Architecture for Regenerating Living Ecosystems: Designing a clay module for a vaulted dome structure

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Abstract: Coral reefs are rapidly vanishing in the Great Barrier Reef. Design may play a part in coral reef preservation. This paper describes the design process for developing a clay artificial reef inspired by the geometries of the \textit{Oulophyllia bennettae}. The design aims to: 1. provide a structure for the rapid regrowth of a coral reef ecosystem, and, 2. demonstrate how the material clay can guide the development of form. The design process follows a material-centric approach. The paper outlines two manufacturing methods that transfer the digitally generated artificial reef models to the material realm as clay module prototypes. One process uses a robotic arm with a clay-filled syringe, while another process uses a traditional clay extruder. The results describe how the clay reacted to each method and how the design for the artificial reef evolved in response to these observations to develop functional form for an underwater environment.

Keywords: clay extrusion, digital fabrication, robotic manufacture

1. Introduction

Coral reefs are modular skeletal structures housing living ecosystems. Twenty-five percent of all marine organisms co-inhabit these complex forms. More than one quarter of coral reefs in the Great Barrier Reef (GBR) have recently disappeared due to widespread coral bleaching (Hughes et al., 2011). Urgent action is required to regenerate the reef. Design has the potential to play a crucial role in contributing to coral reef recovery.

This paper discusses a design project for an artificial reef which may assist in the regrowth of coral reefs. Drawing upon the microscopic and macroscopic forms of the Great Barrier Reef \textit{Oulophyllia bennettae} coral the research develops modules that tessellate to build an artificial reef in the shape of a vaulted dome. There are diverse considerations in designing an artificial reef (Seaman, 1996). This paper’s focus is to question how morphological information drawn from the \textit{Oulophyllia bennettae} translates to a clay structure for an underwater environment. The translation uses digital modelling and manufacturing in a material-centric design process (N. Oxman, 2012; Oxman & Oxman, 2014). With growing necessity to maintain coral reef ecosystems a number of artificial reefs
have been designed and manufactured. Some are monolithic while others are modular in construction (Barber & Barber, 1996; EcoReefs, 2012; Foundation, 2015; Goreau & Hilbertz, 2005). Adding to this continuing body of work, this paper’s contribution is the study of how form inspired from a modular coral reef is abstracted into clay by the use of two extrusion manufacturing processes. One process uses a robotic arm with a clay-filled syringe tube to manufacture conical extruded modules, while another process uses a traditional clay extruder to manufacture tubular extruded modules. These manufacturing tools enabled a craft like interaction with the material allowing an appreciation of the clay’s limitations and potentials in the design process.

This paper begins by explaining the Background to the research; this includes a brief description of the Oulophyllia bennettae, from which the geometrical inspiration for the artificial reef is drawn, and, an outline of reflective, material-centric design thinking such as that identified by Donald A. Schön and Tony Fry. The Method section describes how two types of manufacturing tools were used in a material-centric approach to develop modules; while the Results section describes the observations on the material reactions in manufacturing. Lastly, the Reflections and Conclusion section reviews how the material guided the development of form and how the material will continue to evolve once given to the underwater ecosystem to take over.

2. Background

2.1 Microscopic and Macroscopic Geometries of the Oulophyllia bennettae

Similar to the growth of a real reef, the design sequence for the artificial reef discussed here moves from the part to the whole, from the module to the overall structure (Menges, QIAN, & ZENG, 2012). The formal inspiration is drawn from the microscopic corallites and macroscopic dome of the Oulophyllia bennettae, while the design process follows a material-centric approach based on the qualities of the material clay.

