SENTIENCE

3D printed living products

TAHI REWIRI-CHRASTECKY
ADAPT. INTERACT. EVOLVE.
Sentience: 3D printed living products

by

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FOREWARD

I’d like to give thanks to my supervisor **Ross Stevens**. His contribution and insight within the realms of future design has guided my master’s research as well as provided some fantastically bizarre conversations.

I’d like to thank **Bernard Guy, Tim Miller, Edgar Rodriguez, Simon Fraser** and **Jeongbin Ok** for providing progressive critiques of my experiments throughout the research period.

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I’d like to thank my fellow master’s students for providing me with feedback, assistance, suggestions and design inspiration.

And finally I’d like to thank **Emily Gilmore** for supporting my studies and editing my thesis.
ABSTRACT

This thesis is a research through design based investigation that explores the possibility of creating three dimensional (3D) products that are tactiley responsive, in an attempt to discover whether 3D printing technologies can be utilized to generate contemporary products that adapt, evolve and develop features synonymous with living organisms.

It looks at the possibility of sentient, 3D printed products and explores the potential that these objects have to interact with both the user and their surrounding environment. It also looks into the possibilities for 3D printed processes to allow for materials to better reflect the sensory and information processing capabilities of digital interface technologies. By placing a series of iterative design experiments within a contextual background this thesis not only explores what is currently possible, but theorizes about what could be possible in the future, when current technological and material limitations have been surpassed.

Essentially, this thesis focuses on answering one underlying question: can 3D printing be utilized to create a product that appears to be alive.
Sen-tience

n.

1. The quality or state or quality of being sentient; awareness
2. Sense perception not involving intelligence or mental perception; feeling
INTRODUCTION
MOTIVATION

This thesis is a research through design exploration that examines the theoretical potential to create sentient products that feature tactile abilities. My personal interests are directed towards the capabilities and development of 3D printing technology, in particular the potential for this technology to be applied to digitally fabricated products in the future.

Designing products within a future context can be difficult due to unpredictable technological and social changes. One thing designers may rely on however is the gradual improvement of technology as a whole. With this in mind I have set focus on the exploration of future products through an iterative, aesthetic and hypothetical process. To do so, I have utilized physical experimentation to test material qualities and visual media to convey unattained potentials to a wider audience. This allows me to avoid concerning myself with the technical limitations of current technology, instead focusing on the potential for products and processes that have yet to be realized through a visual narrative.

3D printing technology is developing rapidly and the prospect of 3D printed products potentially developing sentient features is compelling. Living products could generate new ways of understanding product interaction and functionality. By utilizing 3D modeling software, I aim to create intriguing designed forms that can generate critical discussion about the future of digital technology.
AIM OF STUDY

The intention of the work described in this thesis was to investigate the future potential for 3D printed contemporary products to adapt, evolve and develop life-like qualities.

The aim was to use a process of iterative compositional experimentation to develop a range of surfaces with characteristics associated with sentience.

This research was primarily focused on generating dynamic products with a responsive skin that better reflects the evolving capabilities of digital sensory and information processing technologies. This study, which was conducted using research through design methods, attempts to address its aim through an iterative series of 3D printed experiments.

The ultimate goal for this research was to develop and design a range of experiments with a visual narrative that conveyed its potential clearly and concisely. This research conclusively aimed to ignite interest in the future of 3D printed living products.

Figure 1:
Experiment Model 1 inflation testing.
This thesis, alongside compositional design elements, aims to provide an interpretation of 3D printed products that feature qualities synonymous with sentient life forms. Whereas digital software technology is evolving rapidly, physical hardware is often limited in form due to the restrictions imposed on it by the materials it is comprised of. Visual lighting displays, such as the LED screen, for instance, have evolved and are becoming increasingly precise over time, whereas the physical case that first encapsulated the screen still features most of the same tactile capabilities as the contemporary television, computer or smart phone. This thesis recognises that the consistent development of software technology is allowing for digital power and interfaces to constantly improve and, in some instances, even take on sentient qualities. Through research that utilises multi-material 3D printing technologies, this thesis aims to discover what opportunities exist for the physical form of the product to evolve on a similar scale.

The all-encompassing scope of this research aims to establish the potential for living products as a whole. The experiments conducted within this thesis are presented as surfaces with the intent of contextualising each surface as an exterior to any physical product. By primarily utilising surfaces as a platform for creation, the design of each experiment could be treated like the fabric or skin of an existing product type with the potential for numerous applications.

This thesis focuses on the possibility of living products. It seemed logical, therefore, that the initial design experiments took inspiration from living organisms. For example, when designing skin-like surfaces, it made sense to use the features of living sea creatures as a starting point, such as the scales of a fish or the contracting and expanding nature of a puffer fish. While I considered it necessary to reference living organisms during the initial experiment phase, it was also important that this research led to the development of a unique visual aesthetic. This transformation of aesthetic qualities, from the natural to the refined, evolved through a process of iterative development.

The capabilities of the most intriguing experiments were displayed using narrative methods through visual media. The media was then presented to a range of designers at Victoria University of Wellington in order to receive critical feedback and suggestions as to how these experiments could be refined. Once the experiments reached a satisfactory state of refinement it was possible to begin the development of a final design.
The final design for this thesis is a conceptually realised, living product. This product needed to be recognisable and able to visually convey qualities alluding to its sentient abilities. The popularity, compactness, portability and technological adaptability of the smart phone made it an interesting vessel to explore for a refined surface experiment. There were also opportunities to touch on the potential of a smart phone’s relationship between the digital screen interface and its physical tactile form. The product’s skin sought to better reflect the internal electronics sensing and information processing capacity. Following this, visual media was created for the final design in order to give the audience a quick and concise understanding of this research.

Once the final design criteria had been met, an analysis of the living product and its relation to the greater body of knowledge within this thesis was conducted. Finally, this thesis rests on a discussion about the prospects of living products in the future. In this discussion, literature and contextual research was utilised to hypothesize potential developments for 3D printed living products.

Figure 2: A 3D print during the support material cleaning process.
THESES STRUCTURE

The main body of information for this thesis is contained within Parts One and Two. Part One presents an introduction to Digital and Sensory Technologies, The Living and Sentience, 3D Printing, and Functionality versus Emotional Response, all of which are focal elements within this thesis.

The literary research is integrated within these four sub-topics and provides insight towards the progression of 3D printed living products. Contextual analytical data acts as both a precedent for experimentation and provides the research with a contextual relevance.

Part Two presents the design methodology, compositional design experiments and final design. It lists the specific details of each design experiment, noting their significance and relevance to the greater body of knowledge. Following the completion of compositional elements, an overall summary and conclusion to this research is conducted. Lastly, a post-conclusion discussion theorising potential outcomes for the future of 3D printed living products is presented.
Figure 3: Acrylic reflections from Experiment Model 2.
BACKGROUND ANALYSIS
DIGITAL AND SENSORY TECHNOLOGIES

In the contemporary world, digital technologies are abundant and have become fundamental components of many of the ordinary rituals that make up everyday life. Society has an increasing reliance on objects that utilise digital power and, due to ever-increasing technological developments, these devices are consistently changing and improving over time.

