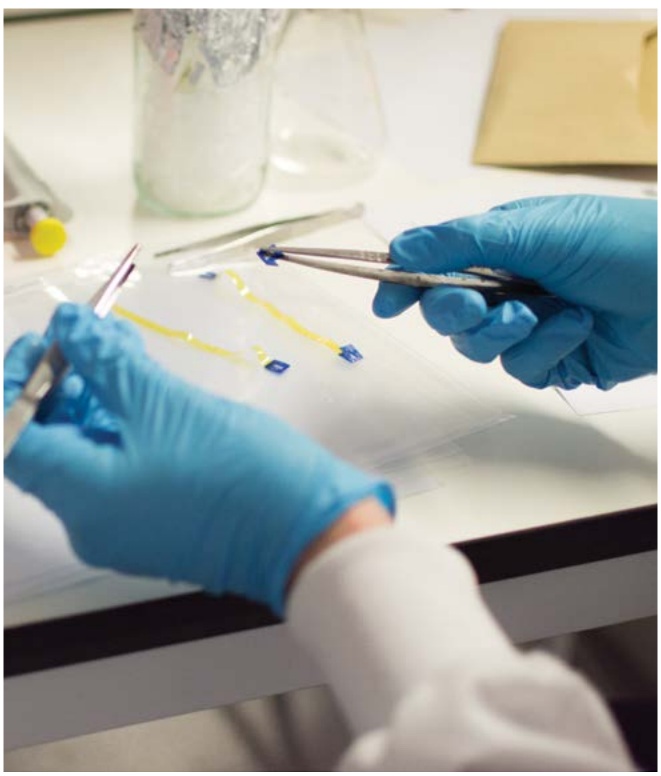

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5 Kapton strips prepared with initial coating of Poly-L-Lysine.

6 Process of preparing elastomer strips.

the air—converting, for example, the energy held within evaporating water into mechanical work. These have been of particular interest in architecture, as they are integrated in the research and development of intelligent skins and dynamic envelopes, which aim to produce sophisticated assemblies that respond dynamically to their environment (Velikov and Thun 2013; Wigginton and Harris 2002) In this context, hygroscopic materials respond to open-air environmental conditions without complex mechanical sensing and actuation that require high levels of maintenance and energy input (Hensel and Menges 2006; Hensel, Menges, and Weinstock 2006).

Hygromorphic materials are also interesting for the way in which they constitute a hybrid of computation and actuation. They can be said to compute, as their configuration (output) changes in response to an external input. Traditionally, the capacity for a material to exhibit hygroscopic properties is associated with natural materials such as wood, whose internal cellular structure promotes water exchange, producing physical changes in the material (Holstov et al. 2015). These systems can be programmed through a range of methods, including the lamination of materials in composites of active (hygromorphic) and passive (unresponsive) layers (Holstov, Bridgens, and Farmer 2015; Menges and Reichert 2015; Correa et al. 2015).

We have identified a new type of hygromorphic material which uses bacterial spores to create an active layer coated onto a passive layer. Some bacteria species have a complex life cycle that allows vegetative cells to undergo morphological changes to form spores that display interesting hygromorphic proprieties. A spore is a dormant and resistant stage that allows a bacterium to preserve its biological integrity and genetic material to survive adverse environmental conditions (temperature, starvation, chemicals changes). Spores can expand or shrink in response to relative humidity. Some *Bacillus* species can lose 12% of their diameter in dry environment but recover it with rehydration. This is connected to the mechanics between the different parts of bacterial spores. For instance, *Bacillus subtilis* spores have at their center a dehydrated core containing genetic material. This core is enveloped by different layers—moving outwards from the core, these are: the inner germ wall, made of cross-linked peptidoglycan; the outer cortex; a lipid membrane; coat layers; and a final crust layer (Baughn and Rhee 2014). The function, composition, and organization of these layers are different, but ultimately allow the spore to expand and contract as it absorbs water or dries out. Bacterial hygromorphs described in this report exploit specific proprieties of Bacillus subtilis cotE gerE, a mutated strain that lacks some outer coat proteins, which amplifies the expansion of the spores.

