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Designing a Living Material Through Bio-Digital-Fabrication

Guiding the growth of fungi through a robotic system

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Designing with living materials require designers to look for new methods of fabrication since living cells exhibit their own agency, and are able to sense and respond to environmental stimuli. Therefore, there is an urgent demand to design a framework for fabricating living materials. This paper investigates the digital-fabrication of fungi as a new way of designing and crafting living materials without genetic manipulation. In this research, fungi act as a bio-material probe to generate and test new design strategies that enable a dialogue between digital and biological systems. Conceptual experiments, that use fungi to investigate the proposed bio-digital-fabrication scenarios, are central in this study. The research attempts to generate new information for the design process of an organism in the field of architecture. The project will expand on the latest thinking on the bio-material fabrication by allowing the living material to be engaged in the fabrication process.

Keywords: *Bio-digital-fabrication, Biological interactions, Self-organizing material systems, Robotic growth chamber*

INTRODUCTION

Mushrooms are the fruiting bodies of fungi, formed by a stipe (stalk) that supports a pileus (cap) where the spore production occurs (Watkinson et al. 2016). Mycelium, the root network of fungi, is of general interest as a building material as it can be grown rapidly on various forms of waste creating a bulk building material (Islam et al. 2018). Recently, some architects have been experimenting with mycelium to create structures, which include 'The Growing Pavilion' and 'Hi-Fi Tower' [1], [2]. However, while mycelium is relatively simple, the fruiting bodies (which are composed of cells with the same genetic code as the roots) are morphologically complex with a high degree of cell differentiation and plasticity. Plasticity allows mushrooms to alter their morphology to adapt to changes in their environmental conditions (Skipper et al. 2010). Harnessing this self-assembly system of fruiting bodies for the development of materials offers an interesting contrast to the existing work on mycelium. It also offers some challenges to existing ideas of fabrication since the relationship be-

tween genetics, environment and cellular growth is complex.

This study suggests a form of bio-digital fabrication for fungi in which the fruiting body is grown with minimal direct physical intervention (ie typically moulds are used to constrain fungus growth) but is guided through the digital control of the growth conditions of the mushrooms in terms of temperature, humidity, CO_2 level and light exposure. This fabrication process involves both biological and digital sensing, and feedback. The aim is to guide mushroom growth digitally following similar approaches offered by projects such as 'Florarobotica' which focuses on the symbiotic relationships between robots and plants and Zolotovsky's 'guided growth' of cellulose-producing bacteria (Hamann et al. 2017; Zolotovsky 2017). Both these projects, and the work described in this paper, can be considered as biohybrids which combine computational tools and living materials to build manufacturing systems for architectural purposes.

This paper describes a 'robotic growth chamber', which is used to inform the morphology of the oyster mushrooms (Pleurotus ostreatus) through the initial biological experiments (humidity and CO_2). Although the mushrooms obtained as a result of the experiments have no apparent value to architecture, they help to demonstrate a broader concept, indicating a new type of parametric design. The mushrooms are used as a bio-material probe to gain new knowledge and transfer that knowledge for future studies on how to guide the growth of a bio-material with its own morphological tendencies and capacities. The adaptation of the probe method to biomaterials was pioneered by Ramirez-Figueroa to enable direct engagement with the biological systems. She conducted design experiments using organisms to explore ideas, for example, the patterning of bacterial growth (Ramirez-Figueroa 2017). In these contexts, bacteria and mushroom, acting as bio-material probes, are explicitly not for the development of 'useful' materials but for the development of design frameworks which reveal the complexity of biological systems and processes.

METHODS

The design and construction of a robotic growth chamber

The project is based on the design and construction of a growth chamber in which the environmental conditions of the growing mushrooms can be controlled. This in turn alters the developmental pathway of the mushrooms leading to different morphologies.

To make this system, an Arduino UNO, a computer, Arduino sensors (DHT11 air humidity and temperature sensor, SEN0219 infrared CO_2 sensor, V1.0 soil moisture sensor and HC-SP04 ultrasonic distance sensor) as shown in Figure 1 and devices (12V DC fan, humidifier, 450 nm LED blue light source and 75watt heat bulb) have been integrated into a plastic container as shown in Figure 2 [3]. This chamber can be called a robotic chamber since it *senses*, with the Arduino sensors; *thinks*, with the algorithm; and *acts*, through command implementing devices (Ben-Ari and Mondada 2018).