Developments in hardware have allowed for digital display technology to change drastically over the last three decades. It is remarkable to think that the contemporary Light Emitting Diode (LED) screens were recently preceded by Cathode Ray Tube (CRT) Monitors around the early 2000’s, in fact, many people still use CRT Monitors today (Babyak, 2000, Pg. 48). Visual display technologies such as Apple’s Retina Display screen technology feature a pixel density so high that the human eye is unable to discern individual pixels. (Apple, 2014).

Technology today has enabled products to detect anomalies such as heat, light, sound, motion and identity. Products such as Apple’s iPhone 5s contain sensors that make it capable of interactive functionality with both people and the physical environment. For example, sensory technology embedded in the iPhone 5s allows the owner to unlock their phone, not just with a passcode, but by pressing their thumb against the screen. The phone is able to detect the identity of the user; if the thumb print does not match the one registered by the owner when they purchased the phone, they are denied access to the device. (Apple, 2014).

Sensory technology is also allowing smart phones to detect identity through geographical ‘finger printing’ technology. Roy Choudhury is part of a team developing SurroundSense, a cell phone GPS technology so accurate that it ‘may soon be able to know not only that you are at the mall, but whether you are in the jewellery store, or the shoe store.’ (Anonymous, 2009, Pg. 14). SurroundSense works through the use of image mapping, made possible by innovations in cell phone camera technology. Choudhury also notes that the more a person uses the application, the ‘smarter’ it gets. Essentially, as the system processes information about a particular location its ‘fingerprint’ becomes more distinctive. (Anonymous, 2009, Pg. 14).

The ability of sensory technology to contextualise information from the physical world makes it a powerful tool that could be utilised within the exploration of products that feature sentient abilities. If a products skin could develop tactile features capable of physically responding to digital sensory feedback, it would be interesting to see how people might interact with these products, how these products may adapt, and ultimately how these products may potentially evolve over time.
Figures 4, 5, 6, and 7: The components for iPhone 5s fingerprinting technology. The software for this technology activates a visual interface that determines if a user's fingerprint matches the phone's owner.
THE LIVING AND SENTIENCE

The physicality of living things is determined by many uncontrolled factors. Living things grow, evolve and develop features to adapt to changes both outside and within. Not all life is conscious, with the ability to think, but all living things can feel. Sentience is simply the ability to feel and experience physical sensation. Sentient things are intuitive, intelligent in their own way, and have an ability to utilise their surrounding environments to enhance the quality and continuity of their lives.

Digital software can be programmed to register sensory data, contextualise it, and utilise this information to change itself accordingly. This has allowed current technology to be capable of artificially mimicking features of sentient life already. Some digital software advances are being pushed further than mimicry. **WormSim**, for example, is a project developed by team Open Worm which explores the digital recreation of sentient organisms, aiming to digitally simulate a living worm with complete biological features, down to the level of each individual cell. (Jabyr, 2012).

The creation of sentient features within physical materials is also being explored within the scientific field. Synthetic biologists are currently attempting to create ‘living materials’ that may eventually be useful in the development of everyday products. Timothy Lu of Massachusetts Institute of Technology is part of a team of researchers that have reprogrammed the genetic data of bacteria to create living materials. According to Lu, the idea ‘is to put the living and nonliving worlds together to make hybrid materials that have living cells in them and are functional’ (Service, 2014, Pg. 1421).

This synthetic biology may eventually be utilised to explore living products. In **Artificial Evolution: A Hands-Off Approach for Architects**, Rachel Armstrong states that recent discoveries at the molecular level suggest that it is possible to transgress the conventions of biological design, raising the possibility of manufactured living forms. (Armstrong, 2008, Pg. 78). With imminent developments in both technology and biological sciences, there is a potential opportunity to develop sentient products through the marriage of digital power and living materials.
Figure 8: A 3D visualisation of the simulated worms muscle and internal systems.

Figure 9: A 3D visualisation of the simulated worms nerve systems.
Three Dimensional printing is an additive manufacturing process used to generate physical models from computer aided design (CAD) systems. 3D printers can make these models from an expanding list of materials that include resins, plastics, polymers, metals, powders, rubbers, glasses, ceramics and more. 3D printing technology also has the ability to quickly generate objects once only achievable through expensive mass-manufacturing processes. This makes it an exceptional tool for the creation of unique, one off items.

Currently, commercially available 3D printing materials still require development to reach the quality of their simulated natural counterparts. However, the abilities of these materials are consistently evolving over time. Researchers from Warwick University for example, have developed a printable conductive plastic composite that can be used to produce electronic devices. The material is named *Carbomorph* and allows engineers to 3D print electronic tracks with touch-sensitive areas that can be connected to an electronic circuit board. This research has led to the development of technologies such as touch-sensitive buttons for video game controllers and a mug that can tell how much coffee it contains. According to researchers, the next step is to develop printing materials that can make more complex electrical components, such as wires and cables that are required to connect the devices to computers. (Zolfagharifard, 2013).

Advancements in synthetic biology and stem cell technology suggest that it may eventually be possible to 3D ‘bio-print’ materials with living tissue. Bioprinting technology is primarily being explored for the purpose of human organ fabrication. Researchers aim to 3D print usable organs with complex physiological functionalities such as hearts, pancreases and kidneys. (Ozbolat, 2013, Pg. 2220). Bioprinting would lead to greater potential for the development of living products. Living tissues, such as muscle, feature a diverse range of physical and mechanical properties that simply cannot be imitated by contemporary electronic components.

The potential for envisaging the future of 3D printing living products may lie within the emergent multi-material printer technology, which can build several varying material parts within one model. The value of multi-material printing is in its ability to allow for the creation of 3D prints with varying physical qualities that could not be achieved in one material alone. Living things feature an abundance of diverse physical attributes. Living things can be simultaneously elastic, rubbery, stabilised, hard and fragile all within a very compact amount of space, which makes the capabilities of multi-material 3D printers very useful for the experimentation stages of this research. The development of this technology is still at a very adolescent stage; however, its growing presence is being praised as the next industrial revolution, set to change entirely how things are made and how designers manufacture their products. (Jones, 2013, Pg. 68).
Figure 12: Dr Simon Leigh showing a 3D-printed game controller with Carbomorph touch-sensitive buttons.
From a technological perspective, the prospect of working, 3D printed living products is already attainable within certain confines. Materials can be manipulated to mimic sentient features using electronic microcontrollers such as Arduino. Responsive design projects such as Mark Goulthorpe’s Hyposurface and Philip Beesley’s Hylozoic Ground (further discussed within the Contextual Analysis chapter), although not 3D printed, already exemplify sentient-like features within designed objects. Contemporary responsive design experiments such as these are beginning to fulfil predictions that humans will eventually interact with technology in a mutually constructive way. Perhaps even more exciting is the realisation that as technology becomes smaller, it can easily be embedded into our buildings and objects so that they adapt to our needs, something Susan Walker touches on in the article It’s Alive (Walker, 2013, Pg. 81).

However, one obstacle that responsive design experiments will eventually need to address is the physical limitations of the technology driving them. If a product is to be physically responsive, it needs to contain elements that drive this physicality. Electronic parts such as motors, servos, circuit boards and Arduino all require a specific volume of allocated space within the designed object. Even with the progressive miniaturization of technology, these parts are energy taxing and experiments featuring several parts may require a permanent power supply which either increases the size of the designed object, or makes it immobile. These issues can be dismissed if the responsive design experiment is architectural or a permanent fixture installation, however smaller objects, such as portable digital devices, face certain technological restrictions.