7 Introductory workshop to pipetting.

Recent research has looked to utilize these properties in the generation of evaporation-driven engines and electrical generators. These systems involve mechanical contraptions that integrate spore-coated elastomers which expand and contract in response to fluctuations in humidity (Chen et al. 2015). Applications for bacterial spore actuators have been explored in design contexts, including intelligent fabrics and human-computer interfaces (Yao et al. 2015; Heibeck et al. 2015).

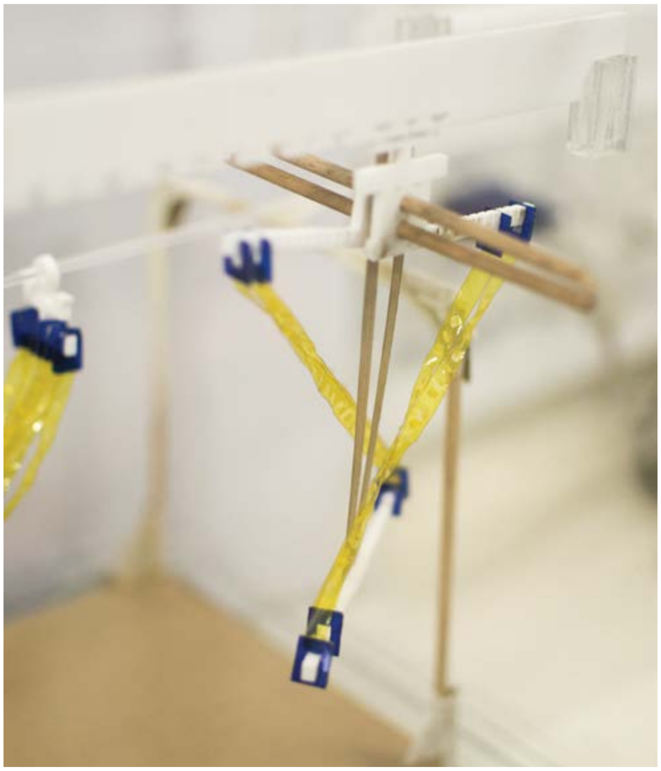
Spore-coated elastomers constitute a potentially powerful technology to produce highly programmable architectural hygromorphic materials. As with wood based hygromorphs, they may represent a low-energy, low-maintenance dynamic building component—with potential application in, for example, advanced building skins. It is estimated that a spore-coated elastomer can operate up to 1,000 cycles before replacement and would not require special conditions for operation (Chen et al. 2015). There are, however, several challenges in designing systems using this emerging technology. Bacterial-based hygromorphs require their mechanical assemblies to be carefully optimized to the scale and power of the delicate coated elastomers. Access is also required to specialist laboratories, and knowledge is needed to grow, isolate, and prepare the spores and the coating solution. To address these challenges, we ran a design studio which included lab-based experimentation combined with *material proxies*, which involved more traditional workshop-based prototyping and that allowed us to negotiate limited access to laboratories and living materials.

METHODS

Set as part of our Stage 3 Program (3rd year undergraduate) we developed a five-week design project based on a brief to develop an actuated system which could open and close an aperture depending on the levels of humidity. This design component was conceived as part of an intelligent building skin.

Laboratory Strategies

An intensive two-day laboratory session was conducted to give the students direct experience working with the material, and to begin the process of prototyping to inform later designs. The central task of the session was the inoculation of bacterial spores onto the elastomer surface. Students initially familiarized themselves with the preparation of the spore solution, consisting of glue and a spore suspension. This was used to coat 15-centimeter-wide strips of eight-micrometer Kapton, a translucent polyimide film manufactured by DuPont. The film is prepared with an initial coat of Poly-L-Lysine, a liquid form of a synthetic polymer which increases adherence of spores to the elastomer surface. Once dry, the spore solution is deposited on the film using pipettes that allow a precise control of the deposition of the spore solution. The patterning of the spore solution allows us to program the hygromorphs with specific behaviors. Figures 2A and 2B show an elastomer strip which has been programmed to react by contracting and expanding as a cantilever—folding as humidity drops and the material dries. This is achieved by coating an elastomer strip on one of its faces. When humidity raises, it triggers a reaction in the spores, which expand to allow larger