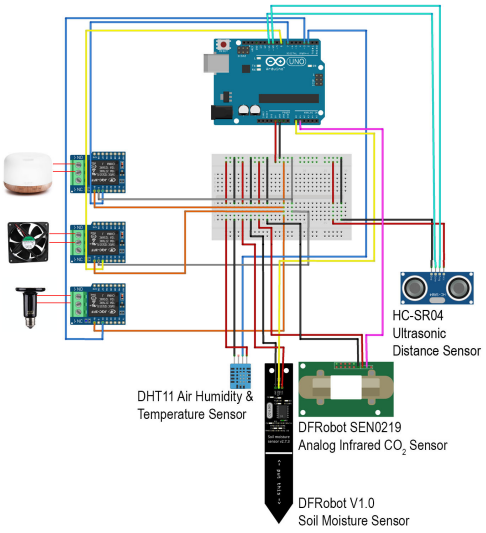
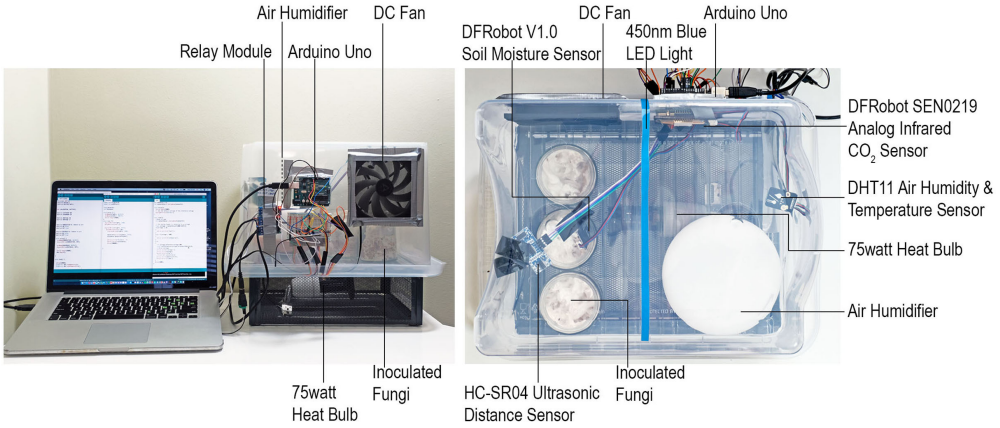


Figure 1
The wire connection of Arduino, sensors, relay modules and command implementing devices

Figure 2
The robotic growth chamber [3]



The system, for the growth chamber, as seen in Figure 3, is relatively straightforward. It works principally with 'on' and 'off' codes which can be set by inputting the numerical value for the condition according to the designer's desires. This in turn modulates the device, which controls that variable by simply turning it on or off.

All the sensors, other than the distance sensor, measure the environmental conditions of the chamber. The distance sensor measures the growth of the mushroom. This, in turn, provides feedback for the control or the environmental controls to create the conditions to inhibit or promote growth.

Experimental design

The scientific method is adopted to explore and test the effects of humidity and CO_2 levels on the morphology of fungal fruiting body. Firstly, a direct comparison of the specific conditions helps to understand the influence of each condition on the organisms' morphology. To achieve that only one variable is changed at a time and all other variables remain constant. The ambient conditions required for fruiting body maturation and mass cultivation for agricultural purposes are summarised in table 1 (Jang et al. 2003, Bellettini et al. 2019, Watkinson et al. 2016). These results have been used to give some scope to make decisions while setting up experiments.

All experiments were conducted in triplicates to help to detect the 'typical' fungal morphology formed each time under a single condition. Each set of mushrooms grown in the experiments started with the same substrates (10g of strawbale, 10g of wood shavings, 10g of coffee grounds), which were sterilised in an autoclave at 121^0C for 15 minutes. This mixture was then seeded with 10g of oyster mushroom spawn from GroCycle, UK under the same conditions (in sealed plastic boxes, in the dark, at ambient temperature). After three weeks, they were exposed to different environmental conditions, for 8 days, controlled by altering one parameter at a time.

Humidity experiment

The variable of humidity in this controlled experiment was measured using a DHT11 air humidity sensor and adjusted with a humidifier. In this way, the ambient conditions could be adjusted to 75%, 85% and 95% air humidity, utilising code which programs the Arduino. The other variables ie CO_2 level at 3000 ppm, light exposure for 4 hours per day at same time of the day and temperature at 22^0C were kept constant in this set of experiments.