This research aligns itself with the works of Mark Goulthorpe and Phillip Beesley but focuses on the exploration of sentient surfaces that can be applied to any product or construct. Essentially, this means that the design of these surfaces need to be scalable, portable and functionally self sufficient. The significance of portability within this context raises an important question:

**Will these design experiments convey their intentions through emotional response (Narrative) at the expense of conditional functionality?**

In *Sentient Design*, Louise Russell states that:

> Opening ourselves to understanding design beyond statistical analysis and technical specifications is paramount to reaching a higher ground of sentient design. Understanding principles of subtle energy within objects can allow us to create furniture, lighting and products that wed interconnectedness and metaphysical interaction... (Russell, 2011, Pg. 24).

Similarly, this thesis is primarily an investigation into the possibilities for design products that transcend contemporary technological restrictions. Consequently, the development of narrative potential within these experiments is more important than limited functionality. Animation and video manipulation techniques can be utilised to convey subtlety, fluidity, sensitivity and responsiveness that would be otherwise difficult to capture with an Arduino based portable 3D print.
Figure 16: Hyposurface.

Figure 17: Hylozoic Ground.

Figure 18: MorphoLuminescence (Also Discussed in Contextual Analysis).
CONTEXTUAL ANALYSIS
Developed by *Inconvenient Studio*, *MorphoLuminescence* (2009) is an interactive fashion photography installation that is used to enhance the experience of trying on clothing in a fitting room environment. *MorphoLuminescence* is comprised from an array of laser-cut petals, stems, and hinges that adapt their form in order to accommodate changes in space. The installation physically amplifies the fitting room experience by expanding and contracting when a user bends over or reaches up for clothing. In its final state, each panel of its surface lights up in order to provide efficient, optimized lighting for the individual. (Says, 2010).

*MorphoLuminescence* intuitively demonstrates physically purposeful movements that elevate an otherwise unremarkable daily routine. It serves as a convincing statement for future reactive design experiences.
Developed by Achim Menges in collaboration with his colleagues Steffen Reichert and Oliver David Krieg, Hygroscope (2012) is an installation project that absorbs moisture from its environment to animate and transform itself. Hygroscope is a biomimetic meteorosensitive pavilion that utilises the intrinsic physical characteristics of wood and its one-directional nature to create a mechanism that requires no energy or mechanical features to run. Paper thin triangular wooden sheets absorb air moisture and expand. As these flaps expand, the one-directional grain forces these sheets to unfold themselves, meeting at a center point and closing like an aperture. (Hudson, 2014.)

Hygroscope looks into ways that architecture can explore living structures capable of responding to environmental changes without the requirements of energy. The physical movements of this project suggest a degree of sentience comparable to nyctinastic plant life, altering its form to maximize environmental potential.
Created by Theo Jansen, Strandbeest (1990-present) is a collection of large, wind-powered, walking constructs. The Strandbeest’s are made from simple materials such as cardboard and electrical tubing and move through a process Jansen calls ‘mechanics based on evolution’. Jansen believes that his creations’ ability to walk gives them qualities akin to sentient beings. (Woods, 2005, Pg. 98). In the future, Jansen expects his creations to become more anatomically sophisticated, developing muscles, a nervous system and a brain that will allow them to make intelligent decisions. (Woods, 2005, Pg. 98).

Strandbeest is essentially a clever feat of mechanical engineering. It achieves sentient features through narrative methods (animated by air). As technology develops over time there is greater feasibility that these constructs may develop genuine autonomy.
ONE HUNDRED AND EIGHT

Nils Völker’s One Hundred and Eight (2010) is an installation made from rubbish bags that selectively inflate and deflate in controlled rhythms, creating wave like animations across a wall space using Arduino controlled cooling fans. (Caula, 2013) The sequences create impressions of lively movements reminiscent of patterns seen in sentient forms such as coral structures or shimmering bee swarm formations.

This installation gives life and energy to an otherwise senseless material. At its core, One Hundred and Eight is a celebration of growth and movement, both of which are essential attributes within sentient entities.
Figures 28, 29, 30, 31: One Hundred and Eight.
Developed by Richard Clarkson, Blossom (2013) is the world’s first known inflatable 3D printed object. Blossom is an interactive, multi-material 3D printed flower that utilises pneumatics to bloom like a real living flower. The rigid structures of this model are made from Fullcure 720, a hard plastic-like material, while the inflatable structures are made from Tango Black, a flexible rubber-like material. The outer areas of each petal contain less resin than parts towards the stem, allowing them to maintain their natural shape as they expand (Palladino, 2014). Richard Clarkson states that multi-material printing offers an opportunity to generate complex forms and dynamic structures that are impossible to make by any other means (Clarkson, 2014), an opinion shared by Will Jones, who believes this technology will spark the next industrial revolution for product fabrication (Jones, 2013, Pg. 68).

The Blossom project utilized narrative methods through videography to present itself as sentient and autonomous. The video media within this project was an essential tool for conveying unattained potential to wider audiences.
Figures 32, 33 and 34: Blossom.
HYPOSURFACE

Developed by Mark Goulthorpe in collaboration with dECOI Architects, Hyposurface (2006) is a kinetic display surface that utilises computer controlled pneumatic pistons to animate interlocking flexible panels. Hyposurface fluidly creates three dimensional patterns, waves, images and text by moving these flexible panels in sync. (Ackerman, 2007). The installation also reacts to movement, sound and lighting from its surrounding environments.

Hyposurface effectively links digital information systems with a physical form to create dynamic, variable, tactile surfaces. Its ability to respond to variables within its environment likens it to sentient entities.
Figures 35, 36 and 37: Hypgosurface.
SILK PAVILION

Created by the Mediated Matter Research Group at the Massachusetts Institute of Technology Media lab, Silk Pavilion (2013) is a construct that explores a relationship between digital and biological fabrication methods. The primary structure was made from 26 polygonal panels made of silk threads that had been applied utilising a CNC (Computer-Numerically Controlled) machine. 6,500 silk worms were then introduced to the pavilion, spinning non-woven silk patches to reinforce various intentional gaps within the construct. The Mediated Matter Research Group employ the silkworm as a biological ‘printer’, tasked with the creation of a secondary structure within the construct. (Visnjic, 2013).

Silk Pavilion evokes possibilities for biologically adaptable fabrications, capable of self analysis and evolution.
Figures 38 and 39: Silk Pavilion
HYLOZOIC GROUND

Phillip Beesley’s Hylozoic Ground (2010) installation is an intricate synthetic environment organised as a textile matrix, supporting responsive actions and living technologies. The organisation of this environment is conceived as the first stages of self-renewing functions that might take place within the future of architecture. The Hylozoic environment is essentially an ecological system undergoing an evolutionary process. Participants can observe the initial state of this environment and influence dynamic changes to its ecology through presence and interaction. (Beesley, 2011, Pg. 81). The atmosphere ripples, swallows, breathes and stirs. Digital software is utilised to provide sentient processes for an array of responsive living structures powered by mechanical and chemical components.