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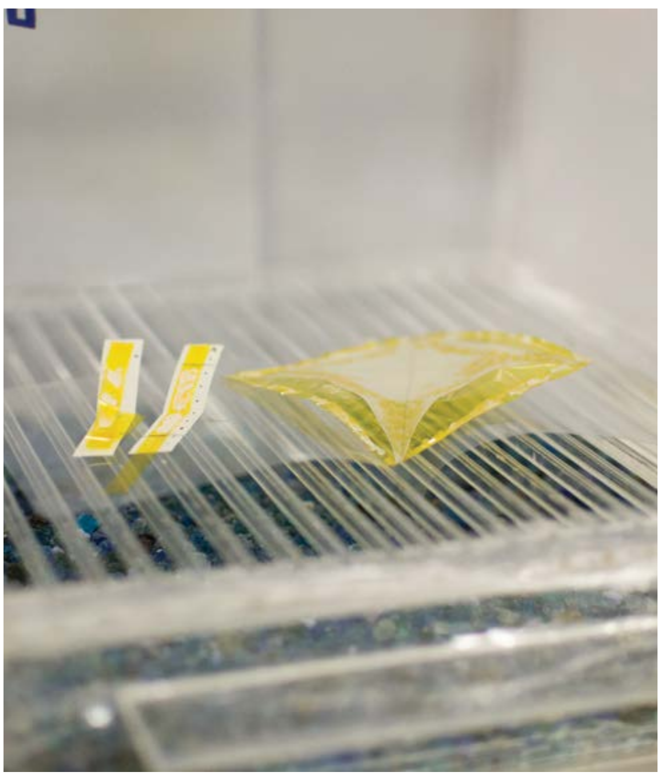

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8 Testing of transversal movement prototype in dry chamber.

9 Prototypes inside test chamber.

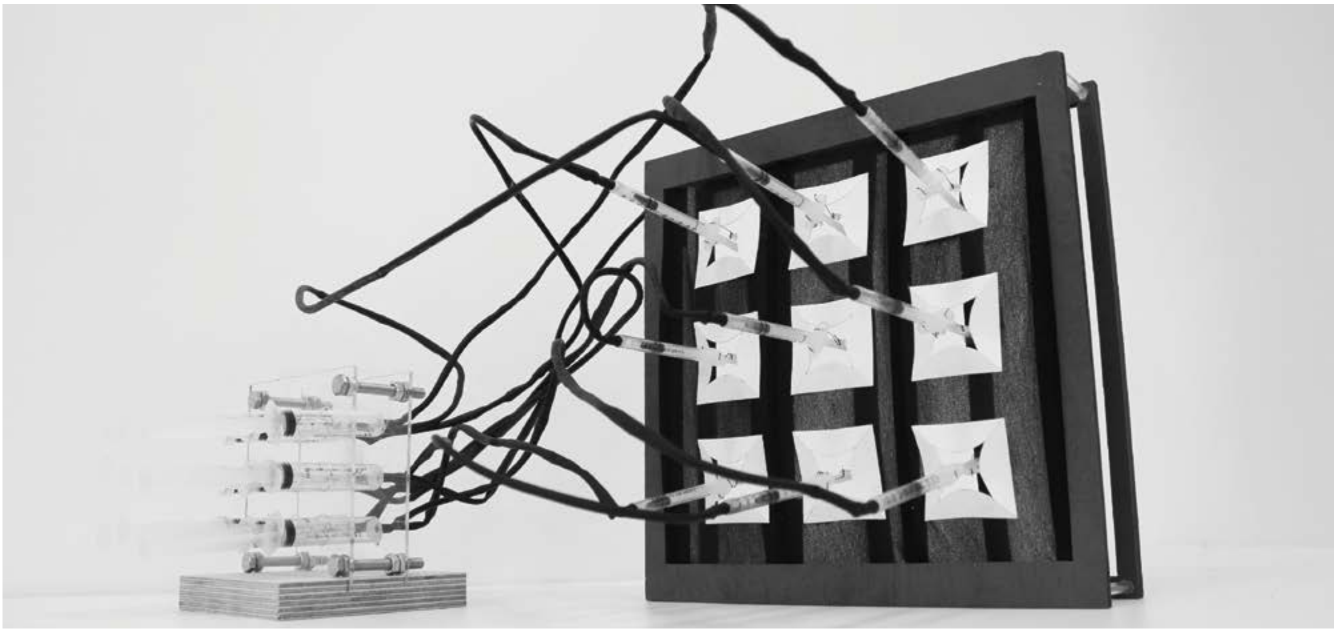
volumes of water within the walls of their membranes. This causes the active layer (a solution of glue and spores) to expand, pushing the elastomer outward. The opposite occurs as the material dries out. Variations of the inoculation pattern allow us to program the hygromorph into different behaviors. Inoculating spores in an alternating pattern on either sides of the polyimide material, for instance, causes the strip to expand and contract in a concertina-like shape (as shown in Figure 3). By coating an elastomer on alternating sides, the pull and push effect of the spores described above interact, resulting in a bending of the material.