Natural reefs are typically made up of aggregative and closely packed modular units known as corallites (Kaandorp & Kübler, 2001; Wood, 1999). A reef’s organic form originates with multiple living polyps that continually secrete calcium carbonate by patterns of additive layering (Kaandorp & Kübler, 2001; Stanley, 2003; J. E. N. Veron, 2000). This additive process builds conical and tubular walls with integrated radiating septo-costae partitions around each polyp (J. E. Veron, 2011; J. E. N. Veron, 2000). The cross-section of corallites have many variations in geometry between different types of reefs (Stanley, 2003). Some patterns have wall geometries similar in appearance to polygon cells (Stanley, 2003). Other corallites have circular and oval forms either expressed as separate branching tubes or as circular patterns integrated within an overall skeleton (Stanley, 2003). The Oulophyllia bennettae appears to have micro corallite geometries made up of irregular pentagons and hexagons. Some of its corallites have one columellae centre, while others have 3 centres in which 3 polygons merge together (Huang et al., 2014; J. E. N. Veron, 2000). These corallites are outlined by a raised skeleton wall, generating “y” shapes and at other times elongated sinuous stretched shapes (Huang et al., 2014; J. E. N. Veron, 2000).
The macroscopic morphology of the *Oulophyllia bennetiae* generally takes the shape of domes (J. E. N. Veron, 2000). The dome shape in reefs is determined by the ways in which module corallites aggregate together and the directions they grow (Kaandorp & Kübler, 2001; Stanley, 2003). Their growth is a response to numerous environmental conditions, including responses to resident and visiting organisms (Todd, 2008). As the reef matures, its dome form evolves with hierarchical patterns of oscillating surface geometries that offer places for a range of marine organisms to live in (MacNeil et al., 2009; Smith, 1978).

Drawing upon the natural manufacturing process and the closely packed hexagonal geometries of the *Oulophyllia bennetiae* corallites, this research develops two types of experimental modules designed to interlock into a vaulted dome; 1. a conical extruded module and 2. a tubular extruded module.

![Conceptual vaulted dome with conical units](image)

*Figure 1. Conceptual vaulted dome with conical units*

When the conical modules are assembled, they create a dome with tangential units. Each conical module is hollow at the centre lofting from a simple hexagonal base geometry to a larger 9 sided “y” shape. When aggregated to be part of the larger structure the modules create a surface texture with ornamental outlines reminiscent of the *Oulophyllia bennetiae* surface.
Figure 2. Conceptual vaulted dome with tubular modules

When the tubular modules are assembled they create a dome with branching hexagonal units. Each tubular unit has an expressive interior void with radiating vertical patterns.

As well as being informed by the morphological characteristics of the *Oulophyllia bennettae*, the design process was also guided by the material and the ways in which it reacted to the different tools. The focus of the research was to understand the kind of forms a designer/craftsman could develop while replicating the variable, imperfect yet stunning forms of a reef into a material other then the calcium carbonate. The research questioned how manufacturing form could embrace unpredictability and imperfection. To explore this concept the design process of the artificial reef embodied material-centric design thinking (N. Oxman, 2012; Oxman & Oxman, 2014).

2.2 Material-Centric Design Thinking

Material-centric design thinking is a description of a mode of designing that denies technical rationality in favour of an approach which is responsive to material feedback in the design context. Technical rationality emerged as a theoretical position in the 19th Century (Schön, 1983). This was a period in which rational and exact technological disciplines began to be privileged (Schön, 1983) and automated machines were built to deliver “perfect” form, overriding the practice of “artistry” and “craft”. In *Remakings, Ecology, Design and Philosophy*, Tony Fry argues that the machine and craft were seen as incompatible. However Fry suggests that this is true only for machines that separate human, material and machine interactions (Fry, 1994). Craftsmanship is still present where the machine is controlled by a human worker (Fry, 1994). Through the activities used in controlling the machine the worker develops “craft skills” by intuitive learning. Led by the senses the worker makes decisions and judgements in his actions as he reflects on the reactions of the material to the machine (Fry, 1994).

In this view the machine is thus not the rival of craft; rather it is the way the machine is used that can disconnect the interaction between the designer and the material (Fry, 1994). The machine can still be used as a tool that allows the unpredictability of the material to be expressed. Donald A. Schön in his book *The Reflective Practitioner* explains that Technical Rationality is restrictive because it excludes the value of unpredictability (Schön, 1983). Schön develops a theory in which knowledge accumulated through “artistry” and “intuitive” methods is embraced. He advocates for design to be a “reflective conversation” in which unpredictable and unexpected design results are considered and reflected on for further decision making (Schön, 1983). Hence design as a process is seen to be
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responsive to unforeseen possibilities. The research presented in this paper takes a “reflective practice,” material-centric approach to design.

