A design exploration of an agent template for multiagent systems (MAS) for shape shifting tangible user interfaces.

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Abstract

In the field of tangible, shape-shifting, interactive interfaces that are based on multiagent systems or programmable matter, communication and assembly mechanism have gained predominant attention. The results from this research has had a more direct influence with respect to more immediate application and implementation. In contrast, in the area of agent design, there has been little progress in moving from the tried and tested cube shape. Whilst the behavioural aspects of an autonomous agents are continuously developing, the body required to house such an awareness is lacking in refinement. The purpose of this study is to focus on an agent design, that has the potential to accommodate artificial autonomy.

Bionics and biomimetics are influential fields that have impacted the research in this study. Biological structures and mechanisms have a strong influence in the field of interface design. This includes informing structural aspects of a design to the possibility of creating an internal and independent energy processing systems that enables an agent to become independent and self-reliant.

Haptic exploration through the creation of prototypes and artworks have helped define the physical scope of the agent design and have contributed in clarifying the type of applications in which shape-shifting interfaces may be implemented in the future. This element of the study is particularly relevant for the aspect of creating an agent design that is versatile and adaptable. It must be capable of accommodating anomalies within its own system as well the unpredictable nature of human behaviour.

Aside from the agent design which is the physical contribution of this study, the approach to the design process itself is also explored philosophically from the combined perspectives of a scientific and creative methodology. The importance of balancing these concepts is reflected throughout the study and is crucial in the development of multidisciplinary experts.
Declaration

I herewith declare that I have produced this paper without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This paper has not previously been presented in identical or similar form to any other Irish or foreign examination board.

The thesis work was conducted from 2013 – 2018 under the supervision of Dr Mikael Fernström at the University of Limerick

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I would like to thank my supervisor, Dr. Mikael Fernström, for his support and inspiration throughout this study. He helped me overcome my fear, and build up my self-belief, an aspect I greatly cherish. He told me at the start of my study ‘Why aim for the treetops when you can aim for the stars!’ In this expression he created a freedom for me to explore the myriad of possibilities in research. I have learned to translate this freedom into other aspects of my life which has had a lasting influence. He encouraged me to nurture my love of learning and showed me the importance of sometimes flowing against the stream of convention.

A special thanks goes to my family, in particular my parents, Ines and Lutz. They were my sounding boards, my research team, discussion partners and proof-readers throughout these past 5 years, as well as fulfilling many other roles by the side. Their continued support throughout this study made it possible for me to get through the tough moments. They have helped me become the person that I am today for which I will always be grateful. They have given me Time and the opportunities to develop into an independent, conscientious and competent person. They are people I greatly admire and hope to continue to emulate throughout my life.

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I am grateful for the Irish Research Council for funding the 1st three years of my study (project GOIPG/2013/351) and indirectly through them, to the tax payers who make research funding possible.

Lastly, I would like to honour a calendar proverb that I chanced upon in 2016

‘If you aim for the stars, make sure you don’t get lost in space.’
Preface

This preface aims to provide the reader with an understanding and insight as to who I am as an author and for the decisions that were made throughout the study and research process.

I am a scientifically-minded artisan, which allows me to work adeptly within the haptic modality. Understanding and translating the freedom of creativity, that is evident in crafts and arts, is a valuable skill. It fosters free experimentations with ideas and materials. Even though it is a diametrically opposite approach to creativity, I can also appreciate and apply the structured, and ordered explorative nature that science encompasses through its methodology. Being able to work with both of these approaches, has made me be more versatile in my ability to take in and apply knowledge. The inclusion of the mindmap at the end of this study, in its specific form is representative of this approach to art and science. It presents an overview of my PhD from a different perspective. Sometimes different strands of research occurred simultaneously and as I find sequential story telling difficult, mindmaps provided me with an alternative method of representing my study.

The typical procedure for a PhD such as this one, is to choose one avenue in which the proposed design should exist and then explore, test, or examine as many avenues as possible within the timeframe of the study. This would yield a clear contribution and result in a high-fidelity prototype. When dealing with concepts such as real-time shape-shifting, interactive interfaces, that are still primarily centred in science fiction more so than reality, the scope of possibilities is vast. In sailing there is a familiar expression that if you are at the back or middle of the fleet, there’s no point in doing what everyone else is doing. Sometimes it’s worth doing something completely different.

With this in mind, it is safe to say that MIT is a leading institute with respect to making science fiction a reality. The intellectual and material resources available are conducive for developing these types of projects. “Even ordinary people like me can have extraordinary ideas.”
But it helps to have them while you are at MIT” (Butera 2002).

Although my project is comparable to the work being done in MIT, my situation and resources were not. Therefore, instead of following the leaders I chose to do something different. Rather than creating another prototype, I tried to create a new template and a blueprint for how it can potentially be developed further. My design aims to be a blank canvas or a reinvented building block that can be used in the field of autonomous multiagent systems.

In the process of creating such a template, I was able to evenly apply practical and academic skills. By the end of this study I would consider myself a multidisciplinary expert as opposed to an expert in any one field because this study spanned the fields of art, sculpting, programming, engineering, 3D modelling, biology and physics. My design is reflective of my character: an expert at being good at many things. I personally believe this kind of expertise is necessary and even though it may be evident in academia, it is my perception that it is not yet as widely implemented or applied in industry or day-to-day life.
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1. Introduction

1.1 Introduction

The concept of shape-shifting technology that can morph into any user defined shape or form is a growing field of interest. Taking inspiration from nature and science fiction, the challenge of creating technology that can accomplish such a task requires ingenuity, creative problem solving and a multidisciplinary approach. The general consensus is that shape-shifting technology is created from many small parts operating together to create a larger entity. Whilst there are many facets to this type of technology, this study focuses on the physical design of the small part: the agent. It explores the qualities, parameters and behaviours necessary to create a more adaptable agent as it is a consideration that it should be applicable in a variety of different scenarios. The tangible output of this study is a review of the literature aimed at defining design guidelines in relation to the research question, a 3D printed prototype of the proposed agent design, a model of a rudimentary behavioural rule set of such an agent and a documentation of the STEAM methodology applied through out this study. As this study progressed it became apparent that many designs, although functional, rarely surpassed the prototyping stage or lab environment. It prompted the discussion as to how the agent design, in this study, can be developed with the advancement of new technologies. In developing the blueprint for such an agent, it meant that the design considerations or parameters were not always clearly defined. As a result, it was often necessary to combine the application of artistic and scientific methodologies. Shape-shifting interfaces are one avenue of research that aim to improve the quality of interaction with respect to the haptic sense, broadening the scope of tangible interfaces.
According to the Tangible Interface (TI) classification scheme as define by Ishii and Ullmer, the agent design proposed in this study falls into the category of constructed assemblies and to a degree that of continuous plastic TUIs (Ishii and Ullmer 1997).

- Constructed assemblies are comprised of modular components that can be arranged or organised into larger more complex structures. A priority for these assemblies is the manner of fit between components or agents, their ability to create assemblies in 3D or 3D relief and how these assemblies interact with the environment (e.g Topobo (Raffle et al. 2004)).

- Continuous plastic TUIs were developed in order to provide the users with a malleable and flexible building material with which to manipulate digital information. It is to accommodate a user’s free and direct interaction and not limit them to using predefined, form-fixed elements in the interaction process (e.g. clay (Ishii et al. 2004a)).

Within the scope of the agent design described in this study, it is not only the overall or whole entity that is changing (i.e the larger whole made up of smaller parts) but each individual agent can change its form and size as well. This behaviour creates a sub category to continuous plastic TUIs were the concepts of this category are applied to each individual agent as opposed to the whole structure. Whilst the primary function of the agent’s shape and size change is to facilitate the generation of micro structures to aid in overall assembly, e.g. line, curve or cluster, to eventually create a mixing desk, the effect of this behaviour on the macro structure can utilise the full potential of the haptic modality. If each agent can change or react to specific stimuli without effecting the overall structure, it could create texturally dynamic and fluidic interfaces. Similar behaviours are evident in SMA or push-pin based interfaces (Minuto et al. 2012, Follmer et al. 2013, Rozin 2015).

These types of interfaces combine programmable matter concepts with ambient computing, generating interfaces that are more reactive to the individual user or their environment. This reactivity highlights the possibility of new interaction methods with tangible interfaces but also the manner in which digital information can be perceived and handled. The ability of an agent to generate structures as well as facilitate a mechanism for it to physically react to its environment brings the agent closer to emulating the unique haptic characteristic of bi-directionality.
Tangible interfaces that embody shape- and size-shifting on the macro as well as individual level potentially provide a new category in the TI classification scheme in which it is possible to describe interfaces that encapsulate biologically inspired living interfaces which have the ability to convey their effect on and reaction to the user or environment.

The contribution of this study is predominantly twofold: the first contribution lies in the exploration and insights gained from multiple domains to define elements that can be used to address issues such as scalability, adaptability and energy supplies in the production of a tangible prototype. The secondary contribution is the acquisition of skills that are vital to the multidisciplinary approach. This includes bringing together research from a diverse range of domains, to evenly represent both strands of science and art, and bridge the gap between the logical and emotional aspects of human nature.

![Figure 1.1 Agents](image)

The commonalities of the the images in Figure 1 are that both entities represent the small part of a larger whole. They can make structures larger than themselves and they are directed from a central command centre. Even though they have different shapes and life purposes, the most significant difference between them is that one exists and one is fictional. They do however represent the same concept: both are agents that function as part of a multiagent system.

An agent in this study refers to an autonomous entity, which has a physical shape and form. Based on rudimentary behavioural coding it can make decisions and learn according to its capability.
1.1 Introduction

A multiagent system (MAS) is a term more commonly used with respect to coded systems whose agents exist solely in digital form. These systems can be designed to simulate biological systems such as ants or people and their primary function is to aid in the understanding and modelling of emergent behaviours. This study is based on developing a physical agent that functions in a similar fashion to a digital version in terms of controllability. However, instead of using it to understand a different system, the agent aims to facilitate new methods of interaction, potentially between the user and interface. The main differences between living and digital MAS are the purposes of application and the ability of an interface to shape-shift in real-time according to a user’s requirements.

The fictional agent, Megabot, illustrated in the animation Big Hero 6 (Figure 1.1b), demonstrates the possibilities and potential of how agent-based technology can function particularly on the macro scale. It encapsulates the idea of a particle-based computer that can be expanded or reduced in size depending on particle volume and that can be used to create any number of structures. Megabot is based on geometric shapes and the concept of electromagnetism. These are the kernels of truth which are evident in a variety of projects discussed in this study and which provide a link to the possibility of a fully controllable inorganic MAS system. Whilst there are numerous examples of a Megabot-based interfaces already present in science fiction (Cameron 1991, Bay 2009, Mangold 2013, Taylor 2015, Lin 2016), the reality is far from implementation. Questions that arise from these representations relate to how far this branch of shape-shifting technology has been developed to date.

In his work, Butera suggests the concept of a paintable computer (Butera 2002). It is a blend of the concept of the internet of things (IoT), whereby objects are connected to one another and communicate over a shared network, and multiagent computing. He suggests that future computer technology could become so resilient, small and cheap, that it would be possible to deal with it in bulk and that it will be small enough to potentially blend into the background and be applicable to everything in the environment. Butera describes agents that function on a basic level, ideally suspended in a liquid, so that they can be dispersed evenly but also be used to enhance the surface onto which they are painted. An agent consists of a ‘brain’, memory, communication
and energy harvesting ability. The predominant method of functioning of such agents is through self-organisation.

Expanding on this concept, it is envisioned that a computer liquid could change its physical shape, i.e. it would be able to create 3D relief structures or even be used as an independent 3D object. Such an interface would be in a quasi-liquid state when inactive and could become solid when in use, comparable to a Non-Newtonian fluid. These types of interfaces are described in Horev’s (2006) work, primarily highlighting the value of haptic affordances. The following scenarios aim to provide context and potential applications for shape-shifting, real-time adaptable interfaces.

1.1.1 Scenario 1

*System states - making the invisible visible.* Certain states are clearly defined and are easy to map, e.g. a light switch – on / off. Mapping gradients of such a system introduce a certain level of ambiguity, e.g. dimmer switches – on / transition / off. In this transition phase, the value or state of the system is not always apparent. This is often the case for computers. The visual cues such as timers and progress bars attempt to indicate the state of an invisible process. From a haptic perspective, a process could be indicated via surface topology changes. The surface could pulsate slower at the start and as it reaches the end of the process pulsating faster. In Horev’s example of indicating the amount of storage left in an external storage device, he explores the concept of inflation and shape-change: as the device becomes fuller a prototype rotates and inflates (Horev 2006).

1.1.2 Scenario 2

*Guiding through a process.* In this example Horev describes a shape-changing interface that is capable of physically guiding the user how to use a complex interface through a correct sequence of buttons that appear out of the interface itself (Horev 2006). If there are 5 buttons that need to be pressed in a specific order then the next button appears only when the user has pressed the current one, etc. This type of
interface can be very useful in conjunction with designing for negative affect. For example, in an emergency situation, the visual and auditory bandwidths are usually taken up with a multitude of alarm lights and sirens. To accommodate negative affect means that the design of the interface must be clear and the information must be easy to obtain and recognize. It favours a minimalist design (Norman 2005). Consider an interface such as a control desk at a nuclear power station that is programmed to perform multiple functions simultaneously. Designing solely for emergency situations is not practical either therefore the potential for an interface to physically change its layout in times of critical situations may be advantageous.

1.1.3 Scenario 3

Enhancing existing interfaces. Where technology is designed to accommodate augmentation of human ability rather than replacing it has greatly improved the aspect of accessibility. The example Horev presents is a keyboard that can change the size of its keys to facilitate different degrees of accessibility. Another possibility is to map the screen visuals onto a haptic interface. For example, files and folders on a ‘desktop’ could be represented by similar icons but be raised up from the surface. Pressing down onto a folder icon would offer haptic and textural feedback as it opens the folder to reveal the content. An interface that can change or update as quickly as the visuals does for screens offers alternative interaction to a mouse and may aid users with visual impairments. Speculating from a long-term perspective, if such an interface could be used to complement augmented reality it may improve the quality of immersion.

1.1.4 Scenario 4

Motor skills and prosthetics. Imagine a shape-shifting interface that could accommodate users with motor skill difficulties, e.g. at present a person paralysed with a high spinal cord injury types on a conventional keyboard using an elongated rod with his mouth. Instead a shape shifting interface could be designed such that the person

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1 Negative affect relates to the experience of negative emotions ranging from anger, fear, and stress to irritation, impatience, panic, etc. These emotional states affect the manner in which people deal with stressful situations and problem-solving tasks. For more details see section 1.5.1.
could use their tongue. Alternatives do exist to aid with computer interaction, e.g. eye tracking, speech to text, however there are fewer haptic alternatives.

Scaled up, shape-shifting matter / technology could be applied to the adaptation of prosthetics depending on function and requirement. For example, even though human hand prosthetics are continuously improving, shape-shifting technology could aid in enabling a more fluid transition between sensations and various grips and actions (i.e. pincer grip, hand clasp, multi-fingered grip, (Bole 1993)).

1.1.5 Scenario 5

*Customisation.* Working with the concept of augmentation, consider the application of shape-shifting technology into a performance mixer interface. Current devices have a set number of sliders, rotary knobs and buttons. If the user has scope to add or remove physical controllers as desired, it creates a unique and customised instrument or tool, similar to the Palette concept (Palette 2013) but also the microfluidic based Tactus technology (Tactus Technology 2012). Aside from generating the traditional style of physical controllers, having the possibility of creating new shapes such as spheres, tetrahedrons, touch sliders, etc. could influence interaction behaviours. The fluidic shifting between controllers could become interesting with respect to live performances. Integrating shape-shifting technology into alternative controllers similar to the APC or Push (Akai Professional 2009, Ableton 2013), creates a tangible as well as visual experience. Elements such as speed of pulsation, textural quality, colour, shape and size can become real-time controllers. Whilst there are touch sensors available to accommodate certain gestures, the ability to physically jab, slide, pinch, rotate, grab, push, flick, etc. an interface helps the performer become haptically as well as visually engaged with the interface.

1.1.6 Scenario 6

*Medical applications.* Scaling below the microscale opens the possibility of the nanoscale. The agents or nanobots designed to function on this scale is presently primarily implemented in the medical domain with respect to targeted delivery methods. Using an agent with individual shape-shifting capabilities, the following
example may be possible. In the diagnoses of an aneurism in the abdominal aorta, being able to send autonomous agents to the affected area, in the quantity required, could increase the time available for emergency interventions. These agents would function together and adapt to the increased volume created by the weakened and bulging arterial wall. Through the packing behaviour of these agents they would fill out the volume, slowly displacing the blood so as not to cause further pressure of the already weakened structure of the vessel. This behaviour is similar to dilatant materials or rheopectic fluids, such as a Non-Newtonian fluid, whereby the excess fluid is displaced and temporarily creates a semi solid mass. The semi solid mass of agents would build up to the inner lining of the vessel wall and the process could prevent sudden and uncontrolled rupture and exsanguination into the abdominal cavity.

In similar situations regarding the sealing of wounds, aside from gels and foams that are currently being developed, agents could be used to fill such an irregular volume. The quality of permeability and the ability to communicate with each other are advantageous characteristics (see Chapter 4). The packed mass adapts to the surrounding and slows down the blood flow. The blood can then begin to clot, avoiding the loss of coagulant factors circulating in the blood stream, which can be a further complication.

Whilst these scenarios provide context for shape-shifting technology, they also illustrate that an advantage of MAS is the flexibility to create defined structures as well as coping with a degree of randomness. This randomness consists predominantly of the unpredictability of nature. Most intriguing in this avenue of research is however the potential of creating a system that is capable of processing energy to achieve self-sufficiency. It will become evident that despite advances in particular aspects of shape-shifting technology (communication, motion or assembly techniques), the majority of the projects are still tethered by the fact that they rely on external actuation, aid or intervention (e.g. changing batteries, prevent agents from falling off of a table edge, etc). The resulting prototype of this study does not differ in this aspect, however the potential for energy processing is incorporated into the design and considered in future development, as is discussed in Chapter 7.

Aside from the aspect of energy, another consideration is how this type of shape-shifting technology can be applied? Many applications suggest replacing existing
technology, like some of the scenarios mentioned earlier. This is a good starting point, however the full potential for a MAS based interface has probably not been realised yet. For example, keyboards and computer mice effect change in the digital domain on a daily basis, as they are the haptic extension of a computer and are successful tools. As such they have undergone several adaptations regarding aesthetic, ergonomic or custom design. Whilst users have adapted to this style of interaction it also means that interaction is limited to what the interface can offer. An interface that can morph into different shapes in real-time, provides users with the opportunity to approach and handle digital data differently. This has become evident in the implementation of touch screen technology. New gestural expressions have developed for tasks that were initially carried out by the mouse and while touch screen make certain task easier (e.g. flicking through a photo album) other tasks are more cumbersome (e.g. typing). The swipe-typing technique as used on current Android phones (e.g. Galaxy J3 2016), is an interesting alternative to typing on an interface without haptic cues. Evidently new interaction styles emerge depending what an interface can offer. Despite the initial difficulty in clearly defining what physical MAS can do, the fact is that they have not successfully moved from the prototyping stage, i.e. from a lab setting, into real world use.

1.2 Thesis Outline
Chapter one aims to contextualise the research carried out in this study and establish a framework through which the contribution of this study can be perceived. It explores possible scenarios to help create a conceptual model of what is envisioned for this type of real-time shape-shifting technology, regarding function and form. Following on from this, it is important to highlight the initial starting points and inspiration regarding research because it enables the reader to orientate themselves in the research domain. The remaining sections in this chapter aim to highlight the ideas that underpin and influence the design process, the analyses of research and the considerations for future development. Even though these concepts may be well established, it is important to show how their influence can affect design choices and research undertaken throughout the development of the agent design process.
Chapter two provides background information into the key areas of research: Non-Newtonian and smart fluids, self-organising biological systems and the haptic sense with respect to tangible user interfaces (TUIs). Specific areas of interest have been selected from each of these domains to explore how to isolate the factors that may be relevant and applicable to an agent design. Current and related work is covered in the latter sections of this chapter regarding the types of interactive interfaces currently available, as well as addressing issues and gaps that are evident in the domain of haptic interfaces. It is possible to determine a set of parameters, from the literature, that will guide the design process and help define specific features of the final agent design.

The first part of Chapter three relates to the practical methodology applied in this study. It ranges from considering well-established concepts such as top-down and bottom-up, to the design and artistic processes, as well as the methods and tools used for knowledge acquisition and prototyping. The second part of this chapter relates to early prototypes and designs that emerged as a direct result of the knowledge gained from the literature review. Aside from gaining practical knowledge, regarding design elements that would or wouldn’t work, it is also indicative of how the ideas described in Chapter one aided in guiding the thought processes and in turn is reflected in the design choices.