Much of the workshop involved familiarizing students with the basic methods to fabricate bacteria-based hygromorphs, which involved producing the coating spore solution and understanding the methods to program behavior through patterns of inoculation (figures 5 to 7). In addition, they also devised their own experiments and novel actuators to test how they related to their initial design ideas. Experiments were performed in a pair of humid and dry chambers, which were custom built for the project (shown in figure 4). The tray of the high-humidity chamber was filled with hot water, which increased the air moisture inside the chamber to levels of 95% relative humidity (dry bulb temperature 25°). To create dry conditions, the low-humidity chamber container was filled with silica gel crystals, bringing relative humidity to 30% (dry bulb temperature 24°). A lid on top of the chamber provided access to the main volume, where prototypes were hung to test. The chambers allowed us to place prototypes inside in order to record their reaction to extreme levels of humidity (figures 8 and 9).

Proxy Strategies

Getting to grips with soft technology is made more difficult by the constraints on its use and the time available for experimentation. While a strip of elastomer inoculated by bacterial spores is estimated to be capable of pulling 50 times its own weight (Chen et al. 2015), at this scale the loads relevant to the actuation of, for example, a window, would require hundreds—perhaps thousands—of strips and other issues begin to come into play. Tiny amounts of friction between components and the stiffness of different materials start to play a part when added up over many parallel components. To better understand this, we needed to incorporate the bacteria in the early stages of the design process. This is challenging, however, as direct experience of the material depends on experimentation that, given potential biological risk, can only be performed in the controlled conditions of a microbiology laboratory.

An alternative to direct use of bacteria hygromorphs is *material proxies*, defined as technologies that mimic some aspect of the material system we are interested in investigating. In this context, we used shape-memory alloys (SMAs), which can be



10 Prototype A, concept model showing connection between panel and pneumatic system.

programmed to contract when voltage is applied to them, in the same way that hygromorphs respond when being wet or dry. For example, Nitinol, a nickel and titanium alloy, remains in a martensite phase at normal temperature. In a martensite state, atoms are arranged in a grid, in which one axis is slightly longer than the others. On a macro-scale, this means that the metal is malleable, adopting any form that is forced onto it. When the metal is brought to its transition temperature, the metal shifts to its austenite phase, in which atoms arrange in the most compact and regular pattern possible. On a macro-scale, this snaps the metal back to its original or so-called parent position (Kumar and Lagoudas 2008).