Hylozoic Ground essentially employs sentient biological systems to create complex growing architectures. It goes beyond the hypothesis of sentient structures by contemplating their ability to evolve and sustain themselves.
PART TWO
METHODOLOGY

The greater majority of this thesis was carried out by research through design composition. This design methodology utilizes a systematic procedure for arriving at a design solution through “diagnosis followed by prescription”. The research activity related to design is exploratory, and is both a way of inquiring and a way of producing new knowledge. In this approach, the emphasis is on the research objective of creating design knowledge, not the final solution. (Frankel, Racine, 2010).

The theoretical context surrounding 3D printing technology and living design was explored and developed in this thesis through qualitative literary research. The contextual analytical research acts as a technical connection to the design experiments and is reflected upon throughout the Design, Conclusion and Future discussions.

Solidworks, a CAD modeling software program, was utilized to develop all of the experiments. The experiments were designed in Solidworks and sent to a 3D printer to be physically prototyped. Each experiment was presented to a range of designers at Victoria University of Wellington faculty of Architecture and Design. These designers offered feedback and suggestions about ways these experiments could be further developed and improved.

Due to current 3D printing limitations, the design experiments were intentionally confined to a linear and iterative process. 3D printing material costs increase exponentially as a model’s build mass increases, which means design needs to be at the millimetre scale in order to be cost-effective. The technical precision required to produce functional experiments at this scale also imposes certain guidelines that must be followed in order to maximise their effectiveness. For example, every edge of each experiment produced during this initial stage required filleting in Solidworks to reduce the possibility of tearing during the testing stage. By nature, experiments feature imperfections that need to be smoothed out through the process of design and, for this reason alone, it became evident that it would be more economical to focus on the development and redevelopment of existing experiments.

The objective for the initial design experiments was to develop a visual aesthetic for sentient capable 3D printed surfaces. During this initial experimentation phase, the primary focus was to develop inflatable models capable of altering their physical form through pneumatics. The majority of these initial design experiments were 3D printed in Tango Clear, a resin based rubber-like material. Gradually, the 3D prints increased in complexity as experiments opted to utilize the multi-material properties of the Objet500 3D printer. The introduction of multi-material properties sought to add a variation of physical qualities into the experiments that could not be achieved by the Tango material alone. Vero White, a white ridged plastic-like material, was eventually introduced to the model experiments.
The *Vero White* material opened up a new range of physical qualities within these experiments and allowed for the creation of surfaces that mimic collagen structures such as hair follicles, fingernails and fish scales. Through the initial experimentation process it became evident that the most interesting and visually appealing animated models were ones inspired by fish scales. Eventually, internal inflation features were removed from the experiments and directive animation techniques were utilized through pressurized air gun tools. This change of animation technique allowed for subsequent models to become smaller, more refined and cheaper to produce. Overall, the development of these initial experiments provided a tacit knowledge base that could be utilized to create refined visual representations of living products.

This research aims to expand knowledge within the area of 3D printing materials. As such, the documentation process for this thesis was detailed technically in order to allow for experiments to be retested by a 3rd party.

The objective for the final design output was to develop an object that merged elements of the most refined experiments with a relatively well known product. Through group discussion, the potential for developing a smart phone based object became apparent. The *iPhone 5s*’s sensory capabilities made it an interesting vessel to explore through a sentient design perspective. This led to the conception of a multi-material *3D printed ‘living’ iPhone case*.

Following the creation of this object, video media was created to communicate the potential for designed products to be capable of sentience. Narrative media was the primary design platform used during this thesis as it best displayed the dynamic visual qualities of the 3D printed experiments.
Figure 43: Experiment Model 17 pre support material removal.

Figure 44: Experiment Model 4, made completely from Tango Clear Material.

Figure 45: Experiment Model 5. The first attempt at Multi-Material printing. Hair-like structures are printed in Vero White.
Figure 46: Experiment Model 16 with thin layers of Vero White.

Figure 47: Experiment Model 10 with thicker layers of Vero White.

Figure 48: Experiment Model 17. A glimpse at the air gun animation process.
Experiment Model I

The intent of this first experiment was to create something that could be perceived to be capable of adaptation and evolution. The goal was to create an object that could alter its physical form in a controllable fashion. The design of this model is inspired by Nils Völker’s *One Hundred and Eight* installation; it features a Tango Clear inflatable rubber-like honeycomb surface that contained a trio of hexagonal segmented chambers. Each hexagonal segment is hollow inside with a thin, slightly concave top layer supported by thicker surrounding walls, which allows the air pressure to naturally expand the segment outwards.

Each segmented chamber has an intersecting air channel. The three air channels all converge along a singular hexagonal control segment that contains a pipe mouthpiece attachment that is used to blow air into the model. The hexagonal chambers can be inflated independently of each other by utilising ‘choke’ buttons on the control segment. The choke buttons are simple sections where a thick padding of material can be pressed by hand to close off a chamber. Combinations of choke button presses may be used to achieve an array of inflation variations.

An issue that presented itself during this experiment was the limitations of 3D printing hollow objects on the Objet500 Multi-material 3D printer. Most 3D printed objects require support material to fill spaces in between model parts. Usually if a 3D model is designed to be hollow on the inside, the support material cannot be cleared without some form of pre-planning at the digital modelling stage. This problem was countered by modelling the object with hollow segments underneath. Each segment had an inner lip to hold thin lids laser cut from 1mm thick acrylic sheets. Thankfully, the cleaning of this particular model was taken care of by Stratasys-Objet using specialised tools. Once the insides of each segment had been cleared the lids were inserted to seal the segments and make them air-tight.

Experiment Model 1 inflated well and showed an ability to be adaptable. It was designed as a honeycomb structure so that it had the potential to be modular. Part of the vision for the first experiment was to have a dynamic inflatable surface that could be used for various applications such as furniture and interior architecture.
Figure 53: Experiment Model 1 Hex Inflation.

Figure 54: The bottom profile of Experiment Model 1.

Figure 55: The Hex controller for Experiment Model 1.

Figure 56: Use of Hex controller to inflate segments.

Figure 57: Experiment Model 1 with inflation tube.

Figure 58: Inflation process.

Figure 59: Inflated model.
Experiment Model 2
The goal for this model was to create a smaller variation of Experiment 1. As such, it retains characteristics of Nils Volker’s *One Hundred and Eight* installation. The model’s design features a modular inflatable Tango Clear surface comprising of circular segments. The concave top layers for this model were slightly thinner than Experiment 1 which increased its ability to inflate. Unlike Experiment 1, the chambers for this model do not converge at a singular segment. Experiment Model 2 contains six chambers that each connect to tubes hidden underneath.

The segments had a similar lip feature for holding lids as in Experiment 1. The lids for Model 2 were laser cut this time using thin sheets of acrylic, which was much cheaper and easier to clean than 3D printing processes. The support material for this model was cleaned by hand which slightly cracked and degraded the rubber, but in turn gave it interesting organic reptilian skin-like qualities. When air was blown or sucked from all the chambers simultaneously the walls around each segment would scrunch up, giving the model features comparable to the contraction of a muscle or tendon.