Chapter four and five detail the physical description of the final agent design - the Dod. It entails how the design is envisaged to function, the reasoning of the design itself and a model of elements that make up a rudimentary part of its behavioural pattern. Whilst communication is an integral component in the development of this kind of technology, the focus of this study is on the physical aspects of the agent’s design. It is implied that the communication techniques and methods described at the start of Chapter five could also be applied to the Dod. The basic model that emerged, as a result of this study on communication, represents how the Dod would behave in specific circumstances in conjunction with what is possible through its physical form, i.e. defining methods of communication based on its physical construct, more so than its computational capabilities.

The findings from explorations, as documented in Chapter four and five, and prototyping completed throughout the study, are discussed in Chapter six. It details how the design elements that were defined in Chapter two and three have been
incorporated in the final agent design and how it compares with existing prototypes. This includes the contribution of the new design and its context in the domain of interactive tangible user interfaces based on multiagent systems.

Chapter seven presents avenues of further research regarding current technology as well as suggestions how the Dod could develop further in the future. Developments in material science not only provide a rich landscape of possible applications for the Dod, but also define how and from what material it may be constructed of. Relevant here is the research into power supplies and reversible-attachment methods, since the ability to scale agents to a desired micro-scale requires novel approaches to energy supplies and assembly techniques. Boundary conditions and 3D thinking are important qualities that are considered in relation to progressing the Dod’s development on a more immediate level.

Chapter eight aims to highlight the most important aspects that have influenced the study and bring it to a conclusion. The output of this study is a tangible prototype and a source for future research that builds upon the potential of the Dod design. Due to the multidisciplinary nature of the study it is important to create a concise overview which this chapter aims to do.

1.3 Research Context

This study is a natural progression, built upon research that came before it and it is important to mention some key individuals and concepts that have influenced the approach to researching shape-shifting, interactive tangible interfaces: Ivan Sutherland: the Ultimate Display (Sutherland 1965, Steinicke 2016), Hiroshi Ishii: Atomic Bits (Ishii and Ullmer 1997), Doughlas Hofstadter: understanding patterns (Hofstadter 1995), Richard Feynman: complexity through simplicity (Dallas 2015) and Buckminster Fuller: the Geodesic Dome (Sieden 1989). Their approach to problem solving, forward thinking, the manner in which they dealt with adversity and general unorthodox nature has greatly contributed to being able to alter perspectives throughout this study to gain a variety of insights like the brain storming aid of the 6 hats (National Chiao Tung University 2017). The researchers and projects discussed in the following section provide a context and grounding for the three main areas of interest related to designing a MAS agent:
The conceptual idea
• Its physical manifestation
• A behaviour model

As mentioned earlier, Butera’s and Horev’s work have been vital contributions. As is evident in the scenarios presented at the beginning of the chapter, Horev details the concept of transmitting object affordances through the quality of shape change. He highlights the scope of haptics as an alternative sensory bandwidth and the concept to give the virtual and digital realm more grounding is an important factor in his work. He also lists a set of applications to which a morphing interface may be ideally suited: “Hidden statuses...Process Guidance...Adaptation to Context” (Horev 2006). These projects provide the reasoning and justification for shape-shifting, morphing or programmable matter-based interfaces. In relation to the communicative aspect, the work done by Lifton is an indicator regarding communications between a large quantity of agents and how they can function in a network configuration (Lifton 2002). He poses the questions how to process, communicate and apply the voluminous influx of data gained through large sensor matrices contained in current machinery, particularly with respect to the robotics domain. As well as this, he explores the emergence of elegance, out of complex systems through the mechanism of self-organization / assembly. Lifton presents a distributed sensory network in the form of hardware and software embodied through pushpin computing. Similar to Butera’s vision, Lifton’s research supports a system whereby it is possible to incorporate the following functions:

• add more agents to an existing system and have them integrate faster because they can benefit from the agents that came before them,
• the ability of a system to self-repair
• compensate for possible failures in specific areas
• localise and isolate problems rather than affecting the whole system.

The practical design contributions from the following researchers has influenced the definition of essential design parameters such as scalability, locomotion, assembly and dis-assembly mechanism, communication mechanism, and ability to change shape and form (of the agent itself or the resulting structure).
Cubli is a cube shaped modular robot that is designed to jump and balance on a corner based on the principles of angular momentum (Gajamohan et al. 2012). Although this technology is difficult to reduce in scale, the approach offers interesting and unexpected behaviours with respect to what is expected of a cube, i.e. its positions of stable equilibrium.

Mblocks are 5cm cubic robots that can pivot in 6 directions and, like Cubli, their method of propulsion is based on angular momentum. These robots can function individually as well as connect to other modules, via magnetism, which means there is a greater freedom in building structures and the movement of individual robots (Romanishin et al. 2013). However, since their connection mechanism is based on permanent magnets, difficulties can arise due to internal structural bonding strength, particularly when a structure of Mblocks is being built upon, and magnetic interference can create areas of weaker or stronger magnetic attraction.

Sandcubes are modular cube shaped robots that achieve structures via a subtraction method, principally similar to top-down processing whereby unnecessary robots are removed from an overall starting mass. These robots have achieved a scale of 1cm and connect via custom made electromagnets that allow a degree of controllability regarding individual assembly and disassembly (Gilpin et al. 2010). Even though these robots have limited communication ability due to the hardware constraints, the overall behaviour exhibited by Gilpin’s design, is the closest to date that is envisioned for programmable matter for shape-shifting tangible interfaces.

A project that follows in the footsteps of Gilpin’s Rock Pebbles is Cubimorph as developed by Roudaut’s research group in the University of Bristol (Roudaut et al. 2016). A striking feature is that the cubic shape has again been chosen. It indicates that despite addressing key issues such as displaying visual images via embedded screens, reconfigurability and scalability, improving the physical design of the agent did not undergo any further development. The functioning prototypes are 7.6 x 7.6cm and even though their scaled equivalents are not actuated, they demonstrate how the modules can be reduced in size and be powered by the piezoelectric technology. The improvement in this design is the ability to use the facets of the cube for alternative functions other than solely assembly or disassembly mechanisms (Roudaut et al. 2016). This adaptability and flexibility of application is desirable for designing an
agent that not only functions with a multitude of other agents but is also able to execute multiple functions within the agent itself.

Regarding the domain of biomimicry, the TERMES robots are based on termites. Termites provide inspiration with respect to behaviour, e.g. climbing, building and navigating a structure. They use whegs to aid in the climbing and manoeuvring of the robot (Case Western Reserve University, Petersen et al. 2014). These robots build a structure from the ground upwards, comparable to a physical manifestation of the bottom-up process. This project in conjunction with concepts such as Karel (Bergin 1997) were vital with respect to providing insight into programming primitive behavioural components, e.g. how basic behaviour components are formed and translated so that a robot can interpret them. While this type of design is not yet adaptable to real world situations, as it currently requires a specific type of block to build structures, the principle of referencing existing and successful features in nature is a key element that links functional and aesthetic design. It is a principle that is evident in the majority of projects that involve design regardless of domain (University of Wollongong 2016).

Proteo is a digression from the shape of the cube and is based on a rhombic dodecahedron. Whilst still originating from the geometric polyhedron concept, Proteo has an increase of complexity simply due to there being 12 faces as opposed to the cube's 6 faces. Even though the physical obstacles regarding design were recognised (e.g. impossibility to reduce the size of the agent), the authors explored the communication and control primitives required for individual robots / modules to interact with each other (Bojinov et al. 2002). It became clear that because geometric shapes do not have inherent communication-specific mechanisms (e.g. eyes, ear, whiskers, skin, hair, etc), the method of communication is dependent on the shape itself and the extraneous sensors that are added by their designers.

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2 Being based on blocks these structures are usually bottom heavy requiring a large base depending on the height. See WallE, (Stanton 2008).
3 Karel is a simple introduction to object orientated programming for robots
4 The Phage is an example of a structurally complex microscaled organism that already exists in nature, (Rohwer et al 2014).
It is interesting to see from these projects\textsuperscript{5} that the most common vessel chosen for accomplishing programmable matter is the cube\textsuperscript{6}. It is a central tenet of this study, that the cube is an inefficient shape for the final representation of what shape-shifting technology or programmable matter is proposed to achieve. Basing structures or a world on a cube is at times convenient but inadequate at providing a wholesome representation of the environment. It is convenient because of its limitations or boundary conditions (6 facets), the familiarity of the shape (cuboid = building blocks, Lego®, voxels, Minecraft) and it is easily calculable. The cube is not very accommodating with respect to coping with error and it does not allow for curves easily.

Refining the earlier question as to how far shape-shifting technology has progressed, the new question is whether it is possible to create a building block that is better suited to realising Butera’s vision of a fluid, shape-shifting tangible interface. This study aims to answer this question. Before defining the output of this study, the guiding principles for approaching the design aspect of the agent will be discussed in the following sections. This relates to perspective: which design elements are applied and why error could be used as a source of creativity, what simplicity is required to achieve constructive complexity, furthermore the element of control via boundary conditions, and most importantly replication versus emulation.

\textsuperscript{5} Each project described here presents its own set of scenarios which are of interest for further reading to expand the field of application for this type of technology further.

\textsuperscript{6} It is important to note that alternative shapes, sizes and type of agents have emerged from the research being carried out in the fields of programmable matter, autonomous, self-configuring, self-assembling, adaptive and interactive multiagent systems. However, each of these shapes tend to address an isolated issue of a multiagent system - communication or assembly or construction, etc.
1.4 Perspective

Consider the concept in quantum physics that the polarisation of a specific particle is determined through observation. Imagine how this is applicable to genius and insanity. Is it possible that they occupy the same space and time and that depending on the outcome of an idea or experiment, will be regarded as a success or failure?

“What I cannot create, I do not understand” – Richard Feynman (Eichenlaub 2015). The reverse is also applicable – a concept that is not understood cannot be adapted, shaped or reused to suit other purposes. In this study, a clear distinction is made between replication & emulation. Even though the difference between these two concepts is subtle, it is sufficient to propagate throughout a system and substantially alter the final outcome.

When an element, system or process is inspected through an acute focus, it is possible to change how it is perceived. Hofstadter illustrates this process in his use of micro-domains. The intense focus enables the researcher to gain access to alternative perspectives which in turn help to understand how each system variable functions:

“less impressive than real world domains, the fact that they are explicitly idealised worlds allows the issues under study to be thrown into clear relief – something that generally speaking is not possible in a full-scale real-world problem.” - (Hofstadter 1995)
What these three influential ideas have in common, among other elements, is *Perspective*. It is also the reason why they are visually represented in this manner. Even though the medium of writing is sequential and linear, the process of research is generally non-linear. Different strands of research usually run in parallel or can occur in disjointed bursts. The manner in which *perspective* is approached and applied can yield insights that are as valuable as those achieved through purely scientific experimentation. Perspective is inherent in every piece of research but inevitably it occasionally becomes obscured. An example that demonstrates the impact of perspective, is Buckminster Fuller’s presentation of the Dymaxion Map. It was the first map of its kind to more accurately represent the world’s landmasses. However, due to its unique geometric division it is possible to rearrange the individual sections to present different emphasises. For example, when Fuller was requested to demonstrate the Dymaxion map to state officials (e.g. British government), he presented it such a way that the country of origin of the state officials, was placed in the centre: in demonstrating the map to Australian officials, Australia was placed in the centre of the map and the rest of the world was arranged around it accordingly, Figure 1.2 (Sieden 1989).

![Dymaxion Map](image)

*Figure 1.2 Dymaxion Map* - (a) land configuration, (b) ocean configuration.
The ability to change perspective is powerful because it is capable of influencing thoughts and decisions, even on a subconscious level. The difficulty with perspective is that it is built upon a person’s past experiences, knowledge and thoughts which means that no two perspectives are identical. Developing skills that enable a person to change perspectives is invaluable but is proving particularly useful in a multidisciplinary approach. Multi-perspectives are an inherent quality of this approach because moving between a variety of different disciplines means adapting to each unique methodology and approach, e.g. mathematics, 3D modelling, biology, art, etc. Being able to interrupt and reassemble these inherent perspectives, via the techniques of microdomains or altering boundary conditions, creates the possibility of seeing alternative elements in information that may initially be overlooked. An example of this approach is commonly used in mathematics, physics, fluid and aerodynamic, among other subjects, whereby an *ideal condition set* is defined (Durst 2008). It represents the controllable situation and one to which other scenarios can be compared to. It aids in the understanding of all the possible variables that can potentially affect the system and enables researchers to model the system. It is important to note that at this point, the modelled system usually cannot exist in reality. For example, the exploration of a water droplet is first modelled in the absence of variables such as gravity, friction, orientation, interaction and other forces. Boundary conditions are modelled accordingly to a weightless and contactless environment – it is the ‘perfect’ state or the ideal state in which the system or object can be modelled. It is not influenced by external factors that could impact on its internal structures and it is possible to decipher the fundamental variables required for existence in this particular state. Once this ideal condition set is established, it is then possible to begin altering variables to model the system, as it exists in reality. In a computer simulation of a particle system, physics (such as gravity, friction, viscosity, density, etc.) can be added independently to varying degrees of accuracy via [digital] physics libraries, e.g. Havok or Box2D. Whilst it is important to consider that these libraries are approximations of physical forces, i.e. models of models, their usefulness lies in being able to explore proof-of-concepts, in a research setting. Adding peripheral or independent variables to a system’s fundamental variables and adjusting them, until the results replicate a

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7 A simple game called Flow effectively illustrates the importance of time and the techniques applied in order to solve each level.
variety of outcomes seen in the natural world. This enables researchers to understand their effect and relationship to the fundamental variables. For example, it enables researcher to clarify that even if variables correlate to each other that it does not necessarily mean that one is the cause of the other.

The ideal condition set concept is integral to this study because it creates the scope for the agent to be designed out of context. The interesting aspect of this process is that since the final agent design emerged from a primarily aesthetic approach and did not previously exist (i.e. it is a new and unique design), the ideal condition set helped build and define the structure as opposed to stripping away existing variables to expose the fundamental system. The process provided insight as to how the fundamental variables develop and how quickly the variable become interdependent on other unconsidered variables.

The ideal condition set highlights that once a system has been fully understood is it possible to manipulate and alter it and have a basic idea of the resulting outcome. In this conceptualisation, building upon a misunderstood error is like building upon a crumbling foundation. It demonstrates that most progress in the exploration of new systems is quite slow because the fundamental variables must first be discovered and / or defined, and it illustrates that it doesn’t always need to be real to be useful. Some ideal condition sets are purely theoretical postulations that have been proven to be true by current means of understanding. It does not necessarily mean that this is the reality but only that it agrees with established and known perceptions of the real world.

Defining an ideal condition set may be applied on any level of research and is important in the process of conceptualisation. Once these sets are defined it is possible to apply them to similar situations, i.e. a good grounding is established upon which other projects can build.

In this study, even though the emphasis is on developing a more suitable and autonomous agent for the programmable / shape-shifting matter domain, a strong underlying influence on the research is the consideration that artificial intelligence is incomplete without an artificial awareness.8

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8 It is important to consider however, that the design artificial intelligence and awareness is merely a recreation or replication of an existing system: animals.
Projects that demonstrate robots with capabilities of responding to human conversation (e.g. Turing test) or exhibiting behaviours that can be interpreted by humans as mimicking emotions, suggests that these components are comprised of specific patterns, motions and algorithms (Togler et al. 2009, Wakita et al. 2009, Nakayasu 2010). These algorithms can be learnt by each system (depending on hardware capacity) but are also formulated from elements beyond text, grammar and content to include movement, sound, visuals, texture, etc. (Clemenger 2014). Children learn through observation, exploration, mimic and experimentation to create biological or organic based algorithms. The element of awareness is less defined because it requires self-reflection and the ability to become more than the initial input or starting point to eventually formulate concepts and processes independently.

The concept of intelligence is itself an issue of perspective and is relative. By comparison, awareness is present at different stages and to varying degrees of self-reflective connectedness. For example, a basic form of awareness is facilitated through sensory modalities, it enables the agent to connect with its environment, without the need for the incoming information to be processed. This is possible for organic as well as inorganic constructs but would only be considered unidirectional. Awareness combined with intelligence enables more effective and varied interactions to occur between agent and its environment, i.e. interactions become a bidirectional process. The greater the complexity of a living system, regarding shape and form, number of sensory modalities, the capacity to process this information, the greater is the complexity in determining the variables involved in awareness and how they affect it. Awareness is a conglomerate of many different aspects (e.g. time, emotion, logic, reason, knowledge, etc). One method of training awareness is by making connections between knowledge, experiences and the effect on the agent. This process relies on the ability to alter and be open to varying perspectives.

Enabling an agent to become aware and think for itself is also an aspect that can be disconcerting because it means that it is no longer necessarily subject to an external force in particular when it becomes stronger or more powerful than the initial force controlling it. This concept is linked to the next important quality that has been very influential with regards to the design process itself: how control can be used as a constructive tool. The manner in which control is dealt with had a direct impact of a
1. Introduction

critical juncture of the design development. How it is handled is unique to each individual, indicating that an agent’s experiences are a defining factor. Control is an intangible element guiding the design and decision-making process but is also important with respect to gaining insight into effective problem-solving strategies.

1.5 Handling Control

What does it mean to have control? The dictionary definition of control states that it enables a person or chosen object to “determine the behaviour or supervise the running of; a means of limiting or regulating” (Oxford Dictionary 2018).

The essence of control is to remove the unpredictable and to be able to influence and direct a system according to specific goals. A by-product of control, particularly in a research setting, is attaining an understanding of every element of a system. For example, in a recording studio, artists are recorded in sound proofed rooms which eliminates reverberation or any extraneous noises and elements that can potentially distort the original sound. This concept is counter-intuitive as this ‘dead’ sound is flat & unrealistic; it lacks the essence and depth of the original sound and does not sound natural. If this method produces such an undesirable sound, the question that arises is, why do it? The main reason is to gain control over the ‘pure’ sound created. This pure sound is comparable to a blank canvas. It is easier to add effects, such as reverb, echo, chorusing, granular synthesis, etc. so that the sound engineer has precise control over each effect thereby accurately achieving the sound that is desired. A simplified example is that a guitar solo can be made to sound as if it was recorded in a small packed room by limiting the reverb or sound as if it was recorded in a church or large hall simply by increasing the reverb and adjusting the balance between dry & wet signals. Seeking the basic element(s) of a system reduces the number of variables, which in turn increases the level of control attainable. With control, the sound engineer has greater scope for manipulation and flexibility in producing different sounds, and thereby creating the artists vision/impressions and other auditory experiences.

The expression “a blank canvas” is a literal as well as a metaphorical analogy that is most often used to express the concept of having complete freedom. It is less often associated with having complete control over a process. In the literal sense the artist may paint, destroy, or leave the canvas as is. The aim of a traditional white, blank
1.5 Handling Control

canvas means that the artist is not influenced by the medium but rather draws
inspiration from his/her environment and / or experience. White is supportive of the
vibrancy of the colour spectrum and is conveniently the most common canvas colour⁹.
However, the interesting contrast to the prior example of controlling sound is that when
control is mixed with freedom, it incorporates elements beyond control, i.e. it can
produce unexpected results. For example, artists may choose different coloured
canvas means or may have no choice: The artist Paul Gauguin, due to his circumstances,
availed of the sack canvas that was used for transporting vegetables & supplies. This
canvas was rough, often yellow-coloured and influenced the colours Gauguin chose to
work with. This meant that he could create a unique and completely different
impression to one, if the same painting had been done on a white canvas. It gave
Gauguin’s paintings the earthy, tropical essence which made his paintings unique.
Even though he controlled the paint he used on the canvas (i.e. how he painted, the
colours he chose, what he painted), an element beyond his control was how this colour
is perceived due to the tinted background and as a result the impressions that were
created. Rather than attempting to control all the materials, i.e. mixing the colours to
counteract the tint of the canvas he used them accordingly and the result is a valuable
and unique contribution to 19th century European art history.

Another interesting approach to the concept of control is the interpretation through
Mathematics which also links with Fullers definition of boundaries (Fuller 1975,
Sieden 1989). As mentioned earlier, control encompasses understanding core elements
and variables that are present in a given system for the purpose of manipulation. Before
fractal mathematics became widely accepted, Euclidean mathematics helped
determine how the world was modelled mathematically. Its inefficiency became
apparent when people attempted to place naturally occurring structures into ordered
dimensional moulds and controllable concepts¹⁰: e.g. straight lines. For example,
measuring coastlines: if the straight line was to be used it would have to be given an

⁹ If the canvas is coloured, it affects the painted colours accordingly, with respect to perception as
well as saturation levels. It is comparable to placing a tint on a photograph. Due to the science of how
light reflects in the human eye, the colours we see are relative to each other. Red on a white canvas
has a different effect on the viewer than red on a yellow canvas, etc.
¹⁰ a curve or straight-line is clearly definable and therefore more comprehensible when compared to
an infinitely self-repeating pattern. This pattern may be broken down into smaller components
however when this pattern must be read as a whole it often does not fit the predefined structures and
mental models which were designed by people to make sense of the environment
ever-decreasing value to accommodate all the curves of the coastline. This meant the calculated length of the coastline would grow dis-proportionally as the inaccuracies of the straight-line geometries would accumulate. By applying Fractal mathematics, a more accurate measurement of the coastline was achieved (Mandelbrot 1977). Relinquishing control over certain elements or variables (in this instance pre-defined mathematical constructs) enables new experimentations to be trialled, accepted and integrated.