2.3 Material – Centric Design

To adopt the methods of a craftsman in the process of designing the artificial reef, it was important to choose the right material and machines to work with. As much as it was essential for the material to closely match the properties of the coral reef material it also needed to be workable and easily manipulated. Clay was chosen as the material for this project as it seems to be appropriate for both requirements. Clay is often deposited underwater (Alfred B Searle, 1912). When it is removed from a site and developed to be used as material it has useful and specific properties (Alfred Broadhead Searle, 1906; Alfred B Searle, 1912). Clay’s most unique property is that it can change state from a soft plastic material, to a hard material when water is drawn out by sun drying or firing. In its hardened state after firing it develops stone like qualities (Alfred B Searle, 1912). As water particles are evaporated they leave air pockets giving the clay a brittle, porous and rough texture (Alfred Broadhead Searle, 1906). These qualities are similar to the calcium carbonate reef material.

In processes of manufacturing the plastic clay, it was also critical to use machines and tools that reduce energy and material wastage. This research works with processes of extrusion. Traditionally these processes use tools that employ no additional casting materials to prop the clay, relying only on the material geometry to be self-supporting. Extrusion processes allow the unpredictable behaviour of the clay to be expressed and easily observed.

3. Method

As part of the ‘reflective conversation’ with the material, the artificial reef geometries designed in a computational model were transferred to the material realm by the use of two extrusion manufacturing machines; 1. a robotic arm with a syringe tube and 2. a traditional clay extruder.

Initially, a robot arm was used; its set up included a clay filled syringe tube as the end-effector. A motor attached to the syringe tube controlled the speed at which the clay was forced and deposited through a 4mm nozzle. The robot has two modes of operation; Manual and Automatic. In Manual, the operator has control over the robot movement. The switches on its controller allow the operator to start and stop the robot as well as increase or decrease its movement speed. In Automatic mode, the robot moves at a set speed. To control the robot movement in an interactive manner the experiments were explored in Manual mode to additively layer clay. Another machine used, was a hand-powered extruder. This machine has a hand held lever that forces clay downwards through a steel barrel with a laser cut stencil attached at its base. The greater the force exerted on the lever the faster the clay was pushed through the stencil. The extruder was used to produce direct clay extrusions.

Over the last decade researchers have focused on exploring the potential of additive clay deposition in manufacturing large structures ("ELstudio," 2016; "Fab Clay," 2012; Friedman, Kim, & Mesa, 2014; Mostafavi & Bier, 2016). Their research aimed to develop a system in which the observed behaviour of clay was integrated as part of the digital design process to create components for screened vertical or arched structures. Similarly, this research examined in this paper attempted to harness the behaviour of clay to develop form; the experiments presented here however, developed a module for an underwater dome structure. The potential of clay was explored by both robotic additive extrusion and the traditional process of direct extrusion. Similar to Fry’s craft worker both manufacturing methods were carried out in an intuitive way. The machines involved were used in
manifold mode to allow an investigation of the clay behavior, probing its capabilities and limits of workability (Ganiatsas, 2013; Mostafavi & Bier, 2016), leading to discoveries that guided the decisions in creating the artificial reef.

4. Results

4.1 Manufacturing method 1: Generating conical modules through additive-layered extrusion

The first design experiments developed a conical module through robotic additive layering. The conical form has 150mm high by 100mm wide dimensions with a hexagon base that lofts to a 9-sided upper form. A script developed in a computational model provided the numerical information for the robot movement to follow the lofted form through a series of 2mm contours as it deposited clay. The design intent of the module was to provide sheltering spaces for marine organisms through its hollow centre while its side walls were designed to topologically interlock into a dome and additionally provide miniature scaled spaces for smaller organisms by the formation of a high relief texture. To discover the types of surface textures that could be generated by the layering process it was important to develop an understanding of the clay material behavior in relation to the manual control of deposition speed from the syringe and the robot arm movement speed. Two types of layering were explored.

One series of layering studied how clay reacted when the syringe deposition speed was maintained at a moderate constant speed while the robot speed was varied within different segments of the module (Figure 3). In these explorations it was observed that the first hexagonal clay layers needed to be deposited on the work surface with slow robot movements. This allowed the clay to thicken and stick to the base material. The subsequent layers were thinner and more precisely deposited with faster robot movements. By the middle zone of the module, the robot movement was controlled to slow down and stop at certain steps. When this occurred it was discovered that the clay began to thicken as it was being pushed through the syringe nozzle creating a dense swelling of clay strands extending beyond the conical walls and altering the envisaged module geometry in an unpredictable way. By manually controlling the robot speed, continuous layers could still be looped over the uneven deposition to complete the top segment of the module as designed.

Other layering explorations studied how clay reacted when the robot was controlled to run at a constant speed, while the syringe deposition speed was controlled to slow down, stop and start on alternating layers (Figure 4). At certain sections of the module two clay layers were guided by the robot and deposited by the syringe nozzle as a full loop whereas on the third layer the clay deposition speed was varied. This process produced a broken layer. At this stage, it was discovered that to be able to create a level surface for the next layers to sit on top, the robot speed needed to be varied over the broken layer. The robot speed was manually controlled to go faster over the lumps of clay and slower over the missing portions of the layer. This type of deposition pattern did not completely fill in the gaps of the broken layer, instead the clay mixture created an unexpected texture of alternating miniature voids and bumps.

This process demonstrated that material reactions within a specific environment are unpredictable (Mostafavi & Bier, 2016). The clay layering created a varying horizontal texture that couldn’t be predicted or identically replicated in other modules (Friedman et al., 2014; Mostafavi & Bier, 2016). This confirmed Schön’s contention that the design process is not one in which the ‘mental image’ of the designer is simply given in physical form. The designer has to make instant micro decisions and
reflections in their actions to guide the material into form (Schön, 1983). The unpredictability of the clay mixture was embraced and the robot arm movement speed as well as the syringe deposition speed were kept in-tune with the designers observations in the layering process.

Figure 3 and 4. Additively layered experimental conical modules.
4.2 Manufacturing method 2: Generating clay tubular modules through direct extrusion

The second set of design experiments developed tubular modules using a manufacturing method of direct extrusion. This method used a hand-powered extruder with a laser cut stencil developed to include a hexagonal shape as the perimeter edge and an internal pattern that consisted of twelve radiating ridges reminiscent of the micro corallite septa plates. As the clay was forced through the 2D stencil, 70mm diameter hexagonal tubular components were generated with vertical radiating compartment spaces of 7mm by 10mm that opened to a central void space of 30mm in diameter (Figure 6). The sides of the modules were digitally designed to tessellate into a dome while their internal compartment and void patterns were developed for both fixing points as well as for miniature marine organisms to settle and grow into.

The first few extrusions were wire cut laterally at 55 to 80mm in length these were fairly vertical with minor curvature (Figure 10). The extrusions to follow were cut at 110mm to 170mm in length, these had geometries that curved and tilted. As a consequence of the plasticity of the clay, it appeared that the longer the extrusion, the more the clay bent in unpredictable directions.

Figure 5. Digital conical module with 2mm contours.
Figure 6. Assembly of extruded tubular modules.

Figure 7. Extruded tubular modules.
4.3 Material feedback from manufacturing methods 1 & 2

The two manufacturing methods explored offer different benefits and possibilities. The advantage of layered extrusion is the ability to develop tapering form. As was shown in recent experimental research (Friedman et al., 2014; Mostafavi & Bier, 2016) this type of extrusion follows the geometric complexities of a digital model whilst also enabling the clay material to express its behaviour. Layered extrusion was studied in this paper to understand how conical form could be created in clay. It was observed that the clay could generate a changing horizontal texture within the module walls. Extruding clay through a stencil, on the other hand produced a module with walls that expressed vertical texture. The clay took on unidirectional tubular form as it was forced through the stencil. Investigations in brick screen construction demonstrates that direct extrusion can produce highly orate vertical detail depending on the design of the extruder stencil (Celento & Harrow, 2008).