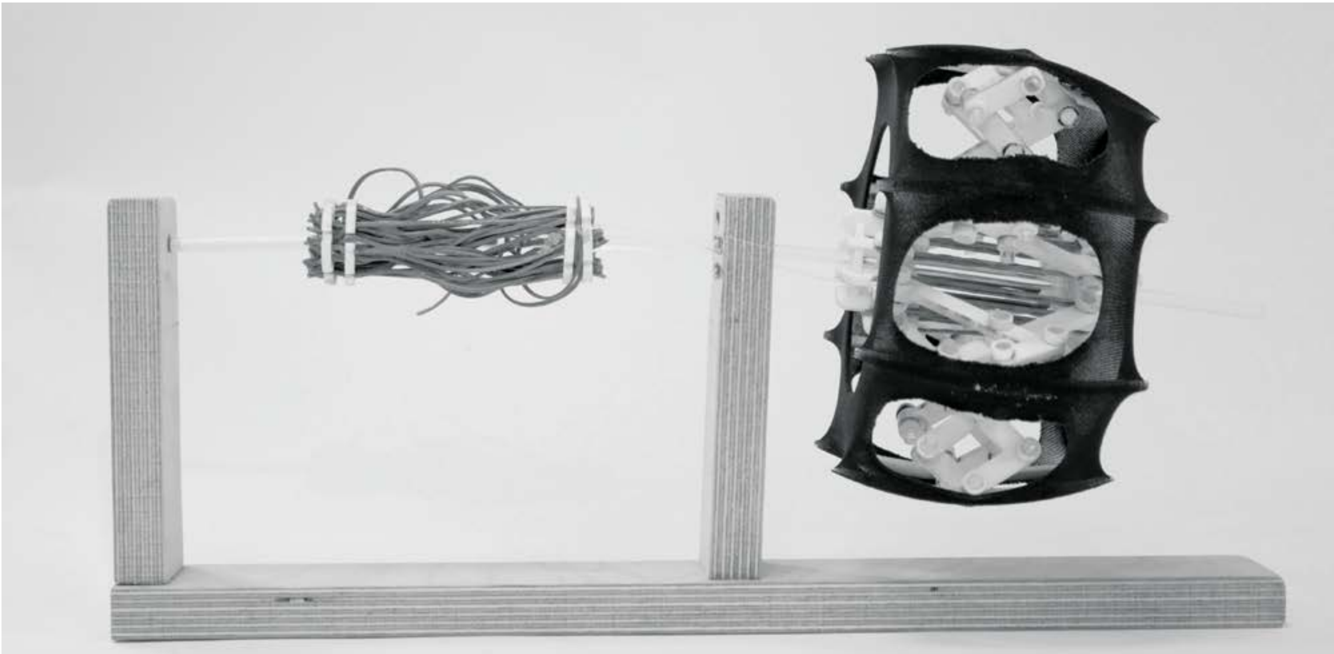
SMAs provided a simple way to integrate actuating components, close to the range of operation of bacterial hygromorphs, into the physical prototypes produced in the design strategies phase. Students were provided with 0.005” diameter Muscle Wire, an SMA produced by Dynalloy Inc. The datasheets suggest a pull force of 0.49 lb for this gauge of wire (Dynalloy n.d.), which allowed us to establish a rough equivalence of one strand of SMA for 37 strips coated with bacterial solution.

RESULTS

Bacterial-spore-based hygromorphs appear to offer potential in architectural design, especially in their capacity to bridge seemingly unrelated scales—the response of a single cell, measuring less than 2 micrometers, could be made to power an actuation system relevant to the design of building components. Our initial experiments have shown some of this potential, but also revealed some of the challenges in using this new type of system. In all, ten students participated in the studio and, in presenting their designs here, we reflect on some of those challenges and opportunities.

One central challenge in designing with bacterial-based hygromorphs is in bridging their scale of operation to that of the built environment. This requires adapting our current models of actuation, which have often been informed by industrial technologies, to the soft power afforded by these new materials. In approaching this, we initially directed students to 507 *Mechanical Movements* (Brown 1903), a nineteenth-century handbook that compiles mechanisms with different strategies to transform and make use of different sources of power and motion. The mechanisms are relevant in the context of this project, in that they are optimized to take advantage of relatively high-power inputs from steam engines to hydropower. Using them as point of departure involves actualizing their configuration to respond to and harvest smaller sources of power by orchestrating accurate movements. Bacteria-based hygromorphs, in contrast to industrial power sources, generate power at small scales, which must either be amplified or arranged in parallel—as hundreds of actuators in complex combinations—in order to become relevant to the scale of the built environment. In architecture, we simply don’t yet have a repertoire of actuated mechanisms that can make use of such sensitive but low-powered components.