A recent development that enables scientists, in particular marine scientists, to define the growth and structure of corals, was discovered via crocheting (Wertheim 2009). This handcraft enables a person to create the same shapes and structures of a variety of different coral structures. Crocheting is a well understood, defined and established technique of essentially looping and knotting thread. Thus, in working with crocheting it was possible to gain control over previously undetermined parameters and thereby gaining insight and understanding about the creation of fundamental coral structures (Wertheim 2009). This understanding can be translated into mathematical equations, which can potentially act as universal blueprints. These blueprints are used, particularly in technological development, to inspire unique and new creations or solve existing problems (e.g. construction (Petersen et al. 2014), upside down drilling (JPL 2012), fibre optics (Ray 2013), etc).

These examples have shown how control is relative to a situation and to the person using or exerting it. They also illustrate that control is a human construct and being so means that it can be influenced by logic and reason as well as emotion. Humankind has a fundamental desire for control and has demonstrated this desire to varying degree in a large variety of domains, ranging from the social to the physical sciences. In the biological sciences attempts are being made to attain control at the most fundamental level – DNA. With the ability to program DNA it is hoped to be able to build microstructures by designing a type of programmable-glue that can hold hydrogel particles together (Qi et al. 2013). These examples demonstrated how people attempt to gain control over a medium or system to achieve an alternative result. This type of control is useful and necessary in conjunction with defining an ideal condition set. Control aids in unravelling and isolating fundamental variables as well as helping researchers understanding how these variables function. The intangible aspect of
control that emerges is a desire to be able to directly influence something. This indicates that aside, from a practical application, control can have an emotional response attributed to it, depending on context. For example, in scientific experiments physical control of the environment and the materials is necessary in order to achieve accurate results, i.e. control in an experiment – control relates to the experiment components. The emotional state or response is generally neutral because control in this context is part of a factual procedure and relates to the researcher, i.e. control of the experiment.

The manner in which a person approaches and deals with control is reflective of themselves as a person and their experiences. This in turn is indicative of the results that emerge in situations where control is necessary. Throughout this study three approaches to dealing with control have been identified A) total control, B) no control and C) balanced control. Even though this study is centred around the design of more adaptable agent, recognising these approaches and their effects contributes to employing better problem-solving strategies, among other implementations. Since the concept of control is relevant on many levels for this kind of shape-shifting interface technology, exploring it provided a valuable contribution to this study.

People move within the three approaches to dealing with control on a regular basis. In the descriptions that follow it is important to contextualise the concept of control and its application. For this purpose, an extreme situation is chosen, i.e. how control is applied to chaos. The term chaos will be viewed from a physics perspective: ‘behaviour so unpredictable as to appear random, owing to great sensitivity to small changes in conditions.’ (Oxford Dictionary 2018). In this situation control is an attempt to bring order and structure to a system or situation. Control and order are seen as means of eliminating or reducing the unknown and the unpredictable. The more structured and ordered a system is, the more potentially energy is contained within the system. Living organisms embody this concept: young children have higher energy levels as they are growing and learning whereas older people have expended significant energy throughout their lifetime and begin to decline. A system that tends towards disorder has increasing entropy levels. Relating this to MAS, it is important

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11 It is important to reiterate that the concept of control described for this project is a human interpretation, it has emotion inherently incorporated into it; hence the descriptions of the three states are interconnected with the emotional states that drive them.
to enable individual agents to become independent so that energy can be directed to
the overall shape-change of the interface as opposed to being directed to each
individual agent.

Even though the previous sections suggest that there are three perceived states of the
application of control, the two states that are relevant for this study are the effect of
applying total control and balancing control. There is an emphasis on viewing control
from a human psychology perspective because it is based on the author’s personal
observation and experiences. Whilst a large body of research exists on this topic from
the social sciences, psychology and psychotherapeutic perspective, it is important to
document the approach to control in this study because of its effect throughout the
design process. In choosing to predominantly implement an artistic methodology, it
inherently involves the personal characteristics of the artist, i.e. who the person is
comes through in the artwork. Whilst many designers or artists have similar
experiences, describing the process from a STEAM perspective provides an alternative
perspective as to how critical junctures in design or research can be approached. The
following observations may also provide insight as to why there is a difficulty in
clearly defining artistic methodologies.

1.5.1 Total Control
As mentioned earlier total control over a system’s variables enables researchers to
understand a system completely and in turn can manipulate it to fulfil specific, goal-
orientated tasks.

For a person to exert total control over their surroundings or decisions requires large
amounts of energy, either in the planning or execution stages. It is a difficult state to
maintain because of the multitude of variables a complex system is comprised of. From
an emotional aspect, this state is most often driven by fear: a fear of the unknown and
of change, and it represents an inability to let go. Channelling these types of negative
emotions can lead to negative affect, as mentioned earlier in section 1.1.2. Don
Norman describes the effect negative emotions can have in interactions with systems
around us: the ability to see creative solutions and deal with error is significantly
reduced. Tolerance for the unexpected and patience in dealing with difficult
interactions is also reduced. Whilst negative affect enables some people to become
more focused, designing or interacting with systems in this state is not optimal (Norman 2005).

The effects of total or excessive control is demonstrated by the following example. Philosopher Guy Debord proposed the theory of “the Society of the Spectacle” in 1967. He developed a theory for a time that was being heavily influenced by visual media, i.e. reality was not what it seemed and yet people believed nearly exclusively what they saw because they thought that the new technology could not lie. He stated that the Spectacle was often re-purposed by those in power as a tool to maintain total control. For example, a government creates a problem and makes sure that it is the only one that can solve the problem. Society sees only that the problem exists and will turn to those who will be able to solve it. Therefore, the government can maintain control over the society (Debord 1967). This state however is too rigid as it cannot adapt to the unpredictability of human nature. It will inevitably collapse as it becomes impossible to control all the variables and maintain the energy that the state requires.

For a MAS controlling each individual agent is inefficient as such a system would be weakened and susceptible to error. Therefore, it is necessary for each agent to cope independently without the need for external assistance in relation to basic functions, like localisation, orientation, communication, etc.

1.5.2 Balanced Control

Balancing control is an intermittent state and it can be described as guiding the continuously changing variables of a system or process. It is the skill of knowing when direct intervention or inactivity is required. It enables opposing sayings such as ‘the early bird gets the worm’ and ‘good things come to those who wait’ to exist and both be correct. Recognising when either behaviour is applicable is the challenge.

The tenuous nature of the balanced state, is dependent on the character of the person. For example, if a person tends towards anxiety then the desire to regain total control in order to create an illusion of security and understanding, is greater. If a person is insecure, they can let themselves be influenced more easily, as well as doubt their own decisions and thereby have little control over situations. Being able to take control as well as letting it go requires a degree of self-confidence and self-belief. The effect of
choosing particular moments in which to apply control is evident in the decision-making process. It is important to remain open to events and opportunities and it is just as important to control specific moments in order to nurture progress and development.

Another quality of balancing the application of control is the ability to create meaningful boundary conditions. This is a necessary skill in becoming autonomous. To describe this process visually, artist Oosterman turned her daughter’s doodles into recognisable images. The child’s doodles are an analogy for the flow of chaos and the images that the child’s mother depicts from these doodles are representative of guiding chaos into a specific form or concept (Oosterman 2015). Not all the strands of the doodles are incorporated into the final drawing, indicating that control is exerted in the decision of what is perceived. Dealing with balancing the level of control exerted on a process was an important milestone in the development of the Dod prototype in this study.

To provide some context for this specific impasse, Time was perceived to be a non-negotiable boundary condition in this instance and it became necessary to establish a design that could be developed further, rather than remaining in the early testing or brainstorming stage. There were two viable choices: to succumb to anxiety and continue with a design that was proving to be problematic and too complex or to revert to a prior skill but move the design in an opposite direction, i.e. shifting the focus from function to aesthetics.

The second choice meant that the agent design would initially move further from fulfilling its original aim, if at all, and it also represented the unknown and therefore less control:

- is it the right avenue to follow?
- Is it conducive to the overall study?
- Will it yield an actual result?

Whilst these fears/questions are a normal part of any study it is necessary to make a choice regarding specific avenues to explore further. These concerns, as well as the emotions of fear and anxiety, increased the probability of choosing the first option.

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12 These situations are common occurrences in life which is why being able to cope with them more efficiently is beneficial on professional as well as personal levels.
As is evidence in this study, the second choice was made which enabled the agent design, the Dod, to be developed and explored in depth. Therefore, by letting go and relinquishing some control of the situation, a space was created that enabled the new idea/design to gain traction. Once this new idea was established and proved its merit, it could be moulded to suit specific requirements, i.e. control was exerted again in the process of defining specific functions that affect the overall design.

These ideas about control are not new and may have been expressed in different words in different domains but their meaning essentially stays the same. Similar to intuition, control is an intangible quality and uniquely perceived by every individual, it becomes evident throughout the outcomes of its application. Understanding the effects of control and the manner in which it is applied helped mature the decision making and problem-solving process with respect to design the Dod prototype in this study. In working through Art, it was possible to develop the prototype but also provided the possibility of self-reflection and growth. With the aim of creating aware and autonomous MAS, these reflections may provide further insight into the process of awareness.

1.6 Guiding Principles

Aside from the approach to handling control and thereby defining specific boundary conditions, there are three concepts that have guided the philosophy behind the agent design proposed in this study:

- The replication versus emulation principle,
- The importance of error (perspective),
- Keeping it simple (ideal conditions)

1.6.1 Replication vs. Emulation

The difference between replication and emulation is subtle but yields substantially diverse outcomes. Replication is the process of reproducing an exact copy of an existing system, artefact or structure whereby reliable repetition is an inherent quality of the process. Understanding and learning are rooted in this process and it is vital to complete this phase as thoroughly as possible in order to construct a knowledge
foundation (Robugtix 2013, Ridden 2015). The development of hand prosthetics is an example of this. The improvement in prosthetics reflects the continuously increasing knowledge base gained through understanding all the variables involved in the human hand. Comparable to Hofstadter’s microdomains, which functions on reductionism, it is possible to understand the interconnectedness of the variables involved: finger localisation, pressure sensitivity, accuracy and resolution, feedback and delay, texture and temperature recognition, etc. Other than in the physical aspects of a prosthetics, another difficult challenge lies in integrating the inorganic mechanism with the mental awareness and consciousness of the wearer, i.e. dealing with physical and as well intangible variables. Prosthetics therefore can also demonstrate the process of emulation.

Emulation encompasses the idea of copying or imitating an existing system, artefact or structure, however the important difference is that it also holds scope for surpassing the original design, i.e. it represents the evolution of an idea. Original thought or ‘strokes of genius’ occur on rare occasions. In most cases ideas and creativity are built upon the experience of previous generations and through an emulative process. For example, in Art, painters like Picasso first painted in the style of the time: Realism (life drawings, still life, etc.). Only after he had mastered this art of drawing, he began defining his own interpretation eventually leading to Cubism. His approach supports the concept that building a good foundation is essential in being able to manipulate the knowledge further. This approach echoes Feynman’s expression from section 1.4: “What I cannot create, I do not understand” – Richard Feynman (Eichenlaub 2015).

Emulation can be viewed from the perspective of applying the knowledge gained through the replication process. Consider the example of flight: the initial attempts of modelling a direct replication, of a bird’s wing onto the human physiology, did not work. As the knowledge of the wing and its relationship to its environment (air) was uncovered, new wing designs began to emerge. The concept of wind moving at different speeds over different surfaces creating lift or drag helped inform a wing design that could be used by humans. Therefore, through emulation humans can fly but not like birds. The essence of what flight means and how it works has been extracted and the knowledge has been adapted and appropriately altered. Similarly, with respect to prosthetics, some modern leg / foot replacements have isolated core
processes and even enhanced them. From the rudimentary wooden peg leg, carbon fibre spring blades offer alternatives to an exact replica of a human foot (Endolite 2018, Össur 2018). The blades represent a design that accommodates a reduced set of variables inherent in the foot / leg mechanism. Even though it is not shaped like the biological spring present in a foot, it functions better and is potentially more suitable for a new context.

With respect to agent design in this study, it is evident that some of the shapes and constructs used in earlier prototypes often did not function as well. Whilst they were replicated directly from their original use, they were taken out of the environment for which they were initially designed for and used for tasks that were outside their scope of adaptability (see cat-claw prototype, Chapter 3). This highlights the limitations for direct replication and a reason why it is important to extract the core concept or essence of what is needed to provide the parameters for the design.

1.6.2 Error as creativity

“Any measurement that you make without knowledge of its uncertainty is completely meaningless” – Walter Lewin (OpenCourseWare 2008).

Error, mistake, inaccuracy, and miscalculation – these are some words to represent the concept that an event has not gone according to a preconceived plan. Since most plans are designed to work to the advantage of the planner, when an error occurs it is most often viewed negatively. It is indicative of how the concept of making a mistake is shameful and can lead to negative experiences. The concept of error being an integral part of creativity emerged as the final agent design was being explored. Unforeseen results started to emerge from what could be considered a flaw of the shape itself. This will be elaborated on further in Chapter 4.

In this section the meaning of error is illustrated from different perspectives, the interpretations of which attempt to alter the preconception of error.

- Deviation. Certainly, some errors can only be made once and can have a detrimental outcome however error can also have unexpected positive results. These are most often encountered in Art or alternative outlets that have a greater emphasis on creativity.
• **Education.** Errors can make items unique and are often remembered more vividly than a perfect performance. In the process of learning and understanding, mistakes highlight areas that require further investigation. Once these areas are overcome, the conceptualisation and understanding is deeper and more complete. It is then possible to alter variables with a greater ability to predict the probabilities of specific outcomes.

• **Imperfection.** Despite a desire to reach a level of perfection in any given field whereby perfection indicates that the occurrences of errors are miniscule, there is also an appeal in imperfection. Whilst this sentiment is predominantly applicable to the creative outlets of human endeavours, the acceptance of error in certain instances provides alternative perspectives.

• **Flexibility.** In Chapter 4, error is addressed in relation to how the agents connect to each other. For example, in facet-to-facet connection, even if the orientation of the opposing facet does not align it is not detrimental to the system. The ability to cope with this error illustrates a degree of flexibility within the system. Accepting this flexibility means giving up some control to the system itself and integrating a certain amount of unknown. Unexpected results that can occur through error may be comparable to moments or contributory elements of creativity within a system and part of a systems strength can be determined by the ability to cope with this type of creativity.

• **Imagination.** The importance of art or science fiction will be reiterated throughout this study on several occasions. In this instance, film, animation or narrative are platforms that allow the concept of shape-shifting interfaces to be creatively explored. This also relates to error being safely and (relatively) inexpensively considered. Through the Arts it is possible to contemplate design via aesthetics and imagination rather than reality and fact. It is possible to postulate how systems should look, function and behave without primarily considering practicality or production costs. More importantly it fulfils a shortcoming that is currently difficult to conduct in a lab setting and has been identified as a significant gap in the background literature (Coelho and Zigelbaum 2011) – the applications and settings of newly conceived haptic interfaces.
In comparison to previous concepts of control and emulation, error is also inherently linked to perception, meaning that it has an intangible component to it. Whether an error is considered to have a creative or negative influence on a system or design depends greatly on perspective and the context in which it occurs and the outcome of the event.\(^\text{13}\)

### 1.6.3 Keeping it simple – emerging complexity

In an interview with Richard Feynman, he outlined the concept that even though an overall view of a system or object may seem endlessly complex because of the vast number of variables working on it, it is essentially comprised of very simple rules. It is the combination and quantity of these rules that define the level of complexity (Dallas 2015). Complexity is a description of the resulting interaction of these rules with each other and their environment. This concept is demonstrated in nature by the silicone-based sponge: Venus flower basket (Euplectella aspergillum). This sponge can create the strongest structure possible, using the optimum amount of material. This is due to the checkerboard-style filled lattice, whereby filling every square of the lattice would not improve mechanical performance or strength (Dr. Joanna Aizenberg, in Ray (2013)).

The basic structure or spicule is illustrated in Figure 1.3a. Each arm extends at a specific angle from the core. This configuration means a circle can be built when these components are combined Figure 1.3b and 1.3c. When another circle structure is offset to the first a square lattice pattern is constructed Figure 1.3d.

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\(^{13}\) *My sister and I were walking in our local park and noticed some blackberries. The fruit was beyond the fenced off pathway and naturally the best berries were furthest away. In order to reach them I leant over the fence. Since it was farther than I could reach on my own, my sister held onto the back of my t-shirt. The situation was precarious - if I fell it would be unpleasant. During the process of collecting berries I posed the question 'Is this actually a good idea?' - to which my sister answered, ‘Well if it works, then yes because it’s team work and if doesn’t then no because we were greedy’.*
1. Introduction

The complexity of the overall structure as seen in Figure 1.3e, is based upon the combination of many of these simple spicules.

In relation to the physical design of the agent and the principle of keeping it simple, the continuous refocusing of the design process is necessary to achieve an efficient and concept orientated agent. This is similar to the process of finding the lowest common denominator in mathematics. The beauty of a system is linked to the simplicity of the rules upon which it is founded and as Dirac proposed, the “principle of mathematical beauty... [as we] advance in fundamental theoretical physics, the theories as they get closer & closer to nature become more & more beautiful”. If an equation was too complex or convoluted, Dirac claimed “wouldn’t pass muster with nature...had to be beautiful for it to stand a chance of describing nature” (Maindrivefailure 2012).

This approach was valuable in the development of the behavioural aspects of the agent design, in particular with respect to the physical coding aspect. Attempting to define simple rules that result in the specific and desired interactions was a good exercise in recognising the degree or extent of control that was necessary. The process is similar to creating a microdomain, like those described by Hofstadter. It provided a greater appreciation and understanding for the process of emergent behaviour.
2. Literature Review

2.1 Introduction

The following literature review details the core aspects of research that support the question of what elements constitutes a better adaptable agent design to function in multiagent systems (MAS) for the use of creating 3D real-time shape shifting tangible user interfaces.

The main areas are Non-Newtonian and smart fluids, self-assembly, haptics and related work. Non-Newtonian and smart fluids are the pillars of the initial research. Specifically, the shear-thickening and stigmergy behaviours exhibited by fluids that fall under these categories, were of interest. The mechanism by which the behaviour occurs as well as the particle that enables the behaviour to exist are the primary focus of the early research.

From this juncture, the next stage was to analyse the ability of liquid particles to self-organise and from this ability how biological agents can self-assemble. In this instance, it is not so much the mechanism for communicating self-assembly but rather analysing mechanisms for physical self-assembly, i.e. how to attach and detach from other individual agents. Biology and nature are the sources of inspiration in this aspect since it is possible to find multiagent systems that can self-assemble as well as exhibit Non-Newtonian / smart fluid behaviour. The elements described up to this point deal with the interface - in particular the most basic component: the agent.

The other major component of this study is human haptics. The range of elements involved in tangible user interfaces is extensive and diverse. Considering how people perceive through touch, the information that can be gathered physically and the ability of bidirectional information exchange are qualities that can also inform the agent design. For example, the perceptual Gestalts that are formed for haptics are an invaluable contribution to the design process (e.g. soft and furry is considered safe whilst sharp and jagged is believed to represent danger).
2. Literature Review

To contextualise the influence of these three fields, the last section of the literature review details the projects, prototypes, and concepts that explore the topics addressed above. These projects enable this study to be positioned in the field of interactive interfaces and demonstrate the contribution to this field.

2.2 Non-Newtonian

An interesting phenomenon of Non-Newtonian fluids is the shear-thickening effect. Continuous research is attempting to discern the exact mechanism, which allows this effect to occur (Fall et al. 2012). A brief description of the current research to date in this area will be detailed in the following section.

Cornstarch and water is one of the most common colloid suspensions known to exhibit shear thickening behaviour. Apart from this behaviour a variety of other formations are clearly and precisely definable, i.e. fingers, rivers, holes, and jumping liquid (Kann et al. 2013a). The basic concept of shear thickening is that under minimal shear stress the colloid suspension has a weak force network therefore behaving like a liquid (Bi et al. 2011) and becomes semi-solid once the shear stress is increased, i.e. it is the result of the relationship between the shear rate and the steady-state shear viscosity (Chhabra 2010, Kumaran 2010, Fall et al. 2012).