Experiment Model 2 was designed to hide the inflation method from viewers; this gave an illusionary effect that allowed the surface to be perceived as self sufficient, living and adaptable to a few types of interaction. Its animated features almost resemble the movements of simple plants or corals.
Figure 65: Reflections from the acrylic underside of Experiment Model 2.

Figure 66: The separated connecting air tubes allow for multiple varying inflation types.

Figure 65: Air tube connection points.

Figure 65: Model Handling during inflation process.
A.I.E Concept Video

The narrative methods used by Richard Clarkson’s *Blossom* project helped to inspire a conceptual video that illustrated my initial research concept. The intent for this video was to create a piece of visual media that communicated the potential for evolving products. The video features Experiment Models 1 and 2 and poses the following questions: *if our products adapted and evolved with us, what would they look like? What would we use them for? And how would we influence them?* The models were filmed to appear capable of living and reacting to human interaction. In a discussion following the critique of this video, the general response was that these inflatable experiments could potentially become artificial living surfaces for products and architectures.

Figures 69, 70, 71, and 72: A sequence of animated inflatable models moving and reacting to physical movement.
Experiment Model 3
The goal for this model was to create a significantly smaller inflatable Tango Clear model with only one lid space for the removal of support material. To prevent Experiment Model 3 from blowing up like a balloon, its internal structure is supported by tiny rows of pillars that surround the square lid lip. The pillars and thin air space allow for circular segments within the model to inflate in a rippling wave motion away from the direction of the air tube. Model 3 introduced an interesting range of motion for its size, but due to a lack of control options it features limited variability in its motions.

Figures 73, 74 and 75: Solidworks model of Experiment Model 3.

Figures 76, 77 and 78: Experiment Model 3 under varying levels of inflation.
Experiment Model 4

The intent for Experiment 4 was to completely remove the lid feature present in earlier Tango Clear iterations. To achieve this, the segment walls needed to be completely removed in order to make the clearing of support material possible. The excess material was crumbled up by pressing gently against the exterior of the model from both sides and flushed out of the air pipe hole with water and a thin plastic skewer. The quality of the Tango material in comparison to its natural rubber counterpart was more apparent in this experiment than early models. The rubber-like material split in several places and required touch ups with super glue. This was the first and only model to feature inflatable segments on both the top side and underneath. Experiment Model 4 inflates like an inelastic balloon and, like Model 3 before it, was too limited in its range of motions to be perceived as adaptable.
Figures 79 and 80: Solidworks model of Experiment Model 4.

Figures 81 and 82: Experiment Model 4 inflation.
Experiment Model 5

Following discussions around, and a group critique of, Models 1, 2, 3 and 4 it became apparent that the experiments could benefit from adopting more features that belong to sentient organisms. The intent for Experiment Model 5 was to play around with materials and textures to give a more fluid, porous and organic top surface. The surface structure was made from Tango Black, a black rubber-like material that features nearly identical features with Tango Clear. Thin hair-like structures were built into the deepest area of rubber pore segments. The hairs were printed in Vero White, typically a hard plastic-like material but, in this instance, they were thin enough to be very flexible. Unlike previous models, Experiment 5 is not inflated through an air tube. Instead, the base is supported by a laser cut piece of acrylic and the interior of each segment is openly exposed. The segments can then be inflated by a compressed air gun.

One of the goals for Experiment 5 was to use inflation to make the hair structures flair up like goose bumps when air is forced into the chambers below. Another goal was to create a concept video that showed a user interacting with this model whilst the inflation method remains hidden, in order to visually sell it as a living surface. Unfortunately, Model 5 ended up being too thin and resistant to successfully expand using an air gun. However, this model served as a valuable introduction to multi-material printing and the compressed air gun, both of which provide greater potential for visual illusions than the method used in Model 2.
Figure 83: The damaged pieces of Vero White hair structures belonging to Experiment Model 5.

Figures 84 and 85: Solidworks model perspective and cross section views of Experiment Model 5.
Experiment Model 6

The intent for this model was to address some of the shortcomings of Experiment 5. The main goal for Model 6 was to increase its width so that it could inflate properly. This model features an elongated semi-circular girth with three rows of segments running along its length. The middle segments for each row are larger than the outer segments on either side. Each segment has the same hair structures featured in Model 5.

Experiment Model 6 cleaned exceptionally well and most of the support material could be removed very easily. The hair structures, however, were printed slightly too thin and some of them broke off during the cleaning process. The model inflated successfully with an air gun and the hairs that remained intact flared up as intended.

The semi-circular girth of the Experiment Model 6 allowed it to billow out in different directions which created the perception that it shared the same qualities as expanding and contracting marine creatures such as pufferfish and jellyfish.
Figures 86 and 87: Solidworks model of Experiment Model 6.

Figures 88 and 89: Experiment Model 6 relaxed state.
Figures 90, 91, 92 and 93: The modified animation technique for Experiment Model 6. This method utilises a clamp and air gun.

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Experiment Model 7

Following reviews of Models 5 and 6, it became evident that printed hair structures wouldn’t be resilient enough at this stage to work successfully as an interesting interactive surface feature. Discussions led to the possibility of utilising other keratin based structures instead. The goal for Experiment Model 7 was to create an inflatable surface with a top layer loosely inspired by the scales of a fish. The intent for this model was to create a surface with the ability to have its form fluidly altered with an air gun. The model’s design features 36 segments arranged on a flat rectangular grid structure made from Tango Clear. Each segment contains a singular concave hollow, with a small nipple-like bump at its base. Above each segment are rubber connection points that join with the upper corners of a single scale piece. The scales were printed in Vero White and penetrate each rubber connection point. The base of this experiment is once again attached to a laser cut acrylic base.

The cleaning process for this model was fairly difficult as the scales had to be cleaned carefully without damaging their connections. At this stage it also became evident that the Tango rubber-like material used in the Objet500 Multi-material 3D printer is permeable and, if the model design is too porous, it will absorb water and expand if not dried thoroughly. Although early experiments had been cleaned with water this limitation had not been as apparent because Model 7 featured a greater concentration of porous areas than preceding models. Despite this issue, Experiment Model 7 performed very well. The air gun was successful in its ability to invisibly inflate segments in a controllable fashion. The bumps inside each segment effectively protruded upon inflation, prompting the scales to pivot from their respective connection points. The relatively small size of each connection point, combined with the flexibility of the rubber, allowed each scale to have a fairly yielding range of motion. The air gun allowed for fluttering, wave like animation qualities. The animation method used reflects projects such as Theo Jansen’s Strandbeest or Nils Volker’s One Hundred and Eight. The narrative dynamics achieved reflect projects such as Mark Goulthorpe’s Hyposurface.

Visually, Experiment Model 7 showed early signs of potential for living objects and architectures. It was decided, in a following critique of this experiment, that the continuation of experiments would be based on this model.
Figures 94, 95, 96 and 97: Solidworks model of Experiment Model 7.

Figure 98: Experiment Model 7.
Figures 99, 100 and 101: Experiment Model 7 during animation testing.

Figures 102, 103 and 104: Experiment Model 7 animation process setup.
Experiment Models 8, 9, and 10

The goals for these experiments were to test the permeable inconsistencies of the Tango printing materials and also create a variation of scale shapes for each model. The rubber surfaces for these models are nearly identical to Experiment Model 7; they share the same segment style, nipple-bump features and connection points. The key difference in these iterations is that they have just over half as many segments, which makes the overall size of each model considerably smaller.