Figures 10 to 16 show some of the prototype systems produced by the students. Projects can be broadly classified based on the way they integrate power generation and actuation. A first



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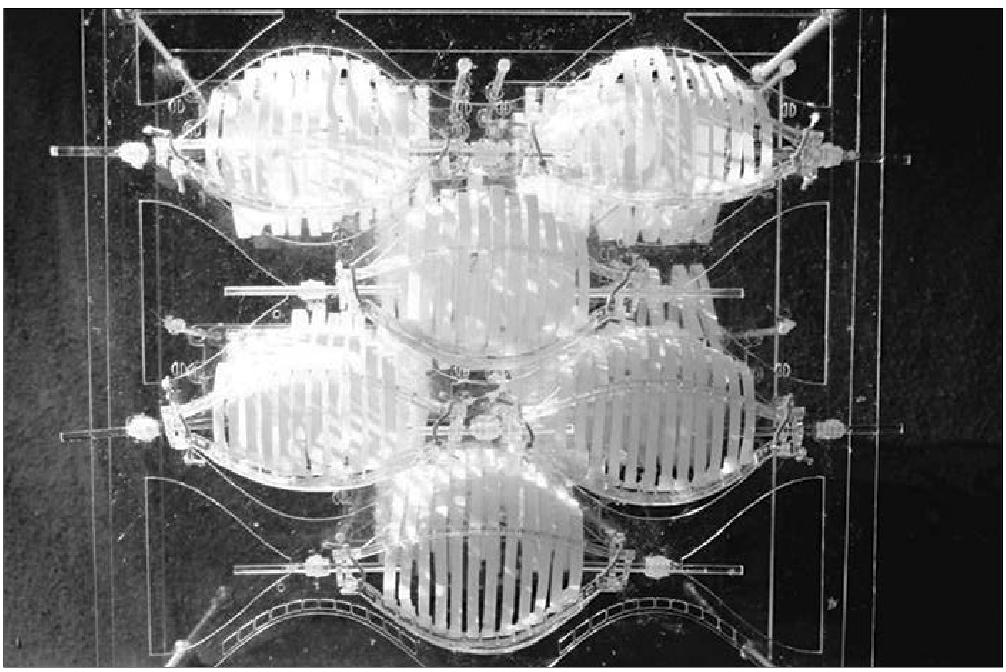

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11 Prototype B, concept model, the bank of bacteria spore hygromorphs is depicted as flexible bands to the left.

12 Prototype E, concept model showing the combination of several panels, hygromorphs depicted as white strips.

13 Prototype C, concept model of the assembled prototype. Curved elements wrapping the main body represent the bacterial spores as connected to actuate the ball-bearing mechanism.

14 Prototype D, assembled prototype showing the rotating mechanism connected to diagonally arranged banks of spore-coated stripes.

15 Prototype E, front view of early prototype integrating bacteria-spore hygromorphs, depicted in semi-transparent strips, and their connection to opening panels.

16 Prototype F, exploded view of shutter design showing banks of bacteria spores hygromorphs arranged opposite to each other, combining their action to produce organic like motions.

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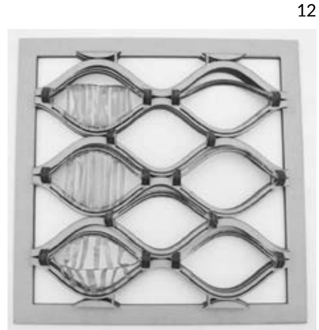

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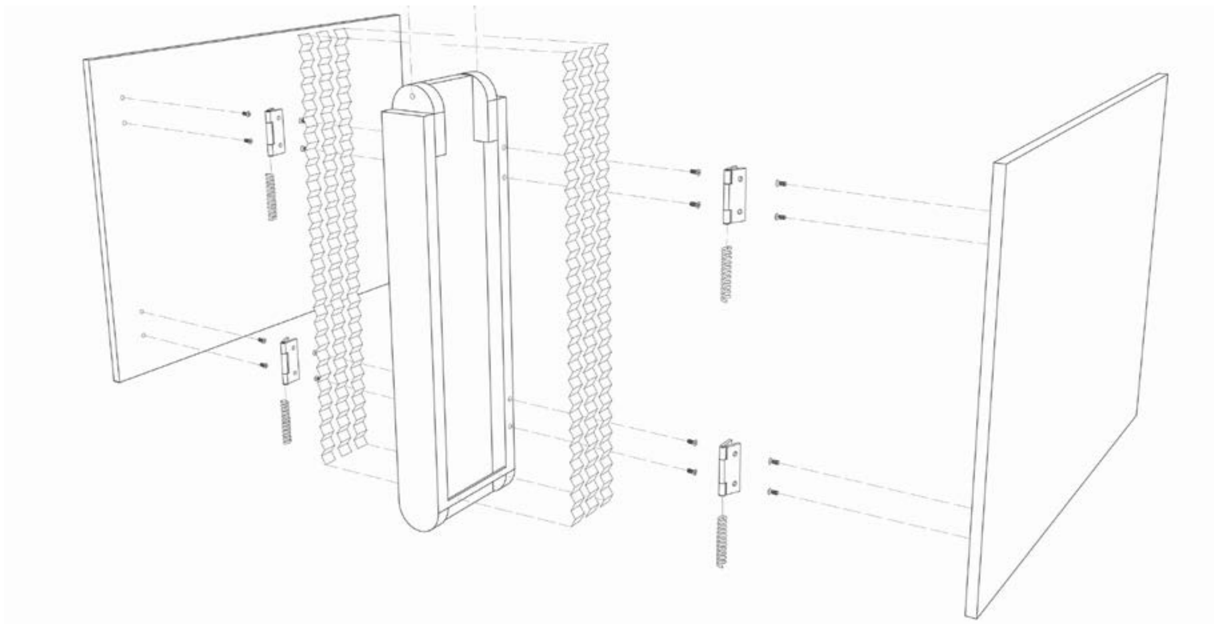

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category separate power generation—in this context bacterial hygromorphs— and actuation systems, incorporating different strategies to optimise their interface. A second category interweave actuation and power generation in a single system.

A good example of the first category is prototype A, designed by George Entwistle and shown in figure 10. It comprises a pneumatic system which uses a bank of spore-coated strips to push and pull the linear motion of pistons in a batch of syringe pumps. Fluid inside the pumps acts as interface to transmit power generation of strips to the actuation system, comprised of panels of flexible membranes that expand and contract. A similar approach is followed in prototype B, shown in figure 11 and designed by Michael Bautista-Trimming. The design allows a flexible membrane to expand and contract following the deployment of the mechanism. Actuation is generated by a linear motion, which is interfaced by a piston connected to a battery of bacterial hygromorphs, arranged radially connecting two sliding rings.

Prototypes C and D follow a similar strategy of separating power generation from actuation systems. The interface between both systems, however, is in direct control of the actuator. Prototype C, shown in figure 13 and designed by Adam Kamal Najia, consists of a rotating ball-bearing mechanism that forces a flexible membrane to twist, closing the aperture. Spore-coated strips are placed to the sides of the mechanism. Prototype D, by Adnan Qatan and shown in figure 14, also makes use of a rotating mechanism that operates an array of blades. Spore coated strips are arranged diagonally, pulling a central ring that allows the mechanism to transmit and transform linear into rotational motion.

A second category of projects merge power generation and actuation together, weaving their components and generating geometric strategies that create tight couplings between mechanical parts and spore-coated elastomers. In prototype E, shown in figures 12 and 15, Aldrich Choy creates a system which weaves spore-coated elastomers within the actuating mechanism itself. Groups of strips are connected to a rotating, rigid element. Conditions of closure and aperture are generated by this element and, in part, by the dense arrangement of bacterial hygromorphs, which provide the power to actuate the system and produce a dense, tissue-like mass that opens and closes as they expand and contract. The strips are connected to a number of fixed points which are separated along the panel's depth, which amplifies the condition of closure. Prototype F, designed by Julian Besems and shown in figures 16 to 17, generates a tight coupling between power generation and actuation, blurring the boundary between both functions. As seen in figure 17, the system incorporates banks of strips arranged in parallel that are embedded to the sides of a chain of hanging panels. Banks of strips are arranged in opposite sides, each facing the inside and outside of the panel. This allows a nuanced actuation, which responds to shifting moisture conditions by allowing banks of strips to counteract each other with jittery, small motions that resemble organic movements.

Other explorations also hinted at different ways in which spore-coated components can, potentially, actuate without association to mechanical assemblies. This is the case of explorations shown in figure 18, designed by Iona Haig, which experiment with the properties of flexible materials, such as fabric, and in the way that creases and folds can take advantage of the hygromorphic properties of spores to create movements that, aggregated within a dense mass, might produce conditions of closure and aperture.

CONCLUSION

What is notable about the designs presented in this paper is that whilst ingenious and elegant, they have developed inevitably in isolation from the hydromorphic materials. Although the lab experiments informed the overall form factor of the actuators, the students consistently underestimated the number of strips which would be required to power their system. The use of the proxy, whilst giving a sense of the power scale, didn't account for the volume of strips required for even modest mechanical power. The use of proxies in developing prototype models needs to be refined further to better reflect the scale of power generation. Also, a further avenue of exploration would not only work to develop more efficient mechanical assemblies that minimize points of friction, but also to develop systems which merge tasks of power generation and actuation into the same component. This is an ambitious task, as it requires new interface and motion logics that depart fundamentally from those produced for industrial sources of energy and motion. A few elements of the exploration presented in this paper hint towards this direction. Notwithstanding, we believe the methodology followed and the resulting prototypes provide useful approaches to the design of living and semi-living materials, which hold the potential to constitute highly programmable, soft computational architectural components.

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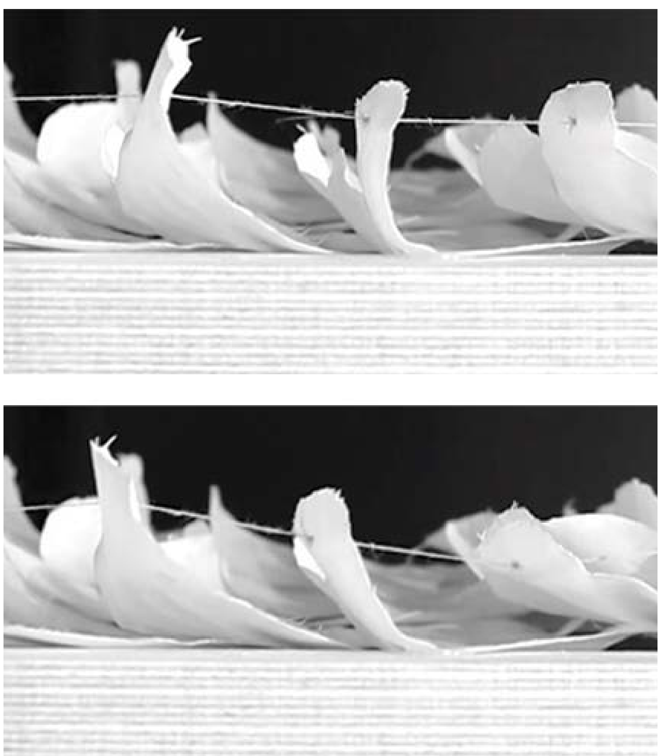

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17 Prototype F, design of the mechanisms allows for a progressive deployment which hints at an organic behavior.

18 31A and 31B. Prototype G, working model of spore-coated elements which operate as scales, providing conditions of aperture by aggregating their individual behaviors.

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