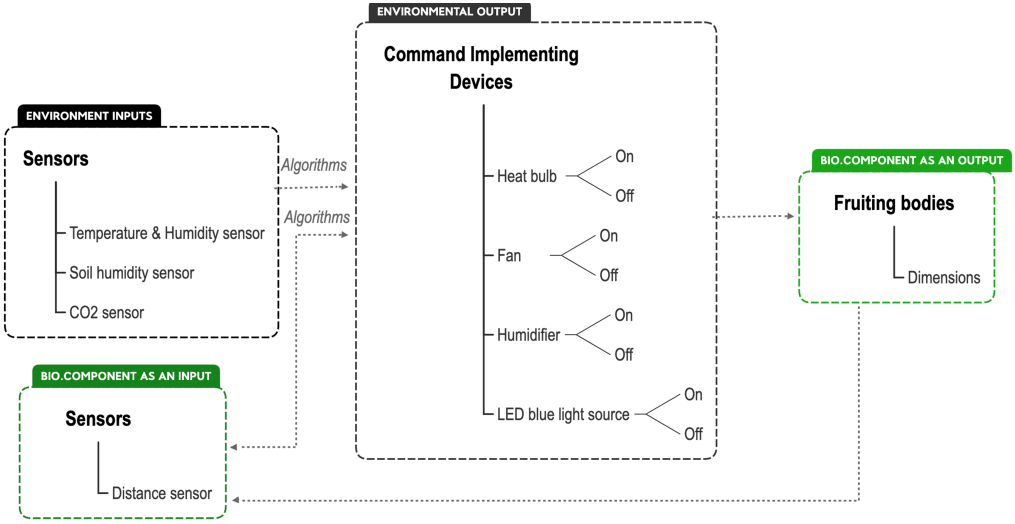


Figure 3
The diagram of relations

CO2 experiment

In this set of the experiments the CO_2 levels were tested at 1000 ppm, 3000 ppm and 5000 ppm. These were achieved by the help of the fan and SEN2019 Analog Infrared CO_2 sensor in the growth chamber. The other variables ie air humidity at 80%, light exposure for 4 hours per day at same time of the day and temperature at 22^0C were kept constant.

Recording results

The experiments were stopped on day 27 as the fruiting bodies tend to start forming by day 21 and wilting often is seen after day 30, as seen in Table 1. The mushroom morphology was documented at this endpoint of day 27 using photography (Fujifilm X-T2 with 80mm lens), microscopy (Dino-Lite digital microscope at 70X magnification) and 3D scanning (EinScan-SE desktop scanner). Photography helped to analyse the overall form and general tendency of mushrooms. Microscopic images captured the details, smaller features and non-measurable characteristics such as the surface texture and colour. The images from photography and microscopy generated the qualitative data for this study. The 3D scanning

	Mycelial growth	**Pinehead Induction** (the transition stage from mycelium to fruiting bodies)	**Fruitification**
Temperature	*5-35 ^{0}C*	*18 ^{0}C*	*20-25 ^{0}C*
Light	*Dark*	*Regular light-dark cycle 500 lx light*	
Humidity	*85-90 % humidity*	*90-95 % humidity*	*80-90 % humidity*
CO_2 level	*2000-2500 ppm*	*1500–2000 ppm*	*1500–2000 ppm*
Duration	*0-14 days*	*14-21 days*	*21-30 days*

Table 1
The ambient conditions required for fruiting body maturation

allowed the form to be translated into a digital model, using Rhinoceros. This helped to measure the angle and dimensions of the caps and stalks more precisely without damaging the organism. It also became possible to overlay the triplicate 3D scans of the mushrooms grown under the same environmental conditions to compare and contrast morphologies through the digital file. It helped to visually represent the average morphology for each condition.

RESULTS

The results evaluate both the performance of the growth chamber and mushroom morphologies in different environmental conditions. The mushroom formations are compared using photographs both in micro and macro scales and digital model comparing measurements of their dimensions.

The performance of the robotic growth chamber

While conducting the experiments, it is noticed that there are factors which complicate the system of the growth chamber. This complication arises from involving a living bio-material and environmental control being multifactorial. Therefore, the system is constantly working and adjusting to reach a desired equilibrium. The cellular respiration of the mushrooms produces CO_2, heat and water, affecting humidity, temperature and CO_2 levels in the chamber. Another complicating factor for the system is the operation of the devices, although aiming to affect one variable it affects the entire system. For instance, running the fan reduces the CO_2 as hoped but also inadvertently affects the humidity level and temperature in the chamber. Thirdly, independently of the devices, there is an innate relationship between the environmental factors such as when temperature drops humidity will rise, which is a feature of closed systems. Although there is this interplay of the mushroom, devices and closed environment, which is quite complex, all the devices work simultaneously to keep the conditions constant. This is achieved by each device having a main action and the result of this being monitored by the sensors to make regular adjustments to maintain desired conditions.

The mushroom morphologies

This robotic growth chamber acts as a proof of concept. It both establishes the conditions for and impacts on the growth and formation of, the mushroom fruiting bodies, with minimal physical contact.

As seen in Figure 4, the copies grown under the same conditions exhibit similar forms, therefore it is possible to state that the morphology of the fruit body is significantly influenced by each condition. Humidity increases the curviness of cap edges and the stalks (see figure 4-a). The texture of stalks gets hairier, gills get shallower, and pinheads swell as humidity increases (see figure 5-a). When observing the cap size there is not a significant trend seen with altering humidity levels (see figure 6). Although the stalk length does suggest linear growth, it does not show as much variation as changing CO_2 levels (see figure 7).

On the other hand, CO_2 mainly affects the size of the caps (see figure 4-b). The caps get bigger with a decrease in CO_2 levels. The stalks get longer with high CO_2 up to a certain level (see figure 5-b). However, after a certain point (approximately over 3500ppm) their length does not increase anymore, and they become leaner (see figure 7). In short, while humidity has more influence on the curvature of the stalk, CO_2 significantly affects the cap size.

CONCLUSION

The initial attempt to influence the growth of mushrooms using the growth chamber points towards a novel form of fabrication. It connects robotic sensing and actuation to the growth and self-assembly processes of a biological system. The robotic growth chamber provides a potential site for communication between designer and organism, where interactions occur through continuous modifications of a range of variables. This interactive and collaborative way of fabricating allows the material to go beyond the role of simply shape filling (Oxman 2010) and accordingly,

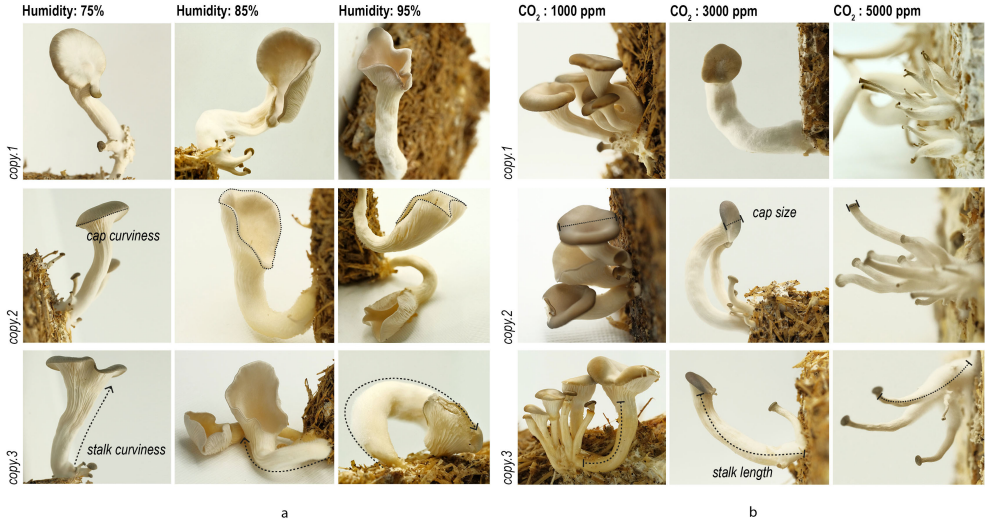


Figure 4
The effects of humidity and #CO_2# on mushroom morphology

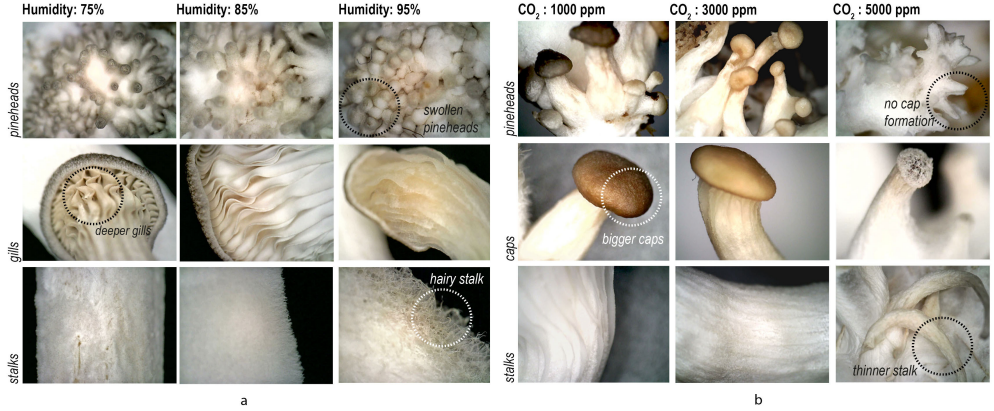


Figure 5
Microscopic images of different parts of mushrooms

Figure 6
The average sizes and the overlayed mushrooms in the humidity experiment

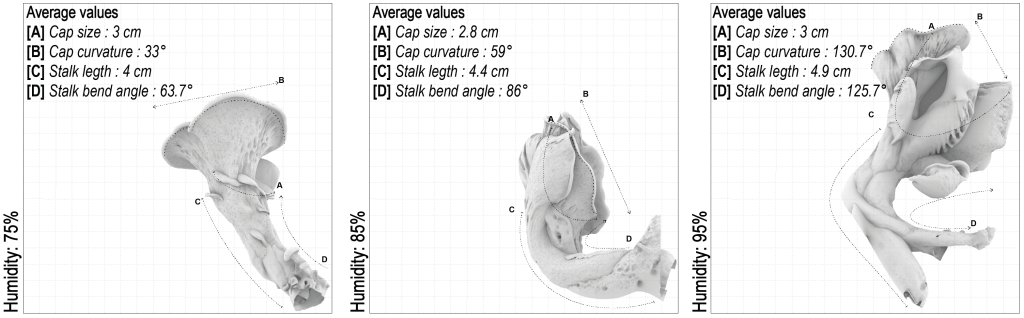
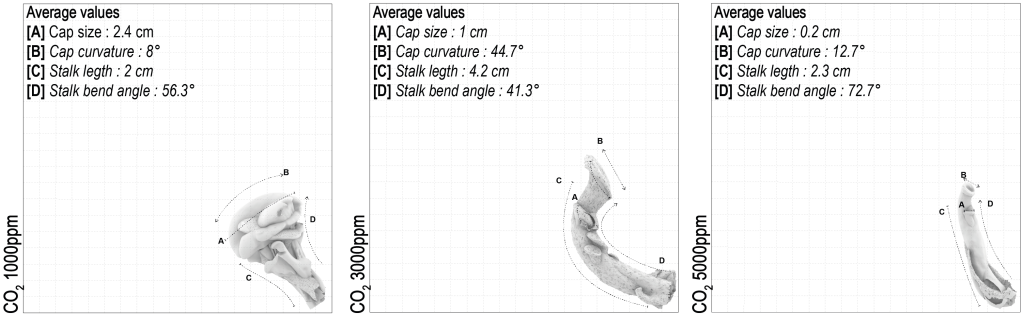


Figure 7
The average sizes and the overlayed mushrooms in the #CO_2# experiment



new relations start to emerge.

This work demonstrates that fungi exhibit parametric properties when a single parameter is changed. However, these experiments were carried out within a limited range. Future research could explore the critical thresholds were changing the variable no longer impacts (or impacts as expected) upon mushroom morphology. A further question might be, what happens if two or more variables are changed in the environment at the same time. Finding that out provides a design opportunity by presenting the parametrisation of a complex growth process leading to a complex 3D form.

Despite the lack of obvious value of the mushrooms within the architectural field, the process of guiding their growth using a digital system is an important demonstration of innovative architectural fabrication. Predicting the effect that altering more than one variable will have on mushroom morphology, and understanding and extrapolating the proportional relationship of the different variables will answer the question of how designers can craft biology through a new type of parametric design approach. It also exhibits a physical manifestation of a 'Creodic' design process. Dade-Robertson translates Waddington's idea of an epigenetic landscape into design framework and defines creodic design as *"...searching for the necessary paths for living cells to fabricate materials and for methods to alter the landscape towards a path which is favorable to the outcomes we want"* (Dade-Robertson 2021). Understanding how to influence the form of a living mate-

rial helps us to design by using the intrinsic properties of that material.

Observing how fungi form in different growth conditions within this research informs an understanding of the influences of the environment on a range of biological systems and the tools we, as designers, have to inform this process. Furthermore, harnessing both biological and digital computation to generate 3D material forms opens up discussion about the relationship between digital and biological systems as well as the role of the designer in processes which are complex and outside their direct control.

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