The cleaning process was intentionally varied for each model to test the absorption qualities of the Tango material. Model 8 was soaked in warm water for thirty minutes before cleaning, Model 9 was soaked in warm water for two hours and Model 10 was soaked for 24 hours before cleaning. Models 8 and 9 took approximately two hours to clean. Model 10 took approximately one hour as the support material had become very soft by absorbing water over a 24 hour period. The rubber bases for all three models expanded beyond their original size. Models 8 and 9 were slightly too large for their laser cut bases and Model 10, despite being identical to the other models, expanded to be significantly larger than its laser cut base and had to be contorted into a concave shape to fit its mould. Each of the models had scale breakage during the cleaning process. Model 8 had one broken scale; Model 9 had six broken scales and on Model 10 almost every scale broke. Each scale had identical connection points so the breakages can be clearly attributed to the model expansion due to soak time duration. The broken scales for each model were successfully reattached to their connection points with super glue.

Despite issues with material expansion and scale breakage, the models animated just as well as Experiment Model 7. By this stage, sufficient information had been acquired to achieve improved results during the model cleaning process and it was decided that the next step would be to develop the model scale design.
Figures 105: and 106:
Experiment Models 8, 9 and 10. The rubber underlayer of Model 10 is visibly contorted due to water absorption.

Figures 111 and 112: Animation process setup.
Experiment Models 11, 12, 13, and 14

The intent for these models was to focus on the potential for overlapping scales. All four of these models feature larger connection points and rubber base variations that are slightly altered from Models 8, 9 and 10. The scale forms for each model were also designed to express varying levels of aggressive behaviour based upon tip shape and sharpness.

In a critique following the display of these models it was determined that the overlapping scales would only allow for an invariable range of motion, so they were not printed. It was also made evident that the visibility of the rubber under layers for Models 8 through 14 visually removed from the impact of each composition as a whole. During the following stages of experimentation, it was decided that more focus should go into the development of scale shapes in a considered array that completely concealed the rubber under layer.
Figure 113: Experiment Model 14.

Figure 114: Experiment Model 11.

Figure 115: Experiment Model 12.

Figure 116: Experiment Model 13.

Figure 117: Experiment Model 14.
Experiment Model 15

The intent for this model was to address a range of unsuccessful features from previous experiments. Primarily, the focus of this model was to conceal the majority of the Tango layer and make the model self-contained so that it wouldn’t need to rely on a laser cut base for support. The design of this model takes direct inspiration from the tessellations of Mark Goulthorpe’s *Hyposurface* installation; it features twice as many segments as Models 11 through 14 within a smaller amount of overall space. Opposing triangular scales were utilised to form a flush rectangular pattern across the overall top surface. The individual segments are rounded, triangular and concave. The segments are divided into pairs of rectangles by a Vero White support layer. This layer also borders the outline of the model and is intended to replace the laser cut bases and reduce overall unintended inflation.

The scales on the model conceal the majority of the Tango Clear layer below, improving the overall visual aesthetic in comparison to earlier experiments. The rubber connection points intersect through each scale, achieving a much stronger bond than in previous experiments. The cleaning process for experiment 15 was very successful and the model emerged without any faults or scale breakages. Unfortunately, the narrative functionality of this model was pretty poor due to the support layer being far too thin to support individual segments during air gun inflation. In addition, the Vero White support layer unintentionally took on features of the dominant Tango Clear material and became very flexible. While this was a disadvantage for Experiment Model 15, it was an useful discovery.
Figures 118, 119 and 120: Solidworks model of Experiment Model 15.

Figure 121: The top surface of Experiment Model 15.
Figure 122: The bottom surface of Experiment Model 15.

Figure 123: Experiment Model 15’s unintentional flexibility.

Figures 124 and 125: Experiment Model 15’s attempted animation process.
**Experiment Model 16**

The intent for this model was to create a successfully functioning reproduction of Experiment Model 15. The first goal for this experiment was to increase the rigidity of the model’s support layer so it could tolerate directed pressure from an air gun without inflation inconsistencies. This was achieved through a build height and thickness increase to the Vero White layer. The second goal was to experiment with printing multi-material scales for the top surface of the model. The scales were designed in two layers. The bottom layer was printed at 0.4mm in Tango Clear and connected to the inflatable surface. The top layer was printed very thinly at 0.2mm in Vero White and connected to the rubber bottom layer.

During the cleaning process for this model, the Vero White top layers of each scale were scrubbed with a cloth brush using parallel strokes along the length of the model. The connecting rubber layer expanded slightly due to water absorption causing each scale to curl upwards. The visual effect of this unintentional distortion was reminiscent of the scales of an African Tree Viper or Horned Lizard. The scales also shared features comparable to the curved wooden flaps from Achim Menges’ *Hygroscope* installation, although this was purely coincidental.

To minimize overall build height, the inflatable segments were made into small concertinas. Unfortunately, the ability of the inflatable segments to pass through the top section of this model was overlooked and the openings were too small in relation to the width of the concertinas. However, this led to the discovery of an alternative animation technique; by simply brushing over the top of the model with a pressurised air gun, the scales moved as intended. Experiment Model 16 performed to a satisfactory level and led to the discovery of potentially removing several unnecessary features completely from subsequent experiments.
Figure 126: Solidworks view of the bottom surface of Experiment Model 16.

Figure 127: Experiment Model 16 curved scales.

Figure 128: Solidworks cross section view of Experiment Model 16.

Figure 129: Solidworks view of Experiment Model 16.
Figure 130: Experiment Model 16’s bottom surface.

Figure 131: Experiment Model 16.

Figures 132 and 134: Experiment Model 16 during animation process.
Experiment Model 17

The intent for this model was to develop a fluidly animated, interlocking scale-based surface. The primary goal for this model was to test the animation potential of a multi-material printed surface without the use of inflation.

Experiment Model 17 features two scale types that form a tight uniform pattern. The size of each scale has been reduced from previous experiments, increasing the overall density of scales within an equal amount of space. The scales are built upon thin cylinders of Tango Clear with a concave fold in each centre so they can bend and flex. The model has been stabilised with a 3.5mm layer of Tango Clear sandwiched between two layers of 1mm Vero White. The support material was easily removed, and paper hand towels were used throughout the cleaning process to absorb any excess moisture and minimise model expansion.

Animation tests were conducted with an air gun and the model performed exceptionally well. The scales moved fluidly, like that of a creature or the living structures that might be found within a coral reef.
Figure 134: Solidworks model of Experiment Model 17.

Figure 135: Experiment Model 17.
Figure 136: Experiment Model 17.

Figures 137, 138 and 139: Experiment Model 17 during animation process.
Experiment Model 18

This model was essentially a rehash of Model 17 with a bolder and more refined and uniform scale pattern. Due to the similarities with Model 17 and the generally high cost of 3D printing, this experiment was not printed. By this stage it had become clear that the intended aesthetic and functional discoveries had been met. From here it was time to start the development of a living product prototype.

Figure 140: Cross section view of Experiment Model 18.

Figures 141 and 142: Experiment Model 18.
A.I.E. Adaptive Skin Video

This video was a directed response to the questions posed in the earlier A.I.E concept video: *if our products adapted and evolved with us, what would they look like? What would we use them for? And how would we influence them?* The video features the interaction between an anonymous user and Experiment Model 17. The 3D printed model responds to sensory feedback from the user’s fingertips through a series of wave-like fluctuations across the scale covered surface. The overall narrative reflects sensory experiences of projects such as Inconvenient Studio’s *MorphoLuminescence* or Mark Goulthorpe’s *Hyposurface*. The model animated with fluidity and the video communicated an example of 3D printed living product potential.
Figures 143, 144, 145 and 146: Images taken from the A.I.E Adaptive Skin Video.
DESIGN
Experiment Models 17 and 18 attained aesthetic qualities that were refined and expressive enough to develop a product from. The premise for this product was that it needed to be instantly recognisable as an existing product, while also retaining the identity and functionality of a living, moving and responsive 3D printed object. The product did not seek to conclude this research, but rather to feature as a metaphor for the potential inherent within sentient products holistically. During earlier stages of research it was decided that a smart phone would be a suitable vessel to develop a product from.
3D Printed Living Skin iPhone Cover

The development of this product concept was the final stage of research through design for this thesis. The intent for this concept was to utilise the most successful narrative elements discovered in the experimentation phase and use them to build a smart phone based product. Throughout the experimentation stage, multi-material printing and scale based surfaces proved to be reoccurring features of the most successful models. All of the model experiments were based around a reactive surface or skin, which led to the consideration of creating a smart phone cover or ‘skin.’

The iPhone 5s is a good example of emergent sensory, digital technology that is capable of human and environmental interaction. The iPhone 5s's ability to detect identity through its touch ID sensor technology evokes possibilities of a relationship between the digital information realm and the tactile physical realm. The touch ID sensor also poses potential for responsive actions that take place when a user doesn’t own the device. The decision to design a 3D printed case for an iPhone 5s was based on the premise of this sensory connection.

The first stage of design for this model started with the creation of a simple case with measurements taken from an iPhone 5s. The wall thickness of this case was slightly oversized to accommodate alterations due to take place in the following stages. This part of the model was intended to be printed in the hard Vero White material.
The second stage was to prepare the case so that it could be fitted with living surface structures. The majority of this model needed to be predominantly covered by these structures. To accommodate them, volumetric space was subtracted from all of the outer faces of the case. To ensure the case maintained stable once 3D printed, the face edges were thickened with a filleting tool.

Figure 150: Solidworks part of the iPhone cover during surface modification.

Figures 151, 152, 153 and 154: Solidworks parts of the Tango Clear structures contained within the iPhone cover.
The third stage was to add a Tango Clear under layer to the case. This layer slotted into the volume subtractions and featured patterned cylindrical segments.
The fourth and final stage was to add the Vero White top surface. The top surface features an interlocking scale design similar to that of Experiment Model 18. The scales connected to the Tango Clear cylindrical segments and formed a flush surface across each face of the cover. Alongside the edges and corners of each face, the scales were cut and filleted to maintain a clean visual aesthetic.

Once printed, the support material was cleaned from the case completely without the use of liquid. Fine wire brush tools were used to break up the support material, which was then removed by a pressurised air gun. As a result of this method, the iPhone case cleaned very well without any water absorption issues.
Figures 159 and 160: Solidworks assembly of the iPhone cover parts with the developing side scale layers.

Figures 161, 162 and 163: Complete Solidworks assembly of the iPhone case.
Figures 164, 165, 166 and 167:
The complete 3D Printed Living Skin iPhone Case.
Figures 168 and 169: The complete 3D Printed Living Skin iPhone Case.

Figures 170 and 171: Animation testing with the 3D Printed Living Skin iPhone Case.
The creation of this model came with a few inconsistencies. During the cleaning process some of the scales peeled very easily off the back surface. The quality of the scales on the back profile was also unexpectedly diminished in comparison to the scales on the surfaces on the top, left and right profiles. Although all the scales were identical in Solidworks, the scales printed on the back profile were jagged and slightly thinner than their counterparts. Through an analysis of the 3D file it became clear that the problem wasn’t with the design of the model, but rather the inconsistencies of the Objet500 Multi-material 3D printing machine.

The Objet500 builds models in layers. If a model printed with Vero White has a large enough build height it will contain multiple layers that will strengthen the model which will also help to improve the quality of the print. In comparison, if a model printed with Vero White has a very short build height it will only contain a few layers to hold its shape, which in turn reduces the strength and quality of the print.

To confirm this inconsistency, another copy of the iPhone cover was printed on its side profile, as opposed to the original which had been printed flat on its back. The results were as expected. The back profile printed perfectly and was very strong. The top profile printed perfectly too, as it also had the benefit of being built upon multiple layers. The scales on the left and right profiles, however, featured rough qualities, as they were printed flat. The left and right profile scales on this model mirrored those of the back profile scales on the original case print. The problem with printing models in this way is that printing costs increase exponentially as build height increases. Unfortunately, the only way to achieve uniform quality with a 3D printed object using current technology is to conform to technical inconsistencies by altering the form of the model to benefit fully from the material layering process.

Regardless of these inconsistencies, the 3D printed living iPhone cover turned out great. The case fit perfectly and the scales were compliant to movement. During animation testing the scales were responsive and moved fluidly. Visually, the scale movement shared features with installation projects such as Hyposurface, MorphoLuminescence or Hygroscope, but in the form of a much smaller, portable product. The animated scale structures featured tactile abilities reminiscent of moving coral structures or shimmering bee formations.

Figures 172 and 173: The diminished scale quality of the first iPhone cover print is clearly visible in these prints. Some of the scales needed to be glued in place.
Figures 174 and 175: Images of the imperfections present in the first model print.

Figures 158 and 159: The reprinted model above and the original below.
Sentience: iPhone Cover Video

Following the creation of the iPhone case, the intent was to create a video that could visually communicate the potential for living products to a wider audience. The essential elements for this video were to show the product working as intended. The intelligence of this product needed to be portrayed through responsive interactions generated by the touch ID technology.

The video was intended to unveil a scenario using the following sequence of events:

- The living iPhone case is moving in a relaxed state with fluttering wave like formations.
- The owner of this phone picks it up for intended use and puts their finger to the touch ID sensor button.
- The phone unlocks upon recognition of the owner and the living case gently acknowledges its owner's presence with a greeting message and subtle movements.
- The phone is then left alone, at which point an unfamiliar antagonist picks it up and attempts to use the touch ID sensor to log in.
- At this point, the phone is alerted by the antagonist's attempted login and reacts with a warning message, loud noises, and aggressive scale movement that deter the would-be thief from taking or using the phone.
- The antagonist leaves the phone, at which point the owner returns to calm it down.

Overall, the video displays potential for digital living products that may eventually be achieved through the development of 3D printing systems. While designed sentient systems have been achieved on a larger architectural scale, this video encourages its audience to think about the prospects of all products, including those that are small, mobile, and can be used in everyday life.
Figures 178, 179, 180, 181, 182, 183, 184, 185, 186 and 187: Images from the Sentience: iPhone Cover Video.
CONCLUSION
This thesis project explores the possibilities for 3D printing products that feature tactile abilities inherent within sentient forms. The aim was to use a process of iterative compositional experimentation to develop hypothetical outcomes for the proposed sentient products. Literary research provided background analytical data on which the future potential for 3D printed living products could be based upon. Contextual analytical data acts as both a precedent for experimentation and provides the research with a contextual relevance.

Through the process of design experimentation, discoveries revealing the properties of 3D printing technology were brought to attention. The experiments showed unrivalled potential for the rapid prototyping capabilities of 3D printing machines. Models with complex and intricately small details could successfully be generated very quickly, a feat that no other fabrication technique can currently achieve. The 3D printing process was ideal for producing multiple, accurate experiment variations, but there were notable obstacles that will eventually need to be addressed in order for this technology to become an essential tool for fabricating living products.

The polymer based Tango and Vero materials utilised for this research feature several complications. Both materials are permeable; water can pass through them and be absorbed in the process. Tango and Vero are intended to be simulations of their natural counterparts plastic and rubber, both of which are typically water resistant materials.
The strength and resistance of the Tango and Vero materials also feature variances that depend solely on the layering process of the 3D printing machine. Models with a short build height will be of lesser quality than models with taller build heights. This is generally problematic because the cost of 3D printing rises exponentially as a model’s build height is increased. Support material can be a frustrating experience to deal with; the easiest method of removal is by using liquid or solvents (which can be absorbed by the Tango and Vero materials), otherwise the process can be lengthy and hazardous (for the print) depending on the size and intricacy of each model. These inconsistencies are currently problematic for the majority of 3D printing materials in general. In The rise of multi-material 3D printing, Ellie Zolfagharifard states that simulated materials often lack the resistance, flexibility and lifespan of their natural counterparts. For this reason, multi-material 3D printing has largely remained in the realm of prototyping. (Zolfagharifard, 2013.)

Before 3D printing technology can begin the process of developing living products, it will need to evaluate the properties of contemporary materials across the board. In Mould Busters, Alex Newson states that:

> Materials must evolve beyond the current list of polycarbonates, epoxy resins and metals. Concrete, for instance, is uniform in terms of how it behaves. ‘We’re coming to the limit of what’s possible with the current palette of ‘dumb’ materials.’ (Jones, 2013, Pg. 73.)

Future developments in material technologies may provide potential avenues for 3D printed living products. Research conducted by synthetic biologists has led to the successful creation of materials complete with living cells. Synthetic biological research aims to develop materials that can tactically respond to interaction from humans and the environment, and these materials are envisioned to be capable of adaptation and self-repair. Researchers aim to eventually link synthetic biological materials to digital devices, which may lead to the discovery of synthetically biological or living products. Synthetic biological materials show great potential for biotechnological applications. However, the functional complexity of these devices are currently limited by available design tools. (Muers, 2012, Pg. 72.)

Regardless of material and technological limitations, the prospect of 3D printed living products existing sometime in the future looks promising. Narrative techniques have provided this research with designed experiments that appear to be capable of sentience. 3D printing technology has provided sufficient intricacy to sell visual elements belonging to the experiment models within this thesis. These experiments are brought to life using techniques that are aligned with architects and designers that share a similar contextual ethos to the content of this research.

The 3D Printed Living Skin iPhone Cover did not seek to conclude this research but, rather, was intended to serve as a metaphor for the rapidly-increasing potential for sentient products. The intent was for the Living Skin iPhone cover to demonstrate the potential for physical products to demonstrate the characteristics of sentient beings, by foreshadowing the impending possibilities. The narrative methods utilised subsequently aimed to generate an emotional response to this world of possibilities, as the animation of the experiments hopefully enables the audience to form a connection with the designs. Unfortunately, these products, will have to exist solely through this form of narrative media for the time being, until the technology to develop sentient products has been developed.
FUTURE
The tools of synthetic biology are galvanizing the development of new forms of architecture that respond to environmental change by incorporating the dynamic properties of living systems, such as growth, repair, sensitivity and replication. (Armstrong, 2010, Pg. 916.)
Personal Bias
Projects such as Phillip Beesley's Hylozoic Ground or the Mediated Matter Research Group's Silk Pavilion contemplate the possibilities for fabrications to evolve and sustain themselves through the use of sentient biological systems and materials. Within the realms of synthetic biology development, researchers are looking into the possibilities of creating 3D constructed tissue. In 3D Printing for Tissue Engineering, Dylan Jack Richards proposes the potential for an effective means towards the assembly of 3D constructed tissue through the use of biomaterials, printing techniques and cell delivery methods. (Richards et al, 2013, Pg. 805.) According to Richards, 3D printing technology shows great promise for tissue fabrication. He claims that with structural control from the micro to macro scale, there is the potential to provide a rapid and robust approach to the assembly of functional tissue 'in vitro.' (Richards et al, 2013, Pg. 805.) Biological research may lead to the development of 3D printable muscle tissue-like materials capable of flexion and contraction. This envisioned material could be printed at any scale, with consideration that the strength of contractions would be dictated by the size and density of the material. Electronic signals from a digital device could be sent through parts of the material to control these contractions. Through this process, the digital device may potentially become a simple Artificial Intelligence (AI) capable of generating commands to physically respond to information generated by digital data.

Figure 189: 3D Printed Living Skin iPhone case
Researchers are also working on the creation of a 3D printable material that will be useful for bone replacement. (Inzanza, 2014) This technology has obvious uses within the medical field, but it could potentially be useful within the realm of living products as well. 3D printed bone-like materials could be an interesting alternative to contemporary materials such as plastic or metal. Bone contains proteins such as collagen which allows it to stimulate regeneration when parts are broken. Products made from this material would, theoretically, be able to repair themselves.

3D printed bone and tissue-like materials could prove to be invaluable within the realms of living products. Potential can be expressed through the experiments conducted within this thesis. The flexible rubber-like Tango material can be envisioned as muscle tissue-like material, able to expand, contract and alter its form. The hard plastic-like Vero material can be envisioned as bone-like material, able to reinforce, protect and stabilise forms. The 3D Printed Living Skin iPhone Cover experiment could benefit from the properties of these bone and tissue based materials. A hypothetical scenario for this product would see the smart phone device sending electrical signals to specified areas of the muscle tissue-like material, forcing them to contract or relax. The muscle tissue-like material connects to the bone-like material scale structures that serve as an interactive and protective casing for the iPhone device. In addition this case would be able to repair damages that occur through a collagen based regeneration process.

On a final note, researchers at the Georgia Institute of Technology have developed a friction-based, miniature generator that could enable products to be charged by stroking or pressing against them. The generator produces electricity when two sheets of specially adapted polymer are rubbed or pushed together. This technology may enable external power sources to be redundant. (Griffiths, 2014) Within the context of living devices, it would be interesting to research products with friction based generators that are able to maintain sufficient energy by stroking themselves. This could provide a popular alternative to the bulky iPhone charging cases currently available.

Essentially, synthetic biology may prove to be fundamental for the development of 3D printed living technology. Its processes may allow for complex architectures, artificial tissues and living materials that may be fashioned into devices that feature sentience, interact with their surroundings and protect themselves from unpredictable circumstances. (Service, 2014, Pg. 1421).
END
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