InterspeciesForms

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Abstract. InterspeciesForms hybridizes mycelia's agency of growth with architectural Design intention in the generation of novel, crossbred designed outcomes. In order to establish a direct dialogue between architectural and mycelia agencies, robotic feedback systems are implemented to extract data from the physical and feed it into the digital realm. Initiating this cyclic feedback system, mycelia growth is scanned in order to computationally visualize its entangled network and agency. Based on the logic of stigmergy, computational agents trace around the organisim's patterns of growth, forming entangled and complex networks. Through this unification of biological growth and computational agencies, non-indexical crossbred outcomes begin to emerge. Bringing this hybridized computational form back into the physical realm, form is 3D printed with a customized mixture of mycelium and agricultural waste. Once the geometry has been extruded, the robot, patiently waits for the mycelia to grow and react to the living extrusions. The architect then responds with a counter move by scanning this new growth and continuing the cyclic feedback system between nature-machine and architect. This procedure demonstrates form emerging in real time according to the co-creational design process and dialogue between architectural and mycelia agencies.

Keywords: Keywords are separated by half-angle origin

1 Introduction

Mycelium are threadlike fibrous root systems made up of hyphae, that form the vegetative part of a fungus [7]. Known as the hackers of the wood wide web [10] mycelia forms complex symbiotic relationships with other species that inhabit our earth, as Michael Lim states "Fungi redefine resourceful-ness, collaboration, resilience and symbiosis" [7, p. 14]. When wondering around the forest to connect with other species or searching for food, fungi form elaborate structures by spreading their hyphal tips. Darwin illustrated that root tips act like a brain as they link perception and action, and determine the trajectory of growth. Sheldrake [9] links this behaviour to fungal hyphae, as data is streamed through the organism's tips, determining the speed and direction of growth. The Latin root of the word intelligence means "to choose between" [9, p. 73], suggesting a form of intelligence expressed through the mycelia's 'decision gates'. Due the organisms ability to solve problems, communicate, make decisions, learn, and remember, fungi are indeed an intelligent species with a unique aesthetic that must not be ignored. In drawing on these concepts, I refer to the organism's ability to search for, tangle and digest its

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surroundings as 'mycelia agency of growth'. It is this specific behavioural characteristic that is the focus of this research, with which I as the architect set out to co-create and hybridise with.

2 Mycelium and Architecture

Over the years, a vast amount of interest and research has developed, testing fungi's compressive strength, acoustic absorption, fire safety properties and application to architecture. Due to the organisms ability to up-cycle materials and biodegrade them, fungal mycelium is often considered a sustainable alternative to synthetic materials. Mycelium-derived materials have several key advantages over traditional synthetic materials, including their: low cost, density, and energy consumption; their ability to biodegrade; and their overall low environmental impact and carbon footprint [3]. David Benjamin for example has successfully converted mycelium into known architectural applications such as bricks. Displayed in the courtyard of MoMA's PS1 space in New York Hy-Fi Tower (2014), Benjamin demonstrates the fabrication of organic, biodegradable bricks made of farm waste and a culture of fungus that was grown to fit a brick-shaped mold. In a similar approach, Phillipe Block's MycoTree installation (2017) is made of load-bearing mycelium components that replaces know architectural applications such as columns. Comprised of mycelium-infused waste that is ordinarily weak in tension, Block's team hacked into the mycelia's structural capabilities through form [4]. Advancing this fabrication method further, Pulp Faction by Ana Goidea, David Andreen and Dimitrios Floudas, demonstrates the robotic extrusion of mycelium infused with agricultural waste. This innovative research utilizes local organic waste in order to replace the existing petroleum based plastics, that are commonly used for 3D printing. To convert the living organism into a material that is suitable for the architectural field, the following process occurred with all three precedent projects listed above: The mycelium medium was initially grown on agricultural waste which provide nutrients for the organism to flourish. In the case of Phillipe Block's MycoTree and David Benjamin's Hy-Fi Tower, the mixture was then infused into predetermined digitally fabricated moulds in order for the organism to adopt the generated form. Following the growth period, the composite mixture is removed from the mould and either hot-pressed or oven dried which dehydrates the material and neutralizes the fungus [6]. By applying extreme heat to the fungus, this process converts the once living organism into a pre-formulated static building material by ensuring that it does not grow past the required shape [5]. In the case of 'Pulp Faction' mycelia is grown on agricultural waste and robotically extruded, illuminating the need for a digitally fabricated mould. In a similar process to MycoTree and Hy-Fi Tower, once the living organism has been 3D printed, extreme heat is applied in order to ensure that the organism is no longer able to grow, adapt, or respond past its required geometric shape.

2.1 The Agency of Mycelium

InterspeciesForms however posits that by making nature inert or converting it into static materials, 'appropriate' for the building industry, a crucial, biological- driven design process is being ignored. By converting mycelium into static non responsive materials, I posit that fungi's agency and true contribution to architecture has yet to be explored. Rather than ignoring natures agency, this research seeks to examine the potential contributions of the fungus's aesthetics to architectural de-sign. From this perspective, the mycelia's properties of growth are essential for the creation of hybridized, novel forms. InterspeciesForms therefore explores the possibilities of fungi that transcend its application of a sustainable material. This research explores novel ways to partner with the fungus in the cocreation of hybridized crossbred forms. The purpose of this partnership is to not only expand the imagination of the designer, but to generate novel forms which otherwise would not have been generated if designing individually. Michael Lim explains this notion that organism's should not be understood in isolation when stating "Fungi teach us that we are all interdependent. When we finally surrender our separateness, we realize that we are not outside of nature, but with it" [7, p. 15]. Fungi has been scientifically proven to partner and form symbiotic relation-ships with other species on our planet such its symbiosis with algae that generates lichen. This research questions, can architects and mycelium hybridize in the same way? This developed dialogue and feedback systems between the architect and mycelia agency is described in what follows.

3 Technical Workflow

Methodologically, this project involved the following stages: (i) preparing and applying the mycelium for growth on petri dishes; (ii) scanning the form; (iii) 3D printing the derived form using mycelium extraction, clay and agricultural waste; and (iv) incubating the forms and (vi) continuing the cyclic feedback systems of scanning mycelia data and extruding so that form is generated in real time. These processes involved the introduction of a scanning technology, developed computational algorithms, as well as developing a new mycelium based mixture for 3D printing the forms. In order to work with the organism intricate patterns of growth on a micro-scale, mycelium was initially grown on a series of petri dishes containing agar. Demonstrated in Fig. 1, this medium of growth was selected due to its capability to support a micro-scale growth pattern known as rhizomorph. To cultivate rhizomorph growth, mycelium was grown and sliced into 3 mm $\times$ 3 mm pieces. In a sterile environment, one slice of spawn was transplanted into a petri dish containing an agar medium. During the mycelium's growth, the petri dishes where stored in a dark, temperature controlled, and humid room to encourage cultivation.

In order to convert these intricate patterns of growth from the physical to the digital realm, a series of web cameras and microscopes where installed to track and computationally map the mycelium's dense fibrous network at the micro scale. Through a developed algorithm based on the logic of edge detection, computational agents traced over mycelia's patterns of growth, converting the once static image into a complex labyrinths of polylines. Using an additional process of color detection, the algorithm eliminated

Fig. 1. Mycelium growing inside a series of Petri dishes. Demonstrating qualities of rhizo-morph entangled patterns of growth, mycelia spreads its hyphae tips in order to explore its surroundings.

unnecessary background interference, by filtering out forms that did not represent the mycelium's distinct white flourishing color. This procedure enabled the mycelium's intricate physical data to be accurately represented in the digital realm. As a result, a series of delicate computational drawings were generated, representing the organisms agency and autonomy of uninhibited growth. These computational drawings are exhibited in Fig. 2. Here computational form accurately captures characteristics of mycelia's rhizomorph growth such as: branching, fusing, entanglement, bifurcation and webbing, all which are visible at the micro-scale. Particularly noticeable are the interweaving hyphae tips as they bifurcate, separate and form new connections, resulting in root clusters of entanglement, attracting itself- to itself. In order to hybridise architectural design intention with the organism's agency, an additional algorithm based on the logic stigmergic principals was implemented in order to intertwine the volatile nature of mycelium with restrained computational algorithms. The aim of this process was to form a shared inter-species space to which, each creator may contribute, according to their unique affordances. To do so, InterspeciesForms utilizes stigmergy as a methodology for co-creation in self-organizing systems. Through self-organizing algorithms that are attracted to predetermined paths, stigmergy is utilized in novel ways that enable architectural design intent to follow the paths set by the fungus. In analogy to the ant trail, here too the mycelium's 'pheromones' lead the architect along their trails and the architect responds to these trails through a series of developed rules and restraints. These encoded rules and restraints may not only seed architectural design aesthetic but add a sense of organized complexity to mycelia's patterns of growth. Architectural intention is therefore imbedded by orchestrating the local interactions and micro decisions of computational agents. To do so, the developed algorithm was programed to include the following behavioural protocols: cohesion, separation, flow along curve, seek trail and evaporation of trail. The following pseudo-code describes this application and computational behaviours.

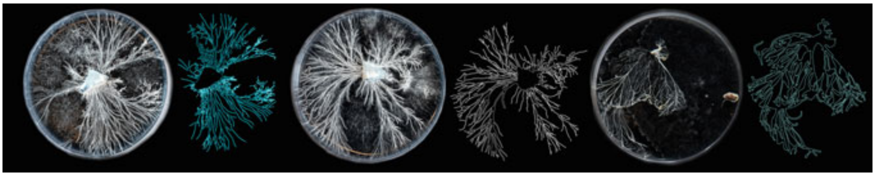

Fig. 2. Petri dishes containing mycelia growth (left) and the generated computational scan (right). Computational drawings assisted by Hanying Zhao and Christine O'neill.

Cohesion	*If* the computational agents move too close together, separate. *If* the computational agents move too far away, then seek the nearest mycelia pathway.
Separation	*If* the distance between the mycelium curve and the computational agent is <200 separate. *If* the distance between the mycelium curve and the computational agent is >200 move closer.
Flow Along curve	*If* the computational agent range is < 50, flow along mycelium curve. *If* the computational agent range is >100, do not flow along the mycelium curve.
Seek Trail	*If* value is >0.1 Seek mycelium trail. *If* value is < 0.1 Do nothing.
Evaporation	*If* the agents have been tracing around the mycelia's curves for 100 iterations. Evaporate.

Responding to the organisms agency, computational agents follow along the designated mycelia trails and simultaneously generate intricate entangled fibrous networks between each hyphae tip. This additional process adds a sense of designed complexity to the mycelium's web, by generating entangled connections between the hyphae tip. The sequential steps of growing the organism within the petri dish, the computational scan and applying the stigmergic algorithm which is seeded with architectural design intention is demonstrated in Fig. 3.

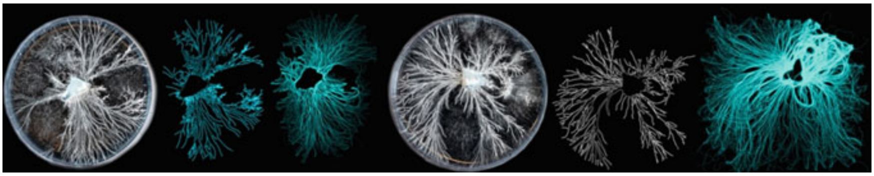

Fig. 3. From left to right, Petri dishes containing mycelia growth, computational scan and mycelia drawings and hybridized stigmergic outcome.

For the purposes of form finding, the goal of this process was to draw out the hybrid emergent characteristics between the natural and artificial realms. The results of this hybridization between mycelia and architectural agencies represent novel outcomes, which are non-indexical back to either mycelia's scan or computational agency. Whilst mycelia's original polylines have therefore been morphed, mutated and manipulated into an unrecognizable result, the organisms original features of fibrosity, delicacy and complexity still remain. Demonstrated in Fig. 4, a delicate balance of agency is achieved as characteristic of mycelia growth and stigmergic processes are still present, but have morphed into something new.

In order to bring these hybridized output forms back into the physical environment and continue this cyclic feedback system between the natural and the artificial, InterspeciesForms where robotically extruded with the mycelium medium it-self. However,

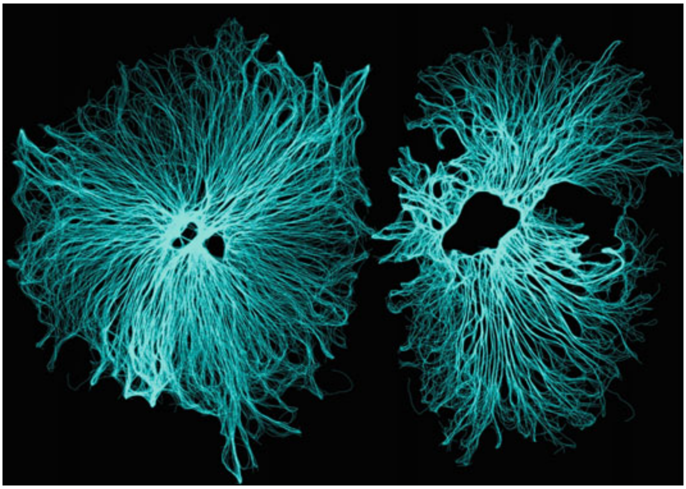

Fig. 4. Hybridized outcomes of the entanglement between mycelia's and architectural agencies.

in comparison to existing projects that 3D print mycelium, mycelia was kept alive in order to enable its patterns of growth to thrive and contribute to the create of form and robotic movement. Demonstrated in Fig. 5, a feedback system and direct dialogue is developed between biological, architectural and robotic agencies as mycelia growth becomes impute into computational form and robotic movement. This technical process is described in what follows:

A customized mixture of mycelium, clay and agricultural waste was created in order to robotically fabricate the biological medium and encourage growth. This mixture consisted of agricultural waste, which provided nutrients of the organism to thrive and clay which acted as a natural binder for the living fibbers to adhere to. Each hybridized form was 3D printed at the scale of 300 mm × 400 mm. The size of the forms could not identically match the original size of the petri dish de-rived forms (200 mm diameter), due to limitations set by the nozzle size and the need to prevent clogging. The following steps were taken to test the points mentioned in the creation of the form:

Mycelium was firstly inoculated and grown on a mixture of wood chips and paper pulp. Over a seven day period this mixture was incubated with controlled temperature (24–30 C) and humidity (90%), under a greenhouse tent. This chamber was kept sterile to prevent bacteria growth, while enabling sufficient natural light to pass through. Ph.D. RMIT diss.

Once the mycelium flourished in growth, over a seven-day pe-riod, it was introduced to the clay medium. Earthenware clay was utilized due to its porous aerated structure, which enabled the mycelia to seep through and even-tually degrade the substrate. Both the clay and mycelium bio composite mixture were fused together, generating a living paste to robotically extrude.

Utilizing a customized clay extruder on a Universal Robot (UR), the mycelium mixture was 3D printed according to the following protocol: (i) Nozzle Height: 23.1 mm

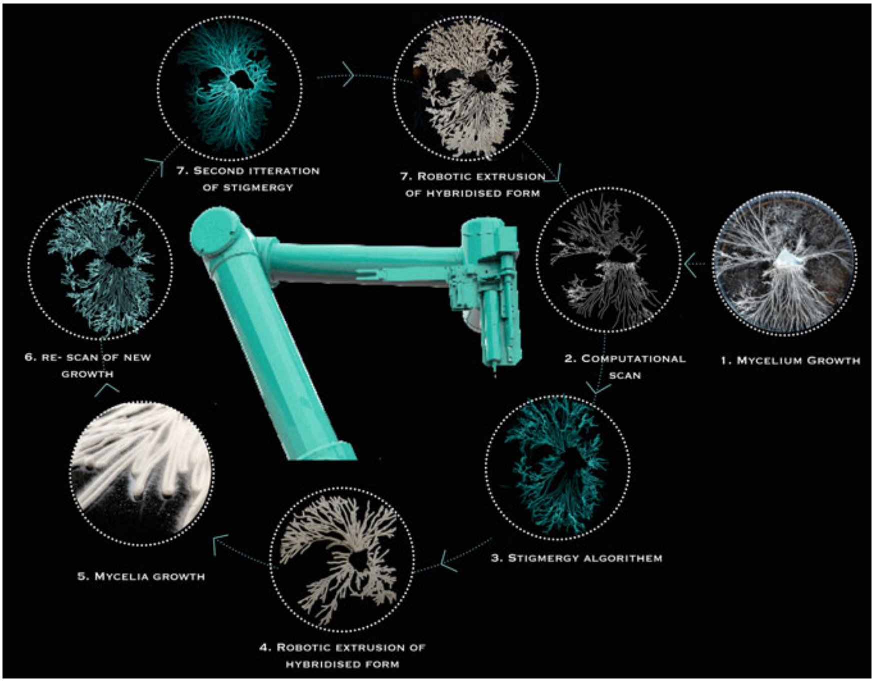

Fig. 5. The developed cyclic feedback system between mycelia growth, robotic intervention and computational form. Initiating this feedback system is the growth of mycelia with-in a series of petri dishes and agar cultures. The organism's physical patterns of growth are scanned and become inputs for computational form. Stigmergic algorithms are then applied to the mycelia's polylines, generating hybridized non indexical results. These outcomes are then 3D printed with the biological medium itself. Over time, the robot waits for the organism to grow and responds to fungi growth by initiating the feedback system of scanning and extruding once again.

from Surface; (ii) Nozzle Width: 5 mm; (iii) Print Speed: 10 mm/s; (iv) Flow Rate: 58%; (v) Layer Height: 1.5 mm; and (vi) Air Pressure: 50 PSI.

Images of the clay-mycelium medium being robotically extruded and growing are shown in Fig. 6.

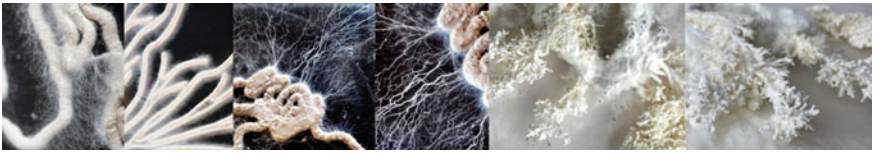

Fig. 6. Clay infused with mycelia robotic extrusions. Overtime, the mycelium began to grow from the organic mixture and wondered around the surface area in search for additional nutrients.

4 Results

Once the organism was 3D printed, the organism began to grow from the living extrusions by extending its hyphae tips away from its designated path that the robot extruded. This behavior not only exposed the organism agency but asserted its autonomy, that the living cannot be completely controlled. During this period, three types of growth behaviour were observed. The first was noted by change of texture and color. Whilst initially the designed form had a smooth grey exterior—resembling the appearance of clay, over time the extrusions turned hairy, fluffy and furry, resembling the texture of hyphae, imbedded in the extrusion. Figure 6 present this formation.

A second noted change was that the form began to fruit. Long cylindrical mushrooms began to blossom and tower over the tapestry. Finally, it was observed that over the course of seven days, the mycelium increasingly biodegraded the clay mixture substrate. When doing so, it began wondering around its surrounding in search for additional nutrients to absorb. This was fascinating to observe, as the fungus was no longer constrained by the extruded form from which it originated, but rather began to affirm its own agency of growth. A distinct set of generative patterns of growth and characteristics such as branching and fusing began to emerge. This volatile behavior resulted in vein like formations, not set by the architect. Here the fungus clearly asserted its autonomy over the design. Once the organism began to divert and grow beyond its set boundaries, an additional scan was conducted in order to repeat the cyclitic feedback prosses of growing-scanning and extruding (Fig. 5). Resulting from this feedback systems, a catalogue of forms shown in Fig. 7 were generated exposing emergent qualities as form mutates and evolves over time.

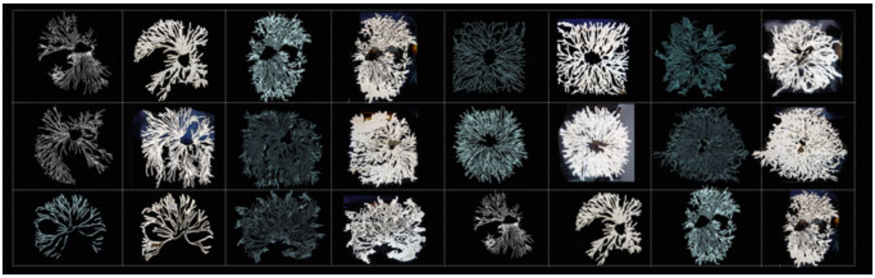

Fig. 7. Computational Matrix showcasing mycelia's original growth and computational scan conducted. Once mycelia has grown beyond its set boundaries, an additional scan is conducted in order to capture its new agency of growth.

5 Conclusion

Through this developed feedback system the formation of architecture is directly driven by mycelium behavior, rather than an a priori parametric model or generative algorithm. Methodologically, the contributions of InterspeciesForms include the scanning mycelia growth in order to computationally visualize its patterns of growth, utilizing mycelia growth as impute to developed algorithms based on stigmergic behaviors, generating hybridized outcomes from the co-creation of architectural and mycelia agencies, and developing behavioral based feedback systems. The findings of this research conclude that by applying stigmergy into biodesign, new opportunities for co-creation may arise. By embracing non-human aesthetics within architectural design, multi-species and biocentric forms may arise. Furthermore, it appears that the allocation of high levels of design autonomy to the fungus, has led to the creation of a new set of forms that embrace the strange and highly volatile nature of the mycelium. No two from outputs in this process were the same, where each fabricated design presented a contrasting set of biological patterns of growth. Reflecting upon the limitations of this research, the hybridized results remained on the two-dimensional scale and did not eventuate into three-dimensional forms. Due to a lack of access to high resolution vision systems that could capture the organism growth in the 3D realm, the scanning of mycelia's was limited to the two-dimensional scale. Thus the stigmergic response mirrored this scale and generated two dimensional hybridized outcomes. In order to advance this established feedback systems further, higher resolution vison systems are required to capture the mycelia's growth within the petri dish on the three-dimensional scale. Rather than responding in the two-dimensional realm, the architect may generate 3D forms which emerge from the interaction of architectural aesthetic and the behavior of mycelia growth. This research demonstrates and offers new methodologies of co-creating with non-human organisms that may give rise to new non-indexical formations for architectural design purposes.

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