The material feedback from both methods was reflected upon continually during the process, resulting in an on-going re-imaging of how the behaviour of the clay could be incorporated into the design. The observed material reactions guided the design process, transforming the originally envisaged vaulted dome design. For example in method 1 (layered extrusion), the formation of the unpredictable horizontal textures caused by the clay mixture was seen as an opportunity to create a surface grain similar to the natural reef surfaces offering miniature marine organisms places to find shelter. The thickening of the clay strands added to the undulating geometry of the module creating further recessive spaces, while the broken layered texturing generated a module with miniature perforations and interesting horizontal indentations within its surfaces. When these conical modules are assembled they will add to the sinuous randomness of the ornamental dome surface; giving the dome a more natural character than originally envisaged.

*Figure 8. Dome structure with conical modules envisaged to be generated by clay additive layering.*
In method 2 (direct extrusion), it was recognised that the clay tubular modules were prone to bending, depending upon extrusion length. These modules were initially conceived to be of similar lengths however it became apparent that the clay bending behaviour could be utilised to become part of the function of the dome. The longer modules could be incorporated to curl over the shorter modules to form other sheltering geometrical spaces. This morphed the dome design to contain an uneven, undulating and branching surface for larger marine organisms to swim between. The clay bending behaviour from the initial prototyping i.e. the height, bending arc length and bending radius of each module, was documented and incorporated back into the computational model to predict possible outcomes for the form of the overall dome design. By varying the height and bending radius of the modules in the computational model possible locations could be determined for the shorter and the longer modules to create specific spaces for different marine species.
Figure 10. Extrusions wire cut laterally at varying heights

Figure 11. Computational model with varying module heights and bending radii
The explorations recognised that a final manufactured clay module could not be totally anticipated as a ‘mental image’. In each manufacturing process the clay reactions revealed different design possibilities for a module. Looking for possibilities in unexpected outcomes is at the heart of all iterative design.

5. Reflections and Conclusion

This paper outlined a material-centric design process to develop modules for a vaulted dome artificial reef. The design process began by studying the existing microscopic and macroscopic calcium carbonate structures of the *Oulophyllia bennettae*, learning from the way its coral polyps secrete material to develop architecture. The research sought to understand if this morphological information could be translated from the calcium carbonate to the clay material. To explore this concept two types of clay manufacturing processes were used to shape modules in equivalence to the ways the coral polyp organism itself builds its tubular and conical exoskeleton; layered extrusion and direct extrusion.
The next phase of the design was informed by material behaviour. With developed knowledge of the *Oulophyllia bennettae* structures specific forms were envisaged to be created in clay. As the abstracted corallite forms were translated into clay it was discovered that clay behaved in unpredictable ways. Both clay-manufacturing processes provided material feedback that offered unforeseen design potentials for the artificial reef. The overall dome design was informed and transformed by the material behaviour occurring at the module scale. Once sited underwater and interacting with the marine environment the dome form will continue to transform in an open-ended form generation process.

*Figure 13. Underside of vaulted dome structures showing possible steel substructure.*

*Figure 14. Top view of vaulted dome structure showing possible steel substructure.*
Designing a structural dome for an underwater environment is different to designing a dome for an above-water site. Underwater conditions are unpredictable with continuously changing loads and stresses due to changing wave conditions. Future development of the design includes investigating a fine skeletal steel substructure with radiating projections into which each clay module can be secured in. The modules will tessellate and topologically interlock. It is envisaged that over time marine organic matter will build up on each of the clay surfaces binding the modules together like mortar binds brick modules. If the clay dome becomes stable and functional as seen in other artificial reefs more marine organisms will be lured to the clay structure (Barber & Barber, 1996; EcoReefs, 2012; Foundation, 2015; Goreau & Hilbertz, 2005). These organisms will continue to expand, add their own protective layers of material, ultimately occupying the entire dome and continually reshaping it. This paper has presented a material-centric (R. Oxman, 2012), nature inspired design approach which uncovers the prospect of initiating the growth of a living ecosystem.

This approach aims to play an important role to facilitate the regeneration of coral reefs. The creation of these modular artificial reef structures, seek to address crucial environmental questions, in sustainability for the survival of the Great Barrier Reef. The recovery of the coral reefs is highly significant, 25 per cent of all biodiversity inhabit these complex forms. The design of artificial reefs addresses a fundamental role in environmental sustainability in the Great Barrier Reef.

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