The temporary solidification is also referred to as a jamming effect. The jammed region occurs before the yield stress boundary and is also related to the discontinuous shear thickening limit (Brown and Jaeger 2009). There are a multitude of different factors that can influence this effect. Those listed below have been identified as being the most prevalent factor contributing to the shear thickening effect:

2.2.1 Particle characteristics

- **Shape**: (Fischer et al. 2007, Francisco and José 2009, Waitukaitis and Jaeger 2012)
2.2 Non-Newtonian

- **Surface topology**: (Maranzano and Wagner 2001a, Kaldasch and Senge 2009, Gurnon and Wagner 2015)
- **Dispersion**: (Stickel and Powell 2005, Fischer et al. 2007, Francisco and José 2009, Waitukaitis and Jaeger 2012, McGavin and Hart 2013)

### 2.2.2 Liquid characteristics
- **Suspending liquid viscosity**: (Fischer et al. 2007, Francisco and José 2009)
- **Interparticle forces**: (Francisco and José 2009, Brown et al. 2010, Gurnon and Wagner 2015, Liu et al. 2015)
- **Dilatancy**: (Fischer et al. 2007, White et al. 2010, Bi et al. 2011, Fall et al. 2012)
- **Boundary Conditions**: (Fall et al. 2012)
- **Time**: (Maranzano and Wagner 2001b, Waitukaitis and Jaeger 2012)
- **Temperature**: (Christianson and Bagley 1983, White et al. 2010, Liu et al. 2015)

By reducing the scale to the level of particle-to-particle interactions it is possible to examine how the particles affect the viscosity of the suspending liquid. Understanding the effect of the above-mentioned parameters on the particle trajectories is also the basis for understanding the shear thickening effect (Waitukaitis and Jaeger 2012). In the presence of a shear field, the interactions between liquid and particle create a difference in speed of flow between the upper and lower hemispheres of the particle. If there is no slip between liquid and particle then the liquid that surrounds the upper hemisphere moves slower than surrounding the lower hemisphere, this induces rotation of the particle, see Figure 2.1 (Everett 1988).
2. Literature Review

2.2.3 Dilatant behaviour

Viscous forces that affect the surface of the particle counteract the rotational motion, thereby increasing the viscosity (Everett 1988). It follows that the general consensus with respect to the shear thickening effect is that there is a distinct relationship between particle volume and the increase in overall viscosity (Maranzano and Wagner 2001a, Cates et al. 2005, Stickel and Powell 2005, Brown and Jaeger 2009, White et al. 2010, Bi et al. 2011, Fall et al. 2012, Waitukaitis and Jaeger 2012, Liu et al. 2015) as well as the relationship between strain rate and viscosity (Chakraborty 2012). As the volume of particles is increased with respect to a fixed amount of liquid, less energy is required to induce shear thickening behaviour. A packing fraction of 0.625 would be considered at the upper limits of maintaining transitions between liquid and solid states of matter, whilst a packing fraction of > 0.3, the viscosity to becomes more obviously reactive to shear stress (Kalman and Wagner 2009, Krajnc 2011).

At the onset of shear thickening distorted particle trajectories contribute to the random organisation of particles, which are defined as hydroclusters. George Batchelor’s groundwork also relates particle trajectories in the formation of hydroclusters and their link to lubrication hydrodynamics (Fischer et al. 2007, Kaldasch and Senge 2009,}

Figure 2.1 Particle rotation - particle rotating in relation to flow speed and direction of shear stress. Reproduced from Everett (Everett 1988).
2.2 Non-Newtonian


Hydroclusters represent areas of higher density of particles that are not fractal or porous in nature, preventing flow by the formation of solid obstructions (Francisco and José 2009, Kalman and Wagner 2009, Jiang et al. 2010). These obstructions enable a force to be propagated throughout the suspension (Wagner and Brady 2009, Kann et al. 2013b). The cluster formations are pre-empted by the formation of particle chains that develop into the complex microstructures (White et al. 2010). These microstructures form, endure and evolve for the duration of the shear field (Maranzano and Wagner 2001a, Fall et al. 2012, Gurnon and Wagner 2015) and can be reversed again once the shear rate is reduced or removed (Brown and Jaeger 2009, Wagner and Brady 2009). In relation to the formation and size of the fluctuating clusters, the surface topology has two main functions. Firstly, an irregular, rough surface creates friction and viscous forces, and in conjunction with interparticle forces, contributes to the constant deformation and flexibility of the hydroclusters (Gurnon and Wagner 2015). Secondly it prevents permanent particle bonding via attractive van der Waal forces, thereby contributing to the reversibility of the shear thickening effect (Maranzano and Wagner 2001b, Kaldasch and Senge 2009). Once hydroclusters have formed, short-range lubrication forces become predominant in the increase of viscosity (Maranzano and Wagner 2001a, Maranzano and Wagner 2001b, Fischer et al. 2007). Lubrication describes the effect of distance between surfaces of the particles and plays a key role in disrupting Brownian motion (Maranzano and Wagner 2001a, White et al. 2010, Liu et al. 2015). It comes into effect if the distance between particles is smaller than the particle diameter (Jiang et al. 2010, Krajnc 2011).

In cornstarch and water suspensions, water is the incompressible component. Once shear thickening has set in and there is insufficient liquid for the particles to flow past each other around the shearing source, they will move around or roll past each other. This causes the particles to move away from the shearing source (Fall et al. 2012) and temporarily increase in volume. Figure 2.2 (Everett 1988) how the lack of liquid affects the void volume. This behaviour, also referred to as dilatancy, can result in a larger solid area being exposed to the surface, increasing the surface to air contact area.
This can lead to a loss of water via humidity and give the solidified area a dry appearance (Everett 1988, Cates et al. 2005).

![Figure 2.2 Void Volume](image)

**Figure 2.2 Void Volume** - the void volume changes depending on particle packing. Recreated from Everett (Everett 1988)

Dilatancy has been used as a means to describe discontinuous thickening (Cates et al. 2005, Fall et al. 2012). This occurs when the critical shear rate is attained and the colloid suspension experiences abrupt shear thickening (Fischer et al. 2007, Jiang et al. 2010). If the shear rate continues to increase the jammed area begins to break and fracture moving into the domain of granulation (Maranzano and Wagner 2001b, White et al. 2010).

There is an inverse relationship between viscosity and the distance to the shearing source, i.e. as the distance between two points increases the viscosity reduces and reverts to its liquid state. As the colloid attempts to dilate from the shearing source, the size and potency of the jamming effect is relative to the volume of the whole colloid suspension and the boundary conditions. These conditions may range from a surrounding confinement to a large volume of a Non-Newtonian liquid sample (Brown and Jaeger 2009, Brown et al. 2010, Fall et al. 2012, Waitukaitis and Jaeger 2012, Kann et al. 2013b). For a small quantity of Non-Newtonian liquid that is confined to a shallow container, force waves from a surface impact reach the bottom of the container and are reflected back towards the impact source without delay, similar to waves in sound or liquid, reflecting off of boundaries. These conditions mean that the
solidification can store potential energy so that a bounce may be detected after the initial impact (Waitukaitis and Jaeger 2012). As heavy objects begin to sink through a sample of cornstarch and water, whereby the particle packing volume fraction $\phi$, is equal to 0.41, it experiences oscillatory fluctuations in velocity. This indicates that each time the object reaches the critical shear velocity the sample jams, slowing it until the shear stress is reduced enough to allow flow again. In confinement, the ability of the object to sink is significantly attenuated (Kann et al. 2013b).

The direction of force, if originating from a surface impact, is downward and then spreads sideways and back up towards the surface (Waitukaitis and Jaeger 2012, Kann et al. 2013b). The ‘dead zone’ is an area that acts as a reservoir around the impacted / jammed region that enables the solidified area to become reabsorbed into the whole suspension. Depending on the size of this area it can have varying effects on the energy required to induce the shear thickening effect (Fall et al. 2012).

### 2.2.4 Particle size and shape

Examining the particle itself, it becomes evident that the particle size is not a defining factor (Kaldasch and Senge 2009, Fall et al. 2012). The particles must be small enough so as not to settle under the force of gravity (Kann et al. 2013a) With larger particles, the clusters that agglomerate are also larger in size, reducing the critical shear rate and the energy required in inducing the shear thickening effect (Maranzano and Wagner 2001b, Francisco and José 2009). There is an approximate inverse relationship between particle size and the critical shear rate, which comes into effect when the formation of hydroclusters is required (Maranzano and Wagner 2001a).

Whilst the shape of the particle has proven not to be a pivotal component involved in creating the desired effect, colloids with cornstarch particles and glass beads have proven to encompass optimum features. Cornstarch particles are roughly spherical in shape with an irregular and cratered surface topology; their diameters range between 5-20 $\mu$m and are suspended in water (Kann et al. 2013b, Kann et al. 2013a). Glass beads are larger in size, with diameters ranging from 88 – 125 $\mu$m (Brown and Jaeger 2009). These particles were suspended in a mineral oil and optimally suited for investigating the packing geometries due to their regular spherical shape. The geometric packing parameter is worth noting with respect to an increase in viscosity,
particularly in relation to defining the critical packing fraction (Brown and Jaeger 2009).

Aside from the particle component, the complex viscosity of a Non-Newtonian liquid is also a direct function of the initial viscosity of the suspending medium itself (Jiang et al. 2010). It is linked to the length of the molecular chains of the suspending medium but also the strength of the interparticle bonds, with respect to attractive and repulsive forces.

The ability to change viscosity due to the application of a shear force is not limited to Non-Newtonian fluids. Certain smart fluids or polymers can emulate a similar change in viscosity to emulate semi-solid behaviour (Halsey 1992, Stanway 2004, Grad 2006, Kciuk and Turczyn 2006). This occurs via a change in the externally applied field rather than an applied shearing force. The predominant advantage of this type of fluid is that the alteration in viscosity can occur within milliseconds, i.e. the viscosity is tuneable to a greater accuracy in real-time and the process is completely reversible (Halsey 1992, Carlson and Jolly 2000, Bossis et al. 2002, Grad 2006, Vicente et al. 2011). The particles within the suspending liquid align themselves along the gradient of the appropriate field (e.g. magnetic or electric) and can also withstand a certain level of shear in the direction perpendicular to the field (Wen et al. 2007).

### 2.3 ER & MR fluids

Electrorheological (ER) and magnetorheological (MR) fluids are two smart fluids that exhibit shear thickening behaviour. The first type of fluid experiences a change in behaviour with respect to a change in an electric field and consists of a dispersion of dielectric particles (Phulé 2001, Liu and Choi 2012). The latter fluid experiences changes with respect to a change in a magnetic field (Andó et al. 2011, Vicente et al. 2011) and consists of particles that can be easily magnetised. High purity carbonyl iron powder is the most reliable and widely used ferrous component used in MR fluids. It is magnetically soft, chemically pure and the particles are spherical in shape (Carlson and Jolly 2000, Phulé 2001, Bossis et al. 2002). Whilst both types of fluids were developed at roughly the same time, MR fluids were initially not viewed with much potential due to the difficulty in preparation, the abrasive qualities and the power required for the external field generation. Therefore, ER fluids initially became the
primary focus within academic and industrial research in an attempt to develop applications and gain better understanding of the solidifying mechanism (Phulé 2001, Stanway 2004). The first types of ER fluids developed, used water-based suspending mediums (Halsey 1992, Wen et al. 2007, Liu and Choi 2012). The ER effect was most prominent when water was used due to its conductivity, however, it had a very limited temperature range since water evaporated when the temperatures rose too high (Hao 2002). As research continued certain anhydrous materials, often polymers, proved to intensify the overall ER effect by aiding the ion transfer between the dipole induced in each particle (Ouellette 2004, Krzton-Maziopa and Plocharski 2009).

Despite this research ER fluids remain sensitive to impurities and require high voltage to induce a change (Hao 2002, Grad 2006). As preparation technology advanced, interest in MR fluids began to increase, however, each manufacture of MR fluid is specialized to individual tasks and must be custom made (Phulé 2001), see Figure 2.3a and 2.3b.

**Figure 2.3 Smart Fluids** - (a) basic components for ER fluids, (b) basic components for MR fluids.
The durability and life span of both types of smart fluids are still under continuous research. Problems such as clumping, oxidisation, sedimentation, and absorption of humidity can arise as a result of constant use, and in particular due to prolonged exposure to high stress and shear rates or high voltages. (Phulé 2001, Hao 2002, Ouellette 2004, Grad 2006, Vicente et al. 2011).

2.3.1 The ER & MR mechanism
Each type of smart fluid consists of particles that are ideally made of a semi conductive material suspended in an insulating medium (Hao 2002). When the fluid is at rest the suspended particles are evenly distributed throughout the medium. In contrast to Non-Newtonian fluids, the size and distribution of these particles affect the magnitude of the ER or MR effect (Kciuk and Turczyn 2006). As the external field is applied the particles become polarised and align themselves between the poles / electrodes along the direction of the field lines (Carlson and Jolly 2000, Stanway 2004, Kciuk and Turczyn 2006, Andò et al. 2011).

The particles begin to form chains, which continue to aggregate into larger column-like clusters similar to hydroclusters found in Non-Newtonian fluids (Bossis et al. 2002, Liu and Choi 2012). A directly proportional relationship exists between particle bond strength and the field intensity (Grad 2006). The chain like structure is a result of the particles along the line of force experiencing an attractive force whereas the particles located in the perpendicular plane repel each other (Halsey 1992). The bridging structure’s strength is strongest at and around the poles / electrodes and if breaks are to occur it would most likely happen towards the middle of the bridge.

This seemingly semi-organised cluster formation makes it possible to tune the viscosity of smart fluids according to requirements, i.e. the stronger the magnetic or electric field the higher the viscosity (Carlson and Jolly 2000, Grad 2006, Wen et al. 2007). In ER fluids, a temporary dipole is induced around the particle surface as it becomes polarised by the electric field and if the suspending liquid is in any way conductive the charge is located primarily at the particle surface (Halsey 1992, Hao 2002). Similarly, since ferrous particles have a magnetic quality, each particle has its own induced magnetic field. Essentially there is a positive and negative pole within each particle.
2.3 ER & MR fluids

There are several layers of forces acting throughout the smart fluids, which can potentially be described as fractal in nature with respect to the self-repeating behaviour. For example, each particle experiences a weaker version of the overall force, i.e. ferrous particles have their own magnetic field which contributes to the overall magnetic field coming from the external field generator. When particles are within a radius distance of each other multipolar interactions of higher orders become as relevant as the individual particle dipolar interactions (Halsey 1992). Whilst there are other thermodynamic forces (e.g. Brownian motion), which contribute to the overall fluid behaviour there is a constant & dynamic exchange of priority amongst these forces (Hao 2002, Vicente et al. 2011).

2.3.2 Maintaining balance

Maintaining a state of balance between each of the different components whilst trying to achieve the maximum effect, is a prominent feature of ER & MR smart fluids (Carlson and Jolly 2000). If one component is changed it has a domino effect on other dependant components. Both types of fluids have between 40% - 50% volume fraction of solid particles (Stanway 2004, Grad 2006). For example, the particle size must be considered in a MR fluid, in order to avoid sedimentation. Fibrous material proved to enhance the ER & MR response and even demonstrated an improved stability against sedimentation (Vicente et al. 2011, Liu and Choi 2012). The size of the particle can also affect the strength of the resulting ER or MR effect when experiencing a change in actuation field.

If a particle is large it can affect the overall magnetic field because its individually induced magnetic field is stronger (Carlson and Jolly 2000, Wen et al. 2007). This can cause areas of constructive and destructive interference resulting in areas of strong and weak magnetic attraction, which can be utilised to overcome obstacles such as wall adhesion or friction (Andò et al. 2011). For these reasons, it is difficult to accurately predict the behaviour of such fluids (Wen et al. 2007). On the opposite end of the size spectrum is Ferrofluid.

Ferrofluid consists of ferrous particles (0.1 – 10 microns (Phulé 2001, Grad 2006) in an oil based suspending liquid. In order to avoid or reduce wear/friction, altering viscosity, improve lubrication and help avoid sedimentation surfactants are often
added (Stanway 2004, Kciuk and Turczyn 2006). These are absorbed onto the surface of the ferrous particles and whilst they can aid in improving the polarisation induced in each particle (Kciuk and Turczyn 2006), the surfactant also has the potential to alter the basic composition & viscosity of the suspending liquid.

The particle shape helps defines the magnetic field distribution. In general, the particles should ideally be spherical, in order to facilitate a uniform magnetic field around each particle (Phulé 2001). Having particles that are of two different diameters can enhance the MR response in that the smaller particles can fill the gaps between larger particles when the chains and columns are being formed and aid in the breaking up of larger particle aggregates. This holds for both ER & MR fluids (Bossis et al. 2002, Vicente et al. 2011).

With respect to ER fluids, by using inorganic materials it is possible to achieve variations in the ER effect due to structural component or pore size of the particle. For example, an amorphous zeolite results in a larger ER response than a crystalline material – this is due to the impurities that lend themselves to polarisation with less energy required (Liu and Choi 2012).

Smart fluids have paved the way for flexible mechanics. It is possible to get quicker response times and smoother actions. MR fluids have become more economically prevalent because of its strength, durability and applicability (Ouellette 2004). It is used in applications ranging from seismic dampers to cooling systems for speakers In contrast ER fluids are advantageous to use in small scale actuating elements such as those used in biomedical instruments and robotics, as well as haptic interfaces (Ouellette 2004). The ability of these fluids to provide a haptic feedback also expands their functionality, being able to execute a task or function and relay progress at the same time (Kciuk and Turczyn 2006).

The literature to date has informed the initial design concepts for an agent / particle design with the aim of building a controllable multiagent system (MAS). The following section briefly explores the area of liquid crystals and polymers as the developments in these domains provide alternative points of inspiration and perspective.
2.3 ER & MR fluids

2.3.3 Liquid Crystals and Polymers

The categories of polymers and liquid crystals (LC) are worth considering in terms of possible functions or behaviours that could be incorporated into the agent design. They share similarity with smart fluids in that the particle alignment can be controlled but they differ in the ability to apply control at different levels. The concept of liquid crystals is a topic of interest for this study because of their use in ER fluids. It is possible for the particles or the liquid itself to be conductive (Hao 2002). For example, some LCs respond to a change in temperature, pressure or concentration (Collings 1990). Exploring crystal-based structures also provide valuable insight especially with respect to determining an efficient and optimized particle design. Crystals grow in a variety of shapes and sizes and represent a spectacular diversity (De Yoreo and Vekilov 2003), see also Chapter 1 section 1.6.3.

As mentioned in Chapter 1 the domain of material science, specifically the research exploring polymers, has opened the possibility of utilising features from a variety of materials in order to improve efficiency of an existing system. For example, in an attempt to enhance the ER or MR response, shell-coating particles or designing shell-particles that contain conductive material are options that are being explored (Wen et al. 2007, Liu and Choi 2012).

An alternative use of polymers is in the form of hydrogel actuators that respond to near-infrared light. Similar to smart fluids the effect is reversible and as the name ‘gel’ suggests, the starting phase is solid as opposed to liquids. Many techniques seen in the smart fluid research are being applied to these types of gels. For example, there is a greater flexibility with respect to the trigger mechanisms: physical stimuli (temperature, sound, light mechanical stress), chemical stimuli (pH, ionic strength) and biological stimuli (enzymes, molecules) (Almeida et al. 2012). The addition of porosity to the hydrogels enables the reduction of reaction time and affects the localised reactive area through the use of a laser, similar to how plants can move towards the direction of light. The ability to use biological hydrogels is also of interest as proteins can be programmed to accomplish specific tasks with respect to self-assembly (Wang et al. 2013). Constructing agent designs based on this type of material enables designers to consider flexible, form-changing robots (Wehner et al. 2016).
2.4 Self-assembly

An element that NN & ER/MR fluids have in common are that they both demonstrate a form of self-assembly and self-organisation that occurs without intent, similar to fluidic self-assembly (Alien Technology Corporation 1999). Throughout academic literature it is clear that self-assembly does not have to have intent inherent in its meaning. For example, ball magnets and a hive of ants present two different styles of self-assembly. When ball magnets enter each other’s magnetic field, they begin to self-assemble and thereby self-organize according to the appropriate polar configuration (north-to-south). In this case there is no intent or end-goal in terms of a clearly defined structure. In contrast to the ball magnets, when examining the way ants self-organize, it becomes apparent that they work together to achieve an end-goal (creating a bridge, raft, etc). This latter type of intent-ful or dynamic self-assembly can be potentially more useful in the field of MAS based shape-shifting interfaces, because it could allow a user to stipulate the end goal, e.g. interface design, rather than become involved in directing each individual agent. Each agent would have enough autonomy to deal with the task and some unexpected events, similar to the Kilobot project’s random packing behaviour (Rubenstein et al. 2014). Another differentiation is made between self-assembly and self-organisation. Creating 3D structures is not automatically implied in the latter concept, rather it bridges the aspect of packing and orientation of agents within a system. It can be said that it relates primarily to the communication between agents in the process of achieving the end goal.

For a haptic interface that can adapt to a user’s needs, and that is based on a multiagent system, self-assembly would be an efficient mechanism by which to initiate the building of structures. Rather than using energy to direct each agent to its specific place, energy can be expended on the process of defining the parameters that the agents need to adhere to. This involves employing techniques such as those applied in microfluidics, e.g. altering boundary conditions, adjusting the number of agents in the system, the fluctuation of pressure and speed of flow. These factors can help determine the cluster shapes that can be formed (Shen et al. 2014).

The primary difference that needs to be accounted for is the autonomy required for agents to assemble, with intent by being aware of the overall structure. Non-Newtonian fluids and MR / ER fluids have been detailed and that they exhibit desirable traits such
as temporary solidification, ability to form structures and for the particles to self-assemble into chains or hydroclusters. However, they only self-assemble when experiencing an externally applied force. Therefore, examining biological systems can provide insights into developing a model by which it is possible to program the behaviour to achieve this intent-based or dynamic self-assembly (Whitesides and Grzybowski 2002).

The most efficient and successful self-organising and assembling systems already exist in nature e.g. bee-hives, ant and termites, etc. Each of these complex colonies can have an excess of several thousand living beings, however each individual has its own task and is appropriately equipped to carry out a specific task (Dumpert 1978, Gordon 2010). Exploring how these individuals communicate and interact with each other in order to create structures many times larger than themselves, is valuable with respect to designing a system that can emulate it. An added advantage of examining insects that exhibit this type of behaviour is the scale at which they exist. Projects such as Bergbreiter’s mini jumping robots (Bergbreiter 2014) and microTug (Christensen et al. 2015) represent progress with respect to scaling mechanical system. However, wear, stress and strain still limit the lifespan of such systems. In contrast, certain species of ant already exist on the scale of 2-6mm (Pharaoh ant). Understanding how these insects’ joints and appendages are constructed can aid in progressing the longevity of man-made mechanisms or provide insight into structures that have adapted to particular types of stress or strain.

The focus of this study is primarily on the physical design of an agent, therefore the species of ant, Solenopsis Invicta (fire ants), was researched for their ability to achieve specific structures indicating that they could repeatedly assemble and dis-assemble. Due to their natural habitat being prone to flooding, these ants have adapted by being able to build temporary rafts until they find a new area of land. The raft consists entirely of ants, which demonstrates that they can maintain structural cohesion, buoyancy and can survive temporary submergence in water. There are three methods as to how the ants hold together: mandible-tarsus, tarsus-tarsus, and chemical excretions through adhesive pads located at the end of the tarsus (Mlot et al. 2011). With respect to self-assembly the tarsus-tarsus connection appeared to have the greatest potential since a key consideration for the proposed haptic interface is not only
the ability to self-assemble but the system must be capable of dis-assembling in order to exhibit the characteristic of reversibility and be programmable in real time.

The other two methods are currently discarded since the mandible-tarsus technique requires active or direct programming equivalent to the ant’s brain to open and close the mandibles and know how much pressure to apply and the 2nd technique requires chemical processes. The tarsus-tarsus mechanism is of interest because an ant tarsus ends with a claw. The shape of this claw is of interest because the ability to attach and detached from other ants, is a quality of its physical affordance. Since the claw cannot be retracted, the arc is such that it must be able to interlock with other ants but release with ease simply due to a shift in position. The shape of the claw encapsulates the necessity to bind to another ant without damage, be secure and be able to dis-assemble quickly, i.e. a bi-stable interlocking mechanism. Interestingly, these ants also demonstrate behaviour similar to Non-Newtonian fluids: when agitated, e.g. swirled in a beaker, they maintain a semi-spherical shape and when left alone begin to disperse again over time, etc (Mlot et al. 2011, Kasade 2014).

Self-assembly is not solely based on the physical shape of ants. Therefore, it is important to consider other elements that contribute to the success of a hive or colony. These elements also provide a good starting point from which to develop artificial MAS. For example, communication is an integral aspect to any successfully functioning system. With respect to ants, the question as how they pass on information to each other has been asked and is still being investigated. Techniques such as olfactory trails, aural or haptic signals executed via vibration of specific body parts or even dance patterns in an iterative ‘step-by-step’ process (Thaler 2004, McGavin and Hart 2013) have been identified as possible communication methods. Defining these methods has helped optimise the programming approach required to control multiagent systems more efficiently and effectively (Butera 2002, Mamei et al. 2005, Poulton et al. 2005, Rubenstein et al. 2014, Le Goc et al. 2016). This research can also be used to inform the agent design. For example, in an ant colony, apart from the queen, there is no defined hierarchical command structure (Gordon 2010). However, it is still possible for the colony to build, repair and clean their home, gather food and rest. The term swarm intelligence is denoted to this type of behaviour (Nirmalraj et al. 2015).
2.4 Self-assembly

This has led to certain research suggesting placing ‘seed’ or ‘leader’ agents throughout a mass of agents (Bojinov et al. 2002) and that messages are passed from one agent to the next consecutive surrounding agents and so forth (Lifton 2002). The research suggests that rather than look different, these particles may have different programming or may exhibit a greater force than other particles, e.g. attraction. These seed particles would, initiate specific commands which then spread to other particles.

Bojinov proposes that it could be more advantageous for a seed particle to be able to alter its physical appearance, i.e. be larger than the others, stronger, be more texturally defined or topologically different. Structurally they could act as core particles around which other particles can build onto (Bojinov et al. 2002) being used as orientation markers and act as guides for the surrounding particles (Rubenstein et al. 2014). They would act as anchors and aid in the formation of clusters. If seed particles are identified or selected according to a structural difference, it means any agent could be chosen to become a seed agent and it would not require additional features.

Alternatively, ants present a system that is flexible, adaptable for different tasks and is capable of self-healing to an extent. In some ant species, the size and shape determine the tasks they are designed for (Dumpert 1978, Thaler 2004, McGavin and Hart 2013, Mersch et al. 2013) however other species are such that their tasks are dependent of the age, i.e. young ants start as nurses, then cleaners then foragers (Gordon 2010). These specific roles are adaptable and subject to change according to requirement. Translating this concept to the agent design could mean that whilst each agent is identically manufactured it would be possible to designate agents to different tasks defined by their shape and configuration. For example, in the case of the Dod design even though all arms have the potential to extend it is possible to arrange different configurations of arm extension leading to small, middle or large sized Dods depending on requirements, see Chapter 4.

The topics to date have discussed research that has directly inspired the design process as is evident from Chapter 3, section 3.3 onwards. To maintain a contextual perspective, the last two sections of this chapter explores qualities of interest regarding

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14 For example, if an excellent food source is located certain cleaner ants may convert temporarily to foraging ants in order to bring back the food.
human haptics and the related work, in the area of interactive interface design, which help to orientate this study in the most current research.

2.5 Haptics

The area in which this technology aims to be applied is within tangible user interfaces (TUI). This section aims to clarify what Haptics is and what it means, by highlighting its relevance for a MAS approach to haptic based interactive interfaces. Several projects involving various approaches to haptic interfaces and their focus on specific qualities of haptics are examined. The considerations gleaned from these projects help inform design choices made throughout the agent conceptualisation. This list is not exhaustive as there is a constant development in the field of interactive haptic interfaces.

Haptics is a description of the various forms that a person can interact with his / her environment through the sense of touch. A person’s haptic sense encompasses their entire body, has varying degrees of sensitivity (Iwata et al. 2001) and is said to register 20 times faster than vision (Saddik et al. 2011). It can be further divided into sub groups relating to the skin (cutaneous) (Lifton et al. 2004), to temperature, texture & vibration (tactile), limb position & movement (kinaesthetic) and feedback (force feedback) (Gr. nwald 2008, Saddik et al. 2011). Each of these sub groups are interrelated and rarely function in isolation.

Tactile sensing entails the perception of texture, vibration, shape & form and is achieved through cutaneous sensing via the skin. Through cutaneous sensing it is also possible to detect thermal differences. As mentioned above, different areas of the body have different degrees of sensitivity. Places such as the finger-tips, lips or nose have a higher number of tactile sensors than areas such as the upper arm, lower back or thigh (Bensmaïa et al. 2006, Kern 2009, Saddik et al. 2011). Another deviation from this is the difference between bare skin and hair-covered skin – the latter has a lower sensing bandwidth resolution but is designed to detect vibratory information or larger changes within the environment (e.g. thermal changes) whereas bare skin is suited to detecting various textures (Saddik et al. 2011). Tactile sensing is most often implemented in interaction with different interfaces because the primary tool for this modality are human hands. For tactile information to be useful it must,
1. Contribute a unique aspect of information that may not be received, as strongly by the other senses otherwise haptic information is superfluous and masked,
2. It is important not to create a textural overload because similar to the other senses it is possible to dull or numb the sense by constant activation
3. Correlating haptic information to the specified interface is crucial in maintaining the transparency of the tool (Jansson et al. 2006).

Kinaesthetic sensing provides a person with information about the positioning of their limbs and muscle movements in relation to the environment or the interaction with a system or object (Kern 2009, Saddik et al. 2011). Proprioceptive sensors are internally located at joints and within muscles providing information about force-feedback, stretching, position, etc. (MacLean 2008).

Force feedback is also intrinsically linked with all types of haptic sensing and encapsulates a unique quality of the haptic sense: bi-directionality. This quality makes it possible to react to and also act on sensory information (Gr. nwald 2008, MacLean 2008, Kern 2009, Saddik et al. 2011). For example, in simply holding a basketball it is possible to determine its texture, material quality and size, and by exerting a force via pushing together or bouncing, it is possible to determine the solidity, elasticity and condition of the object. This quality, inherent in haptics, is of significant interest for the development of audio-visual & haptic interfaces because it also relates to a sense of immersion.

There is copious amount of research regarding the different types and varieties of biological sensors that each has a specific function and output. This research has aided in designing and creating better inorganic sensors and also in understanding how the biological mechanisms functions (e.g. arm-hand, leg-foot, etc). An intriguing aspect of how these mechanisms work, and in addition an integral part of haptics, is their basis on exploration (Chafe and O'Modhrain 1996, Saddik et al. 2011).

- Lateral motion (moving side to side, up or down) – surface texture,
- Enclosure (grasping or covering) – volume & overall shape,
- Static contact – temperature & material texture,
- Contouring (feeling along the outline, edges, corners) – shape distinction,
- Holding, pushing, pulling of objects – weight & shape,
• Kinaesthetic force – material characteristics.

Exploration is fundamental to how haptics work and it is this quality that aids children to learn about their environment independently (to an extent). In general, children employ all senses available to them to create a holistic impression of the environment but also to interact with it – it is a crucial part of emotional & physical development (Mazzone et al. 2004, Ishii 2008, MacLean 2008). At this point, mental models are constructed and associations are made between objects and reactions (Coelho and Zigelbaum 2011). For example, fur, wool, fleece, satin, are probably considered safe, comfortable and pleasant, etc because they are soft, flexible and malleable. In contrast a cactus, wooden plank, broken glass are materials that have potentially sharp edges, are rigid and can possibly result in pain. Naturally this is an oversimplified example, the volume of information that each of these examples holds is substantial. It demonstrates however that the mental model of shapes and textures are formed at an early age and this knowledge can be used in design and in the development of immersive interfaces (Taylor and Bove Jr. 2009). When a person sees a sharp pointed implement, they know what it feels like and they don’t necessarily need or want to touch it\textsuperscript{15}, i.e. the haptic / tactile experience. A person also becomes experienced in how to interact with different shapes and textures, e.g. knowing how much force can be applied to a pointed object versus a rounded blunt object or knowing how to gauge the distance from a hot object. These qualities of haptic perception or memories are useful to explore with respect to immersive technologies that require creating realistic haptic responses, beyond vibration and limited force-feed back. Expanding on the mechanical aspect of haptics, the peripheral side effects are of inspirational value to this study, i.e. the systems that are interrelated with haptics (Horev 2006). These include emotional connection, motor memory, phantom-limb perception, multimodality, cultural context, aural / visual – haptic affordances, etc. Similar to self-assembly, the peripheral aspects that effect haptics are valuable sources of knowledge regarding the influence on agent design. The following sections briefly elaborate on muscle memory, emotional connection and its influence on technological design and the inherent use of multi-modality in the design of tangible user interfaces.

\textsuperscript{15} Similar to Gestalt psychology of Closure, the mind is capable of filling in missing information. This can be applied to experiences whereby it is possible to imagine a feeling without experiencing the haptic / physical stimuli.
2.5 Haptics

2.5.1 Motor memory & phantom perception
Motor and muscle memory are interesting qualities that have great potential in the application of haptic interfaces. Whilst it is argued that muscle has no actual memory capacity, in the traditional sense, muscle memory occurs after years of practising, repetition and honing a particular skill. Pathways between specific and relevant neurons have become stronger which mean that it no longer becomes necessary to consciously think about the action because the sequence of the action is so familiar it is ingrained in how the muscles move. Walking, cycling, knitting or playing music are some examples of actions that become automated and allocated into long-term memory (Carmeli 2016). It is a contributing factor that can help explain why, after several years of interruption, due to accident or change of circumstance, it is easier to relearn or start using the skill again (Darling 2009, Carmeli 2016). The concept of phantom-limb perception primarily applies to people who have had a limb amputated and is strongest in adults and in the following few weeks of such a procedure (Grünwald 2008). Whilst it is difficult to explain how this phenomenon occurs exactly, it can be an area of interest in relation to immersive technologies.

Muscle memory can also contribute to the flow experience. Even though this experience is rooted in the effect of intense concentration, it illustrates the range of possibilities in instances when thought is no longer in the foreground. Instead there is a direct connection between user and the task as the tool or body becomes completely transparent.

2.5.2 Emotional connection & standardisation
In the early stages of machine & computer development, function often took priority over form (Wright 2016). Material constraints defined the possibilities and limits of this technology (Coelho and Zigelbaum 2011) and understandably mass production was a high priority. The user often had no choice but to adapt to the technology. Fortunately, this trend has changed as it has been established that aesthetic and emotion play a critical role in efficient and pleasing interaction. It is no longer sufficient for technology to look or sound good it should also feel good - physical contact is necessary for meaningful and long-lasting connections (Saddik et al. 2011). It
reinforces the perception of the object and can be described as the felt experience. Part of this experience is the emotional component. Don Norman suggested that if something looks good and feels easy to use then people would be more willing to overlook flaws and inadequacies in the system. This is because the design of the system elicits positive affect, meaning people have a greater capacity to devise creative solutions and are able to adapt to certain shortcomings in the system (Norman 2005). Designing according to emotional affect can be beneficial and efficient e.g. in stressful or emergency situations negative affect is prevalent meaning people become tunnel-vision and highly focused due to adrenalin. If well trained or grounded, a person can fall back onto specific routines of actions designed for such a situation. In such a state information needs to be easy to find and clearly presented. An interface that is ambiguous or only looks nice would be completely inadequate. Therefore, emotional affect is a valid factor that can inform interface design. It enables the designer to hone in on the important aspects of the interface and thereby also be more efficient in the design process. A positive emotional experience inspires a deeper connection between user and interface (Parkes et al. 2008).

The other element encountered in haptic design is the overcoming the obstacles of standardization and lock-ins (even if a better product exists – users may not be inclined to change due to social or personal influences (Univerisy of Groningen 2016). To date significant research and development has been invested in developing Graphical User Interfaces (GUI) and the functional aspects of computer technology (increasing memory, stronger & faster hard drives, etc) (Mazzone et al. 2004). It is easier, faster and is based on the knowledge that people are predominantly visually orientated. Therefore, the current interfaces (mouse, keyboard, joystick) are primarily orientated towards affecting visual graphics on a 2D screen. In some cases, it is required to complete tasks counter-intuitively to how a person would do it naturally (Rekimoto 2002, Ishii et al. 2004a).

Haptic interfaces are harder to implement often due to their size, energy constraints and because of their physical nature (Mazzone et al. 2004, Michelitsch et al. 2004, Esteves 2012). It is also still significantly easier to develop a visual aesthetic rather than a felt one. To date haptic interfaces primarily consist of exploiting vibration and force-feedback (Okamura et al. 2001). The fingertips have some of the highest density
of sensors capable of detecting thermal, vibrational/tactile and force stimuli (Bensmaïa et al. 2006). Vibration can be used to represent a varying range of textures as well as a tapping or clicking motion. It utilizes the tactile and cutaneous sensors whilst force feedback can also be adjusted to represent various conditions (Haption 2001, Sensable 2016). It utilizes the kinaesthetic mechanism of sensing. In each instance, a textural effect is most often achieved by fooling the users in creating illusions of the perceived force. For example, in relation to textures, in varying the amplitude and frequency of an oscillating sine wave, it is possible to simulate sandpaper, rubber, grit, etc (Guruswamy et al. 2009, Hurst 2013, Yamaguchi et al. 2015). If any discrepancy between visual & haptic sense occurs then the illusion is broken (Minsky et al. 1990).

It is important to know the limits and bandwidths of each haptic sense, for example considering the just noticeable difference (JND) for sensitivity aids designers in making sure that vibratory actuators are not < 2.5mm together (Saddik et al. 2011). Alternatively, knowledge of the perception thresholds illustrates that it is better to have continuous rather than discrete steps in relation to the force and vibration gradient. Ideally it should also be as close or above the frequency of natural human perception (Leydon 2004, Saddik et al. 2011). Considering these aspects, it becomes evident that the accurate representation of haptic qualities is dependent on the limitations of the mechanical devices and the systems in which they are placed.

- Jitter, bad simulations, network performance and system dynamics relate to the sampling frequency (Minsky et al. 1990),
- Consistency and synchronization relate to issues of congruent mapping, the slightest discrepancy is sufficient detectable by the user (Saddik et al. 2011),
- Scalability and power supplies are facets that encompass issues such as shearing stress and strain due to repetitive action, structural integrity and energy efficiency.

To creatively approach haptic interface design, it is important not only to consider what is present but also what is being omitted, e.g. John Cage’s 4’33’’ the silence in music also has a significant role. This is pertinent for cases where too much sensory input can overwhelm the user, e.g. for each action a user can make a vast majority of minute adjustments and movements. To map these to a haptic response would be inefficient, as these sub-adjustments make no difference to the overall action itself.
2. Literature Review

(Taylor and Bove Jr. 2009). It is required to clearly define boundaries in order to map action to data accurately.

2.5.3 Multimodality

A significant advantage of haptic interfaces is the fact that haptics rarely occurs in isolation, i.e. it is an intrinsic part of a multi-modal sensory system of perception (Taylor and Bove Jr. 2009, Follmer et al. 2011, Nakagawa et al. 2012). If two or more senses are working simultaneously at interpreting the same situation there is more information on which to base a decision (Michelitsch et al. 2004, Horev 2006, Parkes et al. 2008). These decisions can be better informed, which improves judgement of a situation and may result in fewer errors. Another advantage of multi-modal sensing with respect to design are the numerous combinations that are possible with other senses and therefore useable to inform interface design (Holman and Vertegaal 2008).

- An interface that directly engages vision and haptics or sound and haptics (Poupyrev et al. 2004, Fernström et al. 2005, Monnai et al. 2014),
- An interface that works on peripheral senses: a haptic interface that changes surface topology and consequently attracts user attention via peripheral vision (change in movement or pattern),
- An interface that allows the users to gain a ‘phantom’ sense of the interface before making direct contact with it (Lee et al. 2011, Weiss et al. 2011).

The latter styles of interface are unobtrusive and can communicate information in a playful and intuitive manner also often referred to as ‘calm technology’ (Ishii and Ullmer 1997, Horev 2006, Marquardt et al. 2009, Masson and Mackay 2009, Wakita et al. 2009).

In relation to decision making through multimodal sensing, some senses have a higher weighted priority than others, which can often lead to false perceptions or a masking of the other senses (Horev 2006, Grünwald 2008, Saddik et al. 2011, Monnai et al. 2014). For example, in one particular virtual reality simulation, users are asked to walk a plank suspended from the edge of a skyscraper. Even though the users are aware the environment is simulated they have difficulty accepting reality beyond what they see (Kratochwill 2016). In these instances, haptics can play an important role because by
2.6 Related Work: Projects

being able to touch and feel our environment it provides a tangible data stream that is harder to manipulate. When haptic technology becomes more integrated and easier to replicate, there will most likely be a significant improvement in immersive technology used in augmented (AR) and VR reality (Ishii 2008, Parkes et al. 2008, Parkes and Ishii 2010).

Apart from VR technology the benefits of introducing haptic elements into interfaces will aid not just the average user but those for whom vision is impaired or non-existent. Even though aural accessibility is an option for most computer devices some of the difficulties with hearing include environmental surroundings, the control over sound and the fluency of navigating digital information aurally. Hearing is constant and it is only through learning to selectively tune in to and detect the relevant information that it is possible to cope with the everyday cacophony of sound. Haptics has the potential to be turned on or off as demonstrated by the technology developed by Tactus Technology. They create overlay screens, which enable buttons to rise out of the surface once a keyboard or buttons are detected on the flat screen below. This is based on the technology of microfluidics and can be adapted for different screen setups and styles (Tactus Technology 2012). The element of physical morphing is introduced: an interesting and exciting quality of haptics.

Similar to hearing, it is not possible to stop feeling however it is possible to stop receiving information by inertness. For example, to feel texture, vibration, or force, etc requires the user to move over a surface, or to push or pull the object. If a user touches an object but does not move or exert a force then there is no new information being transmitted. Applying this concept to a haptic interface could be of interest regarding the efficient use of energy, i.e. when the system is not in use it does not require energy – like the BlueMotion™ technology in cars (Hook et al. 2009, Vousden 2015).

2.6 Related Work: Projects

This section of the literature review contextualises this PhD in the field of interactive interfaces as well as tangible user interfaces. With respect to designing haptic interfaces, the roadmap to Multimedia Haptics described by Saddik is informative (Saddik et al. 2011). It describes the interdependence of each component and how the development of one area depends on the knowledge and understanding of other
components linked to it. Figure 2.4 illustrates an adapted version of the multimedia roadmap with additions to machine haptics (power supplies), computer haptics (latency), and the branch extraneous factors. These elements have been recorded through the early stages of prototyping agent designs during this study.

![Figure 2.4 Multimedia Haptics](image)

**Figure 2.4 Multimedia Haptics** - Elements and considerations that influence multimedia design

Haptics is elemental in a person’s experiential development. In the combination with the other senses it aids in forming a holistic 3D impression of the world (MacLean 2008, Parkes and Ishii 2010). Unique to haptics is the opportunity to develop morphing or shape-changing designs (Horev 2006). Malleability and reversibility are characteristics that are seen in numerous research papers and provide unique design challenges (Coelho et al. 2008, Coelho and Maes 2008). This type of characteristic inherently supports a visible and textural reaction to the user’s actions and embodies the flexibility of handling digital data (Coelho et al. 2008, Parkes et al. 2008).

It is suggested that shape-changing interfaces stimulate the haptic scope of exploration and that it is also capable of conveying different functional and system information according to the physical shape and texture (Marquardt et al. 2009). Studies have demonstrated that, in instances where it is possible, being able to follow the transition of the changing interface (or animation from one shape to another) provides the strongest haptic connection to the interface (Horev 2006).

Morphing ranges from texture, size, volume, orientation, form, stiffness, viscosity, weight, rotation, movement, fluidity, resistance, materiality, modularity vs. continuous deformation, speed of change, patterns, vibration, etc. These factors can be combined to facilitate the practical and emotional aspect of interaction (Parkes and Ishii 2010,
Rasmussen et al. 2012). For example, a rough, spiked surface may indicate that an error has occurred or fast pulsating vibration may indicate an alarm and similarly a slow, fluid transition between interfaces can calmly guide a user through a sequence of steps. A key difference in the design of future haptic interfaces is the concept of dynamic design, that the original design is no longer static, like a mouse or keyboard. Instead significantly more ownership is handed to the user with respect to creating malleable tangible user interfaces (TUIs).

In the development of TUIs, three predominant styles of interfaces have developed (Weiss et al. 2011): 1) those focusing on 3D relief with emphasis on textural qualities, 2) those that are free-standing use qualities such as force-feedback which is inherent in kinaesthetic sensing and 3) those that are connected directly to the user, such as gestural gloves or wearable technology (Iwata et al. 2001).

The following review will examine interfaces that explore the connection between user, touch and effect on digital information. These aspects are of interest for this project as they define design choices made throughout the agent conceptualisation. Each project illustrates various methods of portraying and interpreting the morphability characteristic of haptics. This relates closely to the concept of organic design and organic interfaces, creating interaction methods that are haptic-ly more intuitive (Taylor and Bove Jr. 2009, Furukawa et al. 2010, Nakayasu 2010, Follmer et al. 2011, Nijholt et al. 2012) as well as bridging the gap between the physical and digital domain more effectively (Ishii et al. 2004a, Lee et al. 2011). This list of projects is not exhaustive and each project addresses a specific research question of their own. However, for this review they will be viewed with respect to the category of haptic interfaces and how they utilize a specific haptic characteristic. It is important to note that other areas such as Micro-Electro-Mechanical Systems (MEMS) (Adams and Layton 2010), microfluidics (Lin 2011, Tactus Technology 2012) and chemistry (Khan et al. 2014)(Khan et al. 2014), can provide insight into new techniques for haptic interfaces but will not be addressed in this review as they refer primarily to the technology aspect rather than focus on haptics.
2. Literature Review

2.6.1 Pushpin computing

The concept of these interfaces is that each element showing on the surface is individually actuated so that it can move on designated planes. These elements consist of actual pins, which are exposed (Raffle et al. 2003, Poupyrev et al. 2004, Follmer et al. 2013), pins that are covered with a flexible membrane often fabric based (Iwata et al. 2001, Marquardt et al. 2009, Leithinger and Ishii 2010) or elements that are made of smart memory alloys (SMA).

The SMA would be contained within a flexible material and move according to electrical or temperature changes. They are useful for small-scale projects as there is no mechanical mechanisms and they are capable of repetitive action (transitioning between two states) (Coelho et al. 2008, Coelho and Maes 2008, Nakayasu 2010). These materials allow for a greater degree of freedom with respect to moving along the x, y and z-plane (Poupyrev et al. 2004, Coelho and Maes 2008, Coelho and Maes 2009, Minuto et al. 2012, Ingpuls GmbH 2015) and attempt to create a greater boundary transparency between the physical world and digital information (Nijholt et al. 2012, Rasmussen et al. 2012).

In pushpin computing, the moveable elements are most often controlled individually however it is also possible to program set behaviours in which several elements may be grouped and move together. The resolution, i.e. number of elements on display, can vary to represent different structures as well as fulfil specific requirements. Adjusting this resolution by adding or removing pins / elements is often quite difficult due to a complex pin-linkage-actuator-computer setup. The overall setup confirms that haptic devices are often difficult to implement, as they are still bulky and rather unrefined when compared to GUIs.

Interfaces based on the pushpin technique are very effective in achieving varied topological changes in real-time and initiating new approaches to 3D interactions. They primarily employ tactile sensing and work with visuals either projected onto the surface, light emitting or through inherent movement of the elements (Iwata et al. 2001, Poupyrev et al. 2004, Follmer et al. 2013).

The following are some of the concepts that are addressed via pushpin-based interfaces:
• To demonstrate and build a framework for the recognition of dynamic affordances and constraints offered by user interfaces that can alter their appearances and the materials used (Horev 2006, Coelho and Maes 2008, Follmer et al. 2013).

• To elicit emotional engagement of the user and to achieve a higher fidelity with respect to mapping digital information to the physical element (Coelho and Maes 2008, Rasmussen et al. 2012).

• To improve spatial and temporal continuity between touch and haptic interface, i.e. reducing the latency as well as improving the integration of visual/aural and haptic sense into one interface (Iwata et al. 2001, Parkes et al. 2008).

2.6.2 Smart fluids

Materials of interest in the use of haptic interfaces are smart fluids. As described in section 2.3, the most common smart fluids exhibit a change in state when experiencing a magnet or electric field. The qualities that are explored in the following projects illustrate how these concepts are translated and used in an artistic and creative way.

The most common smart fluid used in the artistic & interface domain is Ferrofluid, this is primarily due to its unique and unusual reaction to a magnetic field. Depending on the strength and localisation of the magnetic field the surface of the Ferrofluid can change from smooth bumps to spiked towers rising out of the surface, following the magnetic field lines as seen in Figure 2.5.

![Figure 2.5 Ferrofluid - spiked surface topology under a magnetic field influence, public domain](image)

Ferrofluid is expensive to manufacture and is not suitable for direct interaction therefore it is often necessary to enclosed it in a container (Kern 2009, Masson and Mackay 2009, Saddik et al. 2011) or in a flexible pouch (Hook et al. 2009, Jansen 2010, Koh et al. 2011). Even though the push-back force of Ferrofluid is very low and it primarily has a visual appeal. It has the advantage of being able to create smooth,
noiseless, aesthetic transitions between varieties of surface topologies. The typical setup requires the Ferrofluid to rest a certain distance above a 2D array of electromagnets. The electromagnets can be controlled by a variety of factors: sound, light, movement, etc. (Hook et al. 2009, Masson and Mackay 2009, Jansen 2010, Koh et al. 2011).

The jamming effect seen in smart fluids, refers to an induced alignment of particles similar to dilatancy in Non-Newtonian fluids, (see Chapter 2, section 2.2.3). It is also possible to achieve this effect artificially through granules encased in a flexible material and through a vacuum can be moulded into any desired form (Follmer et al. 2012). An interesting quality of these materials is the ability to return to the original state and to repeat the process of shaping and resetting. Being able to control the shear-thickening effect is useful for stiffness feedback and creating malleable clay-like interfaces. Similar to designing vibration patterns to emulate textures, jamming provides a variety of force feedback patterns to emulate different materials beyond the surface texture (Kim and Lee 2010, Follmer et al. 2012).

Regarding pushpin interfaces, the peripheral equipment required to make these interfaces function as desired is substantial. For example, for surface & depth detection equipment such as IR cameras, projectors, computers and power supplies are required to translate the interpretations of pushpin behaviour into digital information. The following are some of the concepts that are addressed via smart fluid interfaces and interfaces that use the affordances of the materials:

- When smart fluids are appropriately contained they can be implemented to augment existing interfaces e.g. joysticks. The change in surface topology creates alternate interfaces, which can be applied in the 3D relief or independent 3D interface style. Changes in surface topology can attract attention (Masson and Mackay 2009) and can be implemented to give force feedback or vibrotactile feedback (Hook et al. 2009, Tactus Technology 2012). Feeling areas of rigidity is at times more distinct and easily definable that discerning vibrotactile information (Jansen 2010).

- An intriguing quality of a fluidic haptic interface is the malleability. It is routed in the concept of organic and dynamic design and enables the user to freely form their own interfaces in real-time (Jansen 2010, Koh et al. 2011, Matoba
et al. 2013, Plasencia et al. 2014). This quality supports the bi-directionality of the haptic sense (Rasmussen et al. 2012).

- Scalability is an important consideration for haptic interfaces, in particular reducing the scale of power supplies and peripheral technology required to make the system work. Since there are many different varieties of interfaces with which people interact (computer, machines, mobiles, laptops, tablets, etc) making haptic technology available for mobile applications is also beneficial from a marketability perspective (Schwesig et al. 2004, Horev 2006, Hook et al. 2009, Taylor and Bove Jr. 2009, Jansen 2010, Follmer et al. 2012, Nakagawa et al. 2012).

- The diverse states that a fluid can undergo presents a wide variety of design approaches with respect to haptics in immersive technologies, where the texture is real and not an illusion (Parkes et al. 2008, Koh et al. 2011, Follmer et al. 2012, Matoba et al. 2013, Rakkolainen et al. 2013, Plasencia et al. 2014).

Other solid yet malleable materials that are of significant interest in the haptic domain are clay and sand (Ishii et al. 2004a, Coelho and Zigelbaum 2011, Follmer et al. 2011). These materials have significant advantages with respect to instantaneous reaction and deformation to the users input. They present intuitive interfaces since the user can use his/ her hands directly to manipulate the data mapped via the interface and gain meaningful feedback in real time (Patten et al. 2001). Whilst they address the morphing and bi-directional aspect of haptics, problems can arise in allowing the user complete freedom with respect to mouldable interfaces. For instance, the majority of people are not sculptors therefore it is questionable whether they could get the desired shape in order to complete the function they require. This may indicate that a certain level of pre-shaping of the interface is necessary, e.g. using microfluidics – the channels manufactured such that the user may have a choice of how to alter the surface topology but the topologies are pre-defined. To have too much choice can be as detrimental as having no choice at all.

2.6.3 Multiagent systems (MAS)

A multiagent system is a system that is comprised of many smaller, autonomous parts working together to achieve a greater goal. They have a fundamental ruleset that
defines their behaviour and when they interact more complex behaviours tend to emerge. MAS are pervasive through nearly all levels of existence (Parkes and Ishii 2010) and exhibit a varied range of behaviour being influenced internally, externally or both, e.g. individual cells working together, a flock of birds, the stock market, solar system, etc.

These types of interfaces consist of modular agents, i.e. they are approx. structurally identical to each other. Thereby the haptic component is inherent in their makeup in either of two ways: A) in the physical handling of each individual component (e.g. a tile) (Gorbet et al. 1998, Kim 2010, Kim and Lee 2010) or B) in the physical handling of the overall system created by the many small parts.

The unique quality of modular interfaces is the ability to add and subtract agents (Gorbet et al. 1998, Goulthorpe et al. 2001, Parkes and Ishii 2010). This presents a unique challenge with respect to communication between each component. Distributed sensor networks (Patten et al. 2001, Rekimoto 2002, Lifton et al. 2004) or self-organisation models are applied to create an adaptable and flexible system. From a haptic perspective, these systems have a greater emphasis on kinaesthetic since the interfaces are completely 3D (McElligott et al. 2002, Kim and Lee 2010). The peripheral technology, as described for pushpin and smart fluid interfaces, is primarily intrinsic to each component in MAS (McElligott et al. 2002, Lifton et al. 2004, Raffle et al. 2004, Taylor and Bove Jr. 2009, Kim 2010). The following are some of the concepts that are addressed via MAS interfaces:


- The exploration and detection of physical effort is key in furthering haptic interfaces with respect to immersive technologies. A modular approach has the advantage that it contains its own sensing circuitry and through the accumulation of each agent’s information, more accurate data can be gathered. This contributes to better mapping possibilities and improved congruency between the user’s actions and interfaces reactions (McElligott et al. 2002, Richardson et al. 2004).
2.6 Related Work: Projects

- Play and haptic exploration with the environment is an integral part of self-development but can also be used as a learning tool. Designing toys with the ability to playback physical movement (Raffle et al. 2004) and using this type of interface to educate about physics concepts (balance, motion, force, etc) is a useful method of adapting TUIs into the everyday user experience from an early age (Özgür et al. 2017).

- Physical MAS may also a useful style of interface to convey digital information in a tangible manner and aiding in the breakdown of complex concepts (physics, self-organisation, etc).

- The examination of how users work with their bodies (how they hold, grasp, feel objects) can provide insight as to how to design more ergonomically and be more attuned to creating a more natural physical interaction with technology (Taylor and Bove Jr. 2009).

From the projects and research that exists on the subject of shape changing interfaces the list below highlights the desirable qualities and provide a framework of design guidelines to consider when creating a morphing agent for multiagent systems (Coelho and Zigelbaum 2011):

- Deformation strength & power requirement
- Speed & Resolution
- Number of memory shapes
- Transition Quality
- Trainability
- Reversibility
- Input Stimulus
- Bi-Directionality
- Environmental Compatibility
- Consistency & Stability

The following are points also worth mentioning as part of the review on designing haptic interfaces but have slightly lower priority for this study.

Of relevance in all the projects described above is the environment in which the interfaces are located since dynamic spatial changes are part of the larger (peripheral)
haptic experience (Parkes et al. 2008, Rasmussen et al. 2012). Creating a transparent link between the digital and physical world presents a unique design challenge. In order to accommodate this transparency, the notion of organic interfaces is commonly used throughout the literature and primarily focuses on describing an intuitive, natural, body-based interaction with inorganic objects. Curved lines and flexibility are strongly associated with the organic approach to design as well as using nature and biological systems as sources of inspiration (Holman and Vertegaal 2008).

Gestures and overall body movements are a peripheral of haptic interfaces. The gestures that evolve through the use of haptic interfaces can change the inter-personal interaction (Malik and Laszlo 2004, Yao et al. 2011). Stability and accessibility are key aspect in interface design and fall under Nielsen’s heuristic of flexibility and ease of use (Nielsen 1995). This simply means that ideally an interface should be able to accommodate a novice as well as expert user through creatively designed shortcuts (Ishii et al. 2004b, Schwesig et al. 2004).

The list of projects mentioned is not exhaustive and even as this study is being written, new technological developments emerge aiding interface design. They explore a wide variety of elements inherent in haptic interfaces: a user’s perspective, the expression of emotion through a change in surface topology or improvement of life-like reaction to facilitate interaction more easily.
3. Methodology and Early Prototypes

3.1 Introduction
Design and multidisciplinary research are central to this study. Aside from traditional research techniques and building upon existing knowledge through the composition of a literature review, the predominant methodologies applied in this study are the artistic and design methodologies. Cognitive concepts such as top-down and bottom-up design are also applied in the design process. This chapter details the approach and tools used to develop and create a new conceptual design for a physical agent that could eventually be implemented in a multiagent system, like that of an ant hive, or termite colony, etc.

The current procedure of such project development, like the one suggested in this study, is to design, prototype, test, redesign (if necessary), create a high-fidelity prototype and possibly end with a finished product. Few projects reach the final stages, whereby the diffusion of innovation process becomes relevant (Interaction Design Foundation 2018). This is supported by Cohelo’s review of shape shifting interfaces: the majority of haptic interfaces do not leave a lab setting. In these circumstances defining appropriate applications is a continuous challenge which in turn is reflected in the design (Coelho and Zigelbaum 2011). Most projects reviewed for this study as part of the background research, attain the level of being a comprehensive demo. Therefore, perception in this instance has an important role. The newly proposed agent design to emerge from this study (the Dod) remains predominantly a conceptual entity. It’s mechanisms and basis of structural design are closely related to existing projects (Butera 2002, Horev 2006, Romanishin et al. 2015, Overvelde et al. 2016).

In order to achieve a good quality demonstration version of a multiagent system ideally requires the resources of several experts. Throughout the course of this study experts in industry and educational institutions, (e.g. structural engineers, mathematicians, AI computer programmers, software engineers, educators, interaction design specialists),
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Institutions (Stokes Institute, Tyndall Institute, Hunt Museum, Intel, Institute of Making, MIT, MSSI) and tools (OpenFoam, Comsol, SolidWorks, Blender, RUBE) were explored and examined for their suitability in the application of this project. Whilst many of these resources were consulted, it proved difficult to form a coherent group required to create a high-fidelity prototype. This was a determining factor for the application of an artistic methodology. It contributes in placing this study in the STEAM\textsuperscript{16} domain, bridging a gap between Science and Art.

Since this study is also orientated towards haptic interface design, an adapted version of the design methodology is also implemented. There are similarities between the artistic and design methodologies, even though the artistic methodology still requires further and continuous refinement due to the nature of its application. With respect to design, there is copious research into what constitutes design, the design process, design components, etc. It is a practical and creative process often with an underlying theme of functionality and application.

The first section of this chapter describes these methodologies, highlights the similarities and differences, and their relevancy to this project. The second section elaborates on the techniques and tools used for prototyping various design concepts. The last section is an illustrated documentation of design concepts that preceded the final design. It illustrates the flow and evolution of research whilst maintaining overarching themes that guide the design process, i.e. agent characteristics, replication versus emulation, error and creativity.

3.1.1 Artistic Methodology

Intuition is an integral component in a person’s decision-making process. As a person builds up an expertise, their knowledge-base and experiences help inform and fine tune their intuitive sense. Despite varying from field to field, the process of starting with an idea based on intuition is oft not appreciated or as openly acknowledged. A possible reason for this attitude is that it is difficult to reliably depend on intuition because it can be influenced by a person’s emotions and experiences. These qualities can be

\textsuperscript{16} STEAM: science, technology, engineering, art and mathematics. This is an evolution from the STEM branch as it includes art.
unpredictable, subjective, and unique to each individual. For example, two people in the exact same situation will not perceive the experience in the same way. There are vast number of reasons why this is, but it predominately relates to phenomenology and the experiential make-up of the person based on their past events. Even though intuition is also present in the science domains it is not usually applied as a means of proof, but more so a means of providing an initial starting point of research or investigation. Experiments and specific procedures exist as part of the scientific methodology in order to provide rigorous and repeatable results. This methodology aims to provide an objective insight to provide a better understanding of a person’s environment. In contrast intuition plays a stronger, more present role in the art domain because this domain facilitates the experiential and creative aspect of a person.

Art is intrinsically a subjective and practical domain, therefore the majority of research from this area is presented in one of three ways, A) an artwork, B) the process itself is the artwork, or C) the work is a purely philosophical, written expression (Hannula 2009). There are not many clearly defined frameworks for presenting the artists’ research process therefore defining the artistic methodology is at times problematic. A possible conclusion that can be made is that the intuitive model is at the core of this methodology.

There are similarities between the artistic and design methodologies with respect to sharing the approach of the basic principles. The contrast is evident in the perspective taken to define that approach, e.g. the function of sketching is the same in Art and in Design, however, the value placed on sketching varies because it is relative to the final result. Inherent in Art, is its vast materiality and predominant focus on the experience and emotional expression rather than on form and functionality. It is fundamentally multidisciplinary in its construct and the distinction between fields is not as stringent as it can be in science. It is possible through the artistic methodologies to amalgamate diametrically opposite subjects such as biology and robotics or quantum physics and film or mechanical engineering and cuisine, etc.

In its nature, Art allows individuals to question and push the boundaries of established procedures and institutions. For example, Paul Feyerabend believed that the unvarying, objective approach present in scientific methodologies had become restrictive and unyielding. He suggested a subjective, more intuitive approach to
articulating research findings (Hannula 2009). This approach essentially enables the researchers to personalize the method by which he/she has attained the end results and emphasizes that it is a reflection on the process itself not the outcome that constitutes the significant research.

The methodologies used in artistic research are primarily practice-based. The term practice in this case is not limited to practically orientated activities, e.g. sketching, glazing, colour mixing, sculpting, etc., but can also relate to socially engaged art practice whereby people are the medium. They also involve traditionally seen scientific methods of experiments, tests, comparisons and analysis as well as social scientific methods, such as interviews, questionnaires, brainstorming, etc. In Art, practice is also related to the concept of repetitive action and recurrent self-reflection (Malins et al. 1995, Hannula 2009). The method of refining an idea, portraying it from every angle, considering its applications, the environment it will be in, the materials it is made of, and its effect on others is as provable via scientific notation as it is via tacit knowledge of the artist (Malins et al. 1995). It is interesting to note that for an artist who works on their own, there is often greater scope for freedom of exploration and space for creativity. In contrast, projects that consist of collaborations or a group of specialists whose main aim is to create a working prototype, the methodologies become more deductive and science orientated (Caduff 2011).

Methodological diversity and flexibility is encouraged within the creative disciplines (Caduff 2011) as maintaining unstructured methodology is a contribution of artistic research in itself. For example, consider the struggle of the psychology discipline to be taken seriously in the academic community. Researchers in psychology began to employ and adapt scientific methodologies in order to gain acceptance and recognition. Whilst it can be argued that it has achieved part of this goal, even though it is still perceived as a soft science, a question that arises is whether the discipline has maintained it’s inherent integrity? In the attempt of disciplines to conform to methodologies of other established disciplines, they can run the risk of loosing the integral meaning and concept of the discipline in question. Attempting to clearly define and organise an artistic method comes from a scientific or logical perspective or orientation, i.e. the desire to structure and order knowledge. However similar to the concept embodied by the 1916 Dadaism movement, sometimes it may be necessary to
accept that certain research methods have to maintain a peripheral status as opposed to an acutely focused one. In relation to Dadaism, as people (academics, critics, artists, etc) attempted to clearly define and describe what Dadaism actually represented and meant, the more elusive and dissipated the movement’s meaning became. While the scientific disciplines remain relatively constant because of their derivations from objectivity and logic, the arts and humanities in contrast reflect the Zeitgeist of the period. The versatility of art has been demonstrated throughout human history, in particular its capability of embracing and integrating elements beyond its scope. From Leonardo da Vinci’s drawings that conveyed scientific knowledge to Duchamp’s appropriation of scientific tools and procedures into the creation and composition of artworks, the openness and less stringent boundary conditions of the arts ensures a space for creative exploration and engagement.

The current trend in artistic research is to shift this flow, of STEM disciplines into the arts, into the other direction, i.e. incorporate elements of the arts into the sciences. The work of Mathew Gardiner, who combines the art of origami with robotics and programming (Gardiner 2004), Justin Zoll, who uses microscopy to open the world of crystalline structures (Zoll 2018), performance artists Tero Nauha and Paolo de Assis (De Assis 2013, Nauha 2016) are just some artists who use artistic research to generate knowledge through the creation of artworks but do not necessarily translate this knowledge into written form or via an established, traditional format (Nauha 2016). Due to the unconventional and varied approaches in artistic research, documentation of the methods used generate research output can be difficult to extract. These examples are a minute representation of a community of artists or technologists that move and continuously develop the STEAM approach.

In order to relate the artistic and design methodologies an analogy can be drawn around the user centre design model (UCD). Each stage of the design process: research, design, prototype, adaptation and review are all centred on user evaluation and feedback. This process typically involves several people who each contribute to the overall project. In contrast, the artistic methodology typically is centred on the researcher/artist. The user evaluation is comparable to the constant self-reflection and detailed documentation of the various stages of progression of an artwork.
3. Methodology and Early Prototypes

3.1.2 Design Methodology
The design methodology used in this project is centred on an iterative evaluation process. Whilst this study does not incorporate user evaluation, an iterative process is useful in honing a design to its most functional potential. In general, the iterative design method includes user involvement in every stage of the product design.

1) Initially a need is identified or a design brief is formulated. It is possible for the design team to run the initial brainstorming session. The user can also already be included at this early stage but is more likely to be involved in subsequent brainstorming sessions. The role of these sessions is to create an open platform for ideas – they are directly related to the design brief but it is also possible to conceive blue-sky scenarios, i.e. ideas that may be outside the scope of the project but can provide interesting goals to aim for.

2) After the brainstorming session, ideas are grouped according to various qualities and prioritized. Since these sessions often make use of various materials and techniques and can be as creative as desired (mind maps, post-it diagrams, pencils, markers, etc), the information is presented: visually through colour: being written or drawn; aurally through active discussion, short sound clips (if appropriate) and physically through the use of white boards, flipcharts, post-it notes or cut-outs, etc. This method of presentation ensures a multimodal approach and that each person can efficiently express themselves amongst the group.

3) Once core ideas have been identified it is possible for the design team to start working on one design. This idea is developed whilst keeping the other ideas and requirements as guidelines that inform and help clarify specific choices along the design development. Once again it is possible to involve the user in particular if it is a specific client-based product. The process may be slower in comparison to methods such as the waterfall technique however it is more beneficial in the long-term process as a large number of mistakes or misinterpretations can be avoided.

4) The next stage is prototyping the design. This can be done in a range of fidelities and should be appropriate to the various resources available. For example, if a project is still in its infancy it is not necessary to have high fidelity prototypes that require significant time and materials to create. Prototypes can also undergo user evaluation therefore it is valuable to consider prototypes that can demonstrate the required
functionality but also avail of the user’s imagination. Once a project is nearing completion it is necessary to create a better prototype that represents a near finalized version of the product. It is possible to expend more resources, as it is less likely that significant changes will be made to the product.

5) During the prototyping phase, it is possible to run user studies, to test whether the product or system functions as originally intended and fulfil the design brief. At these stages, it is possible to discern flaws in the design, to uncover hidden requirements, to detect inconsistencies or uncalculated affordances. Whilst it is important to choose a user group that is relevant for the specific design brief e.g. testing child proof locks with adults has little true worth, it is preferable to test the product amongst a wide variety of users within the specified field. The reason for this is that throughout the design process the design team is primarily preoccupied with the project and all aspects regarding design, therefore it is necessary to get alternative and objective perspectives in order to improve the product, with respect to design alterations.

6) After rigorous testing, the product or system should then be ready for production or presentation to the client for further manufacturing.

It may be that at times steps 3 – 5 can be repeated for each idea that is generated through the brainstorming sessions. It is also possible that after an idea has been developed that another brainstorming session may provide new scenarios and range of possibilities. This is the advantage of the iterative design process: the flexibility and adaptability may take longer than other processes but it is thorough, consistent and supportive of the saying “all good things take time”. Using this approach generally leads to the development of a more stable and sustainable designs. It enables designers to understand every aspect of their design and the implications if changes are made either to the product itself or the environment. In relation to this study the iterative process is adapted slightly so that each prototype not only aims to improve upon the previous design but it also reflects the research as it developed and progressed. The creation of each prototype aids the process of transitioning from a replication stage to an emulation phase. This is illustrated in section 3.3. onwards. Without the process of sketching or prototyping and evaluation, understanding is incomplete and potentially critical information may be overlooked.
The design methodology is also inherently multidisciplinary in nature, as it involves people from different fields and of different expertise. It is an amplification of the artistic methodology whereby reflection is experienced by a design team versus the individual. The value of the multidisciplinary element is important because it is a better approach to analysis as well as design. Similar to multimodal sensing, it is a method of gaining insights and perspective from a wide variety of sources to ensure better-informed decisions and greater time efficiency. For example, the growing field of 3D bioprinting is a domain that equally involves medics, product designers, surgeons, engineers, physiotherapists, patients, and ethical lawyers, amongst others. It is a discipline that is starting to cross the traditional boundaries between engineering and medicine (University of Wollongong 2016). The multidisciplinary approach requires the amalgamation of several different methodologies each appropriate to the specific task and relevancy to the projects development.

3.1.3 Traditional Guidelines
With the scope of materials and methods available today it is challenging to specify the direction of development for tangible shape-shifting interfaces. In conjunction with this uncertainty and the application of an artistic methodology, the qualities of inductive reasoning lend itself to establishing valid premises even if the conclusions are not binding in the long term. As mentioned in Chapter 1, section 1.2, the terms top-down and bottom-up are used to represent more complex processing or reasoning concepts that are common throughout many disciplines ranging from design, engineering, economics to psychology, etc. but generally convey the essence of a particular concept. For example, inductive reasoning is often described using the bottom-up analogy. Bottom-up encompasses working from existing knowledge and building upon this base to accomplish a specific goal or understanding. It is a process whereby the small parts sum together to make the complete whole. In inductive reasoning, the premises that define the argument are specific and enable the process of making observations and pattern finding until it is eventually possible to formulate hypotheses which in term inform a generalised theory. The conclusions drawn from inductive reasoning are based on the evidence of the premises more so that the actual premise itself. It means that these conclusions promote a probability as opposed to a
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clear certainty and that even if all the premises are correct, it is still possible for the conclusions to be false. The more data that is available in the construction of the premises ensures a greater probability that the conclusions will be true. In contrast, the top-down approach is similar to reverse engineering. The technique is based upon knowing or understanding the overall system and de-constructing it in order to gain insight to specific functions or mechanisms. It is comparable to coding in so far as the inputs and outputs might be known but the middle function requires resolution. Deductive reasoning has formed a standard basis for the scientific methodology and is often described using the top-down concept. In this style of reasoning the premises are known to be true and therefore the conclusion follows logically and is also considered to be true. Unlike the conclusion reached via inductive inference, deductive conclusions are formed as a logical progression from the original premises. This means that even if the premises are incorrect the conclusion would still be logical.

Both methods have their advantages and disadvantages depending on their application. For example, inductive inference is comprised of specific premises that are based on an accurate and large knowledge base. It can be time consuming and tedious to build up such a knowledge base, however, once acquired it provides a strong and stable base from which to expand and build plausible hypothesis. In contrast deductive inference in problem solving may be faster because it is possible to identify specific aspects of the problem and hone into these areas in order to build case specific knowledge, i.e. logical conclusions. In narrowing down the number of system variables in order to generate accurate premises, the potential to create constrained or singular conclusions is increased and each new problem may require the repetition of the entire deductive process. Ideally inductive and deductive analysis should be applied equally and for the vast majority this is the case, particularly in dealing with everyday challenges. Children begin by building upon a knowledge base gained through experience and as they mature they are able to apply previous knowledge to different situations, i.e. the process of conceptualisation. Similar for this study, a combination of these two approaches to reasoning with respect to the design decisions underlies the methodologies described earlier. By applying them to varying degrees of rigidity it is possible to maintain a flexible and creative approach to problem solving. Through research a knowledge base is built up and continuously develops whilst specific goals
guide and shape the type of knowledge required. It is a tangible process that reflects the concept of how control can ideally be handled in a balanced manner.

3.1.4 A STEAM methodology
The primary concept behind the STEAM methodology used in this study, is delving into the required areas of research but purposefully withdrawing before specialising in one specific topic. What is sought is a clear and comprehensive understanding of particular aspects of a field whereby it is possible to use the concept of the knowledge but not necessary apply or work directly within the subject knowledge. For example, in this study research began with exploring Non-Newtonian and smart fluids. The modules Fluid Dynamics and Continuum Mechanics were taken in order to assess the requirements and skills needed in order to develop into this strand of research. Whilst the application of the acquired knowledge was beyond the scope of the author, an understanding of the concepts entailed in Fluid Dynamics provided a valuable contribution to the design process, i.e. the ideal condition set see Chapter 1, section 1.4.

Deciding on the degree of immersion into a subject and knowing one’s own limitations requires practice and experience. At this point a deductive method provides the initial structure of exploration. For example, in this study there was a bias towards the arts, i.e. the strength of the researcher lay in crafts, haptic and material exploration and, construction. Various aspects of the proposed agent design however, require expertise in the science, maths and engineering domains. Considering one element of the design, the arm mechanism, the following questions arose (note: this list is not exhaustive):

When the origami spring is rotated slightly past its full extension it can withstand an amount of force -

- How much force can it withstand?
- What is the relationship between the amount of downward force and scaling the spring structure?
- **Is this extended position stable?**
- Can the amount of force be calculated?
- How small can this structure be scaled?
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- **Can anything be done to reduce the stress and strain at the corners of the spring structure?**
- **What material can it be made of?**
- **What effect will the material have on the ability to resist forces?**
- **What if the spring structure is soft, what if it is rigid?**
- **What if the spring structure and the skin functional are the one in the same?**
- **Is this the best origami spring structure, what other types exist?**

As the research progressed through reading, undertaking modules but also contact to related industry professionals, it became clear that the limitations for this line of exploration were also influenced by the researchers own qualification, knowledge base and time frame for the study. The questions highlighted in bold were explored further through studies and through an art perspective, that yielded results in terms of approximate probabilities as opposed to definitive conclusions. As a result, the output of this study has created platforms of further exploration as well experimentation for researchers specialising in specific fields, (e.g. mechanical engineering, evolutionary algorithms, material sciences, interface design, agent communication, etc.).

An important component in this methodology is the researcher’s ability of self-evaluation. As avenues of research are explored (see Table 1, Chapter 3) and the appropriate resources are exhausted (e.g. contact to academic and industry professionals), it is necessary to be able to gauge the value of the contribution that can be made. The evaluation process is subjective and continuous, which is reflected in the implementation of the artistic methodology, see section 3.1.1. An inherent component of this methodology requires researchers to become autonomous and self-critical because they create questions that are most often answered by researchers who excel in deductive reasoning. These questions must be carefully constructed and viable in order to contribute to the enhancement of research and overall knowledge. In contrast, a researcher who answers these questions has a research path define by an external process, their aim is to find conclusive results. These approaches exist in all facets of human engagement, e.g. a prospector proposes where to start a mine, working on probability and a miner creates tunnels that come to specific points.
Documenting the STEAM methodology used in this study aims to demonstrate how it is possible to recombine diverse subjects and their appropriate perspectives and to illustrate the skillset required to implement the methodology to its fullest potential.

The actual research process of a STEAM approach differs little from that of STEM or a purely arts-based approach, however a noteworthy difference is the boundary parameters that are inherent to each discipline. The strict routine of scientific experiments or the logical calculations in maths generate procedural structures and orders knowledge. In contrast art, music or poetry, etc. often diffuses the focus from a technique or routine to that of a personal expression. Without a balance either of these extreme bounded states can become more destructive as opposed to beneficial to the progress of research. It is important to note for this study that even though art was used as a discipline in its own right, via the artworks created, the complementary disciplines encompassed by the arts are also included and considered, e.g. the humanities such as moral implications for biological based computing systems.

The most valuable contributions the art discipline made to this study were,

- the ability to consciously change perspectives (i.e. learning how to think differently)
- allowing the character of the researcher to become more integrated into the research output - *beauty is in the eye of the beholder*,
- being the vehicle to communicate conceptual ideas.

The creative subjects, more so than the logical or reason-based subjects, enables the researcher in all their facets, to be a direct influence or component in the research process. The character, experiences, beliefs and intuitions of the researcher are folded into the exploration or experimentation process and other intangible qualities such as aesthetics, emotions and perception are valid contributors to the progress of research.

The process of self-evaluation and exploration is critical in defining the scope of research, particularly if the traditional approach of using a research question or end goal application is not applicable. The compilation of elements that have formed the final output of this study are reflective of the STEAM process: exploratory studies, prototyping, and simulations were executed to gain empirical data, whereas networking, learning and discussion groups formed the conceptual analysis of the
3.1 Introduction

subject matter. Maintaining a balance among the avenues of research has been an underlying challenge throughout this study but is a valuable skill in the development of becoming a multidisciplinary expert. The value that the arts bring to the STEM disciplines is bringing scientific research into a social context. Disciplines such as philosophy, ethics, psychology, social sciences, geography, cultural studies have values that are focused on the human element in research. Integrating the perspectives of such disciplines with the sciences is necessary to be able to continually shift the priority of focus in order to facilitate the progress of research and technology, e.g. DNA research and manipulation.

Balancing speculative and concrete design thinking was achieved through the exploratory studies and comparative analyses. Exploratory studies support the feasibility of specific design parameters because they result in empirical data. These kinds of study differ from studies completed via a scientific procedure because they do not adhere to the outlined routines defined for an experiment. However, the results are useful as they create a more complete design blueprint. In contrast, comparative studies use existing, functional, peer-reviewed projects and / or prototypes in order to compare and contrast which elements of the speculative design suggestions are viable. For example, in Chapter 6 a project is explored that has elements based on origami, polyhedrons, an extension mechanism and self assembly. The project was analysed and helped determine the validity of the dodecahedron (as a basic building block) and its arm mechanism. Analyses and comparison is the process whereby speculative design begins to find kernels of truth in reality.

3.1.4.1 Self reflection on the STEAM approach

Throughout my life and education there has always been a balance between the arts and science. I love learning, exploring different ideas and looking past the whole to see the smaller parts. Victorian engineering is an example that for me balances technical knowledge with aesthetics (even though it may not have perceived as such at the time). From lego, mechano, drawing, 3d modeling, music, handcrafts, and coding, I have been able to maintain a haptic dexterity because of continuous practice. In school I studied physics, art and music and later in college I completed a degree in music, media and performance technology. The degree covered aspects relating to
video and sound theory and technology, electronics, hacking, programming, interaction design and academic skills relating to research and writing. Developing a well-rounded competency meant that the STEAM approach came as a natural method with which to explore a diverse subject matter. Because shape-shifting technology is still far from realisation, there is a continuous and fluid transition between creativity (i.e. science fiction) and reality (parts of the puzzle that come together). A STEAM approach fosters independence, curiosity, exploration, self-reflection and resourcefulness both in relation to research but also in social networking.

For the first 2.5 yrs of my study, with the continued encouragement of my supervisor, I took on modules relating to automation, fluid dynamic, scientific computation, probability, machine learning, 3D modeling and I would often engage with subjects that initially did not seem to have any relation or connection to my current research topic (e.g. seminars in the material sciences department). Inevitably at some later point, some form of this knowledge informed an aspect of the design process. Being able to make these connections were valuable experience because they gave me confidence and taught me to be open minded and fearless in the pursuit of knowledge.

Aside from my personal studies the areas I have had exposure to through the education of my family. The knowledge gained through these disciplines informed my approach but also provided inspiration at times when I could go no further on my own:

- through the psychology and psychotherapeutic education of my mother I became aware of human nature in its emotional and intangible constructs. It enabled me to gain a greater insight and appreciation for user-centred and emotional design.
- my father’s work as a vet and a homoeopath, informed aspects such as energy, business, biology and ethical considerations for all forms of life,
- an understanding for the unique quality of experience for each individual developed through my sister’s Masters in Philosophy in which she explored phenomenology and existentialism in relation to Merleau-Ponty. In her study she chose to explore the experience in relation to abstract art. The concept of phenomenology is expressed more readily through creative subjects because they draw inspiration from or are always influenced by the artist to some degree.
Another lasting influence that showed me how important it is to train the ability to view a problem from as many different angles as possible, is a simple mobile game call Flow Free (Big Duck Games LLC 2014). It consists of connecting coloured dots in twisting lines on a gridded board. As the levels increased, the boards became more difficult by becoming larger (e.g. 12x12) and introducing more colours. There was one rule: the lines could not cross or interfere with each other. I would play this game to wind down, shortly before going to sleep. Some of the larger boards took minutes to solve, sometimes I would need to turn the phone by 90deg in order to see a connection I had not seen before. Most interestingly were the boards that sometimes took several weeks. Each evening I would play for a few minutes applying every trick of seeing the board from a new perspective. Then one evening I would be able to solve the same board in seconds. The game taught me that forcing an issue or becoming tunnel visioned, shifts the focus on the end goal, rather than supporting a path that leads to the end goal. Allowing myself the time and distance to be able to see the problem renewed, enabled me to process information subconsciously. This realisation ties in with the process of exploring as many different avenues of research as possible because even though the knowledge may not be applied or used immediately, it is still being processed.

3.1.5 Simulation
The aim of a simulation is to test a model in relation to time. The results of a model are often known in advance, to an extent, and the simulation aids in supporting these findings or possibly highlighting elements that were unaccounted for. The model itself accounts for the behaviour, mechanisms and characteristics of the system being tested. For this study and the simulations carried out the model being tested is the Dod and its ability to extend and retract its arm appendages. The simulation is setup to explore the validity of the Dod design with respect to the choice of dodecahedron as a basic structure and the mechanism of extending arm in the shape of an inverted pentagonal frustum ending in a large pentagonal facet. The software used to complete these simulations is a combination of the physics engine Box2D (Catto 2016) and RUBE (Campbell 2012) coded in C++, Appendix E.
3. Methodology and Early Prototypes

3.2 Tools & Technology

Sketching is a central component in both the artistic and design methodology the source of each concept being guided by the specific requirements defined by the research (Buxton 2007). During the sketching process, each illustration is refined further and continuously influenced by specific details, similar to brainstorming. From the sketching, it is possible to build prototypes of varying fidelity. Sketching also provides a fundamental understanding of structure and spatial perception (Brohn 2005). It is a skill that holds strong value despite the vast improvements and advancements in digital presentation technology. The tools of pen and paper are a physical, real and tangible medium that can document the expression of thought.

3.2.1 3D Printing

Whilst sketching underlies this project, it has also benefited from the development of 3D printing, which has enabled the production of medium to high fidelity prototypes with greater ease. The natural process from sketching to creating physical models has always existed. It confirms intuitive creations (Ishii et al. 2004a) but it also aids in the testing and detection of significant flaws in the early stages of project development. 3D printing is a useful tool for improving visualization and conceptualization of the product itself. The 3D printers used in the creation of the following prototypes are the Ultimaker2 and the Form1 printer. The materials used in throughout this project range from PLA, ABS, Rubber PLA, to photopolymer resin. The Ultimaker is based on fused deposition modelling (FDM) of fused filament fabrication (FFF), whereas the Form1 functions via stereolithography (SLA) whereby the structure emerges out of a photopolymer resin. The intriguing aspect of using these technologies is when prints go awry and result in unusual outcomes, see Chapter 4, section 4.3.4.1.

The application of 3D printing has slightly altered the sketching process in that once a basic concept is defined it is possible to model the design using 3D software. Whilst this offers a more detailed insight for handling 3D structures it is important to consider that sketching via pen & paper develops and improves intuitive perceptions regarding structural integrity, the application of forces and the behaviour of materials (Brohn 2005).
3.2 Tools & Technology

3.2.2 Modules
In conjunction with the traditional method of conceptualization via sketching, modelling, printing & building significant influence also came from the undertaking of field related modules. Knowledge acquisition from experts in the chosen fields is the most efficient method if done correctly, as it is not only knowledge that is imparted but also experience.

Of particular influence for this project was the module Contemporary Art in the Public Realm. The fundamental design (i.e. the dodecahedron) was inspired by the subject matter of this module. Exhibit HCM 157 from the Hunt Museum in Limerick City, is a bronze cast dodecahedron from the Roman era. Its purpose and function is unknown but it provided the platform to begin unifying the research and design guidelines, Figure 3.1. The module fostered a haptic exploratory approach to design which influenced the method and format of achieving results.

Figure 3.1 Exhibit HCM 157 - Bronze dodecahedron with different sized holes in each facet.

This shape was explored in several iterations via artistic renderings. Every artwork utilized different materials, each of which had inherent qualities. Similar to prototyping, reconstructing this shape through Art not only facilitates direct haptic exploration of the shape and material, but also provides an understanding for its geometry, potential behaviour, and its physical limitations without the functional restrictions. The various renderings highlight characteristics that may contribute to the overall design or provide sufficient reason to alter the design. For example, using the construction as it is currently defined in Chapter 5, the origami tower as the core arm support allows for retraction and extension movement. When extended it is also possible for the arm to bend slightly allowing for some give with respect to the attachability. However, this may be a method for developing tangible interfaces. To design
3. Methodology and Early Prototypes

for touch, an interface can no longer simply fulfil the aesthetic requirements. It could make use of the vast scope and diversity that haptics can offer.

3.3 Evolution of an idea

The starting point for this study began with the exploration of Non-Newtonian fluids. Previous personal research and experience was based on Ferrofluid, therefore the liquid aspect was of interest in creating a tangible yet real-time morphing interface. The most common initial condition for the proposed interface is the inactive one, i.e. the agents are equally distributed throughout the suspending medium. Therefore, the natural tendency is to enable these agents to assemble into the desired form according to a specific instruction. This task presents a greater challenge in that the interface moves from a state of low energy to a state of high energy, which resists the natural tendencies of entropy and the 2\textsuperscript{nd} law of thermodynamics (Atkins 2010). Current research is still primarily focusing on how to physically embody a self-assembling characteristic. However, the ability to disassemble is of equal importance to create a truly reactive and flexible interface.

Whilst assembly is the most intuitive approach to creating a structure from smaller parts, the alternative method of construction is like that of sculpting whereby the excess or unwanted material is removed to leave behind the required structure (Gilpin \textit{et al.} 2010). This characteristic depends on the final behavioural coding as well as the consideration for the mechanism required to disassemble from neighbouring agents.

Considering these primary yet opposing methods of construction in relation to Non-Newtonian fluids, two main questions arise:

- The rheoplectic characteristic of Non-Newtonian fluids is of specific interest: it is possible to elicit localized areas of semi-solidification and can it be harnessed to build structures?
- What is it in the particle shape itself that allows it to interlock and detach with ease in order to create the shear-thickening effect?

Oobleck (cornstarch and water) was the Non-Newtonian fluid used in the initial stages of this study because of its accessibility and clear manifestation of shear-thickening behaviour. In the analysis of this behaviour, research was also conducted with respect
3.3 Evolution of an idea

to finding other Non-Newtonian fluids that were constructed with man-made particles (e.g. glitter, glass beads, quartz flour (Kann et al. 2013a), to gain insight into optimum particle designs.

The assembling of the cornstarch particles via the shear-thickening effect was researched in order to discern whether it would be possible to introduce man-made agent that could interact with the natural particles. For example, the man-made particles would be mixed amongst the Non-Newtonian particles. These would be able to trigger the shear-thickening effect around them via vibration, creating larger ‘building blocks’ via clusters, which could be used to construct a larger structure. On further exploration, it became clear that:

- scaling a man-made particle to the size required is currently not practical, because of the hardware required to make it controllable, the average size of cornstarch particles being between 0.1 and 0.8 microns,
- forces such as, Brownian motion and gravity means that there are too many variables that could destabilize the overall system, as they cannot all be accounted for.

A high energy level is required to maintain an area of shear-thickening and a clearly defined boundary is always required since the effect always tends towards diffusion into the surrounding unaffected area when the source of agitation is removed. This means that building structures would still be pre-defined rather than the NN being able to construct the structures on its own accord.

The concept of designing self-contained modular agents resulted from this research. These consist of either lock and receiver nodes or solid geometric shapes (Bojinov et al. 2002, Gajamohan et al. 2012, Roudaut et al. 2016). The following factors resulted from the research and were deemed as important guidelines for future designs:

1. The cornstarch particles are semi-spherical in nature with an irregular, cratered surface. They are also varying in overall size
2. It is not possible to maintain control over every individual particle (even in an equivalent man-made system) as this requires a significant amount of energy.
3. Methodology and Early Prototypes

3.3.1 Prototype 1: Lock and Key

As illustrated in Figure 3.2a and 3.2b the outer body consists of two particles: a connector and a receiver. The central body is a cube, which can contain the circuitry required to execute the programming and to activate the polarity of the extended arms. The circular depression would exhibit a negative charge whilst the spherical structure exhibits an attractive charge, Figure 3.2c. This could potentially encourage a better connection between components. The connector has four extending arms with a sphere located on the end and two bowl-like depressions. The receiver has four depressions and two extended arms. The particles are rigid and do not alter their topology and functions on a modular basis. The design aims to amplify and direct the polarity, thereby attempting to achieve optimum particle alignment.

![Figure 3.2 Prototype 1](image)

**Figure 3.2 Prototype 1** – (a) the Connector component, (b) the Receiver component, (c) terminals, (d) printed components.

3.3.1.2 Problems

There is the potential for a greater margin of error if the particles are misaligned or do not fit into the right places. It may require extra programming as each particle must be able to determine where it is. The ability to scale is also questionable, see Figure 3.2d. Whilst the ball and socket style joint enables a certain degree of flexibility regarding bending and flex between the connection of two modules, the majority of resulting structures would remain mesh-like and blocky, Figure 3.3.
3.3 Evolution of an idea

![Figure 3.3 Prototype 1 connected](image)

Illustrations of the bending and flexing possibility as well as the overall mesh construction.

3.3.2 Prototype 2: Biology

The field of biomimicry has seen a significant rise of interest and research. This field attempts to find solutions for man-made design challenges by looking to strategies, patterns and constructs applied in nature (ECOS 2006, Parness 2011, Dynamics 2016b, Dynamics 2016c, Dynamics 2016a, Biomat 2017). Nature’s strategies and structures are vigorously tested against time and evolution. In conjunction with Non-Newtonian fluids, and as mentioned in section 2.4, a biological equivalent was found for MAS, by studying Solenopsis Invicta (fire ants). In nature, these insects can form temporary rafts to survive floods but also bridge small gaps. According to the video evidence (Mlot et al. 2011, GeoBeats News 2015), the dispersion behaviour and reaction to sudden agitation appear to be analogous of the shear-thickening characteristics and high viscous behaviour discernible in rheoplectic Non-Newtonian fluids.

An advantage of the using ants as a source of inspiration is that they represent the concept of an autonomous agent, their behaviour has been studied and modelled
repeatedly via computer simulation since the 1960s (Uhrmacher and Weyns 2009) and they fulfil the requirements of scalability, assembly & disassembly and being able to build structures without an explicit hierarchical chain of command.

As described in Chapter 2, the claw mechanism is of interest because it does not change shape in itself but is designed so that it functions in everyday life, is able to grip another ant and detach without a retraction mechanism. The ant claw represents an optimal shape because its functionality can be attributed to its physical affordance. The hook cannot be too pronounced or else it will lead to snagging, Figure 3.4.

![Image](image_url)

**Figure 3.4 Solenopsis Invicta** - Illustration of the claw at the end of a Solenopsis Invicta tarsus.

3.3.2.1 Prototype 2

The outer body illustrated in Figure 3.5, made use of a protruding arm and ant claw mechanism. The outer body is a capsule shape to aid in movement through a liquid. The advantages of this shape are predominantly with respect to particles moving past each other. Next to a completely spherical shape, there is little resistance, and there is more space within the particle to contain the attachment mechanism and potentially an equivalent to a brain. The capsule shape can also be used to help with feature construction in terms of packing behaviour.
3.3 Evolution of an idea

![Prototype 2](image)

**Figure 3.5** Prototype 2.

The inner component consists of a swinging arm extruding from a disc, which is held in place via pin. The arm extends approx. 5cm. At the end of the arm is a claw modelled on that of an ant, Figure 3.6. Of importance is the degree of inner curvature.

![Ant claw](image)

**Figure 3.6** Ant claw - Representation of ant claw: primarily focusing on the inner curvature.

When the particle is required to flow and behave like a liquid, the arms are contained inside the particle body and the whole particle takes on the capsule shape. When the particle is required to create a 3D relief structure – the arms extend from the top and bottom. They are diametrically opposed from each other, extending the capsule shape.

With the claw, the particle can hook into another particle thus preventing the free-flowing motion of a liquid with the aim of creating a clustered mass.

The issues that became apparent very quickly are as follows:

1. The potential for the arms to be caught in between other retracting arms exists. This would interfere with the capsule shape, which is required for a free-flowing liquid behaviour.
2. The slits out of which the arms extend mean that the body is potentially open and the interior is exposed.
3. The inability to direct the particles would make it difficult to create defined structures as is necessary for interfaces.
3. Methodology and Early Prototypes

3.3.2.2 Prototype 2b
The 2\textsuperscript{nd} capsule-based prototype has modified the arm and claw mechanism. The outer capsule shape is retained, the extended arm is removed and only the claw protrudes. The protrusion is facilitated by the sheathing or retraction mechanism found in cats, Figure 3.7a and 3.7b.

![Figure 3.7 Prototype 2B](image)

The inner component in this design consists of a sliding mechanism. Each claw sits slightly off centre on a bar that spans the capsule width. This is to accommodate both claws side by side when contained inside the capsule itself. The bar slides up and down inside the capsule. The slot in the capsule is designed such that the claw moves straight up and is gradually guided into a horizontal position by its outer curvature. This design is simpler and drew inspiration from how a cat extends its claws, Figure 3.7a. Cat claws have a greater inner curvature as they are designed for hooking onto or into. For cats to retract their claws, their muscle mechanism enables them to lift the claw up (to unhook) and back (to retract), whilst in the particle design the claw is simply drawn back.

Similar to Prototype 2, the capsule shape ensures that a relatively smooth flow can be attained, whilst the claws are contained within the particle body. Once the claws extrude the overall shape has been altered so the particles can now latch onto each other. By removing the extended arm, the retraction process is greatly improved as the likelihood that the arms interfere with each other is eliminated. The claws can now slide back into the capsule rather than swinging forward and catching other extended arms in the process Figure 3.8.
3.3 Evolution of an idea

3.3.2.3 Prototype 2c

The last prototype considered along this avenue remained conceptual but incorporated the above-mentioned mechanisms in order to create a more contained autonomous agent. Developing on from the capsule shape, the last design is comprised of a sphere with arms extending along the x, y and z axis intersection points, see Figure 3.10. For a power supply it assumes the possibility that the solution acts as an electrolyte meaning that the agent can be powered through the solution in which it is contained. The technique by which the stalks would extend is modelled on the puffer fish, i.e. a central capacity that can increase and decrease thereby causing all the stalks to extend and retract simultaneously.

In a liquid state, the agent is as illustrated in Figure 3.9. The spherical shape allows for smooth flow of movement throughout the solution. The extending stalks are contained and the outer surface is sealed. Depending on the saturation levels, it is possible for spherical particles to contribute to the shear thickening behaviour. Spherical glass beads in an oil based suspension medium were tested and recorded as exhibiting similar behaviours to that of cornstarch and water (Kann et al. 2013a).

Once the agent receives the command to form a structure, the agent becomes charged through the solution in which it is contained. This energy enables the stalks to extend and once fully extended the claws extrude. The shape of the claw, in combination with
the sheathing mechanism of the previous prototype, should ensure that the stalks become easily untangled and can revert to smooth spherical form with reduced error.

![Image of prototype](image-url)

**Figure 3.10 Prototype 2c open** - Agent in a dynamic or active state.

A significant obstacle that is reflected in this design is the matter of scaling. Certain avenues of research have managed to maintain the ability to scale and still make use of mechanical mechanisms such as moveable and weight bearing joints (Bergbreiter 2014). Whilst it may be possible to create a macro scaled version of this prototype, it became apparent that reducing the scale would create too many complications. It would require a larger input of energy for this design to be as adaptable as is stipulated by the research to date, i.e. if more energy is required in maintaining the function of each individual particle the overall system begins to suffer.

The following factors resulted from the research and were deemed as important guidelines for future designs:

3. The ability of the agent to shape-shift or morph is an important design requirement. Whether this is limited to a changing surface topology or fundamental form alterations depends on further research and functionality.

4. In order to consider scaling to the proposed size of 2-6mm for an individual agent, it may necessary to construct agents entirely out of one piece / material, i.e. no joints or moving mechanical mechanisms (Kummer et al. 2010). The problem of wear and degradation through continuous use must be considered.

5. A significant design theme that developed through this study is the concept that complex behaviour emerges from simple rules, which is possible because of the interactions of these simple rules. This concept informs the physical agent design but also its behavioural model. Therefore, whilst new research avenues
3.3 Evolution of an idea

influence the overall development and design of the agent the underlying guideline tends towards simplicity, e.g. less mechanical parts, naturally occurring structures (curves, spirals), material and structural affordances, etc.

3.3.3 Prototype 3: Hoberman sphere

Being able to change the surface from smooth to rough and vice versa is advantageous as it aids and supports the ability to assemble and disassemble. However, having an agent comprised of separate mechanisms increases the risk of error with respect to mechanical and physical degradation. Examining objects whose shape change is inherent in their construction lead to researching the Hoberman sphere. The Hoberman sphere was developed by Charles Hoberman and its significance in this research is that the original design can contract to 15cm and expand to 76cm in diameter. When contracted the surface has a spikey, angular appearance whilst when expanded it becomes roughly spherical in nature because it creates an icosidodecahedron. This polyhedron consists of 42 faces in total and it belongs to the Archimedean solids rather than the Platonic solids as it is made up of two basic polygon shapes: 12 pentagons surrounded at each edge by equilateral triangles. This change in surface topology and size is achieved by the unique design of the inverted scissor joints, which allow it to fold in on itself (Hoberman 1990). Similarities can be drawn between the Hoberman sphere and the cornstarch particle. The attributes of the cornstarch particles that are most conducive to inducing the shear-thickening effect are: the basic shape being spherical yet the surface topology is irregular because of its cratered nature and the variety of particle size.

Similar to the last prototype, mimicking biological inspired features (puffer fish), this prototype also remained conceptual. The inner sphere is the mechanism by which the outer structure can be extended and retracted. The outer structure’s basic component is modelled on the scissor mechanism of the Hoberman sphere. Rather than have as many moving components as in the original artefact, this design considered the minimum number of scissor components necessary, which resulted in 8 scissor pairs along each plane, 24 in total, Figure 3.11a and 3.11b.
It is possible to purchase Hoberman spheres in several sizes, therefore the first attempt at replication was aimed at scaling the scissor mechanism to the smallest scale possible. It became evident however, that the assembled mechanism itself (i.e. the pin connection) would limit the size to which it could be scaled. Components were 3D printed on the Ultimaker and the Form1, and both samples eventually failed due to a lack structural integrity during printing. It illustrates how it is not always possible for the variables that define materials or structures to scale relative to each other. For example, a current carrying wire: the relationship between wire diameter, temperature \((\text{the variables})\) and amount of current \((\text{material})\) is not linear. As the diameter becomes smaller, it can carry less current but also the wire \((\text{material})\) itself has a lower threshold of withstanding heat. The pin joints connecting the scissor mechanism, are the weak links of the assembly and limit the size to which they can be scaled.

The following factors resulted from the research and were deemed as important guidelines for future designs:

6. The ability to change size via expansion and contraction is a valid mechanism and has the added advantage of being able to change surface topology. These features are evident in naturally occurring systems.

7. In order to facilitate the ability to change size and shape, it must either be inherent in the materiality or based on mechanisms that can compromise between function and form, e.g. the spiral.

From this initial research and literature review the following factor have been deemed to be the essential characteristics to inform and refine the design process. These principles will be summarised and explored further in their contribution to the final design of the agent detailed in Chapter 4.
3.3 Evolution of an idea

**Physical Characteristics**

- Semi spherical shape with cratered surface topology is a possible starting point for a particle design,
- Ability to change shape: ideally surface and overall form,
- Simple constructs that are capable of withstanding repetitive wear and strain, e.g. spiral, faceted geometry,
- The agent or particle should be able to change volume,
- Shape change can be inherent to the material or physical structure.

**Behavioural Characteristics**

- Particle or agent autonomy,
- Simplicity in fundamental ruleset: requires simple mechanisms – no cogs, gears or complicated joints.
4. The Dod

4.1 Introduction

This chapter describes the final preceding prototypes and illustrates how the current agent design, the Dod, evolved from them. It is divided into five sections and aims to address the design requirements that emerged from the literature and research explored in Chapter 2 and 3 respectively.

The first section describes four prototypes that inspired functional aspects of the Dod design and the aspects of research that directly influenced them.

The second section describes the Dod with respect to its physical and structural appearance. The Dod is still a prototype and questions such as what material it can be constructed from, and how it will be powered remain speculative, see Chapter 7. An obstacle in the domain of interface design, in particular the designs that push the boundaries of current technology, is that the applications for which they will be eventually be used are also not yet clearly defined and the technology often still requires extensive development. An important method in proving the viability of conceptual designs, aside from the creation of prototypes, is by comparing the conclusions reached from explorations with the prototypes with those of existing and established research that deals in similar domains, see chapter 6.

The third section details four artworks of the Dod design. As mentioned in Chapter 3 the artistic methodology has many elements in common with user centred design, but because the evaluation stems only from the artist (researcher) it is necessary to alternate perspectives so that design does not become entrenched. Building artworks and using different material and techniques highlights the strengths and weakness of specific aspects of the design. This is not only with respect to the aesthetics but also regarding structural integrity, function and application. Mathematics offers great flexibility in modelling and simulating possible configurations and interactions through specific behaviours whereby the artistic process provides insight into the
tangible and haptic exploration of design and generates an immediate and intuitive understanding of the design.

As stated in Chapter 1, the guiding principle of relevancy to the design of the Dod is replication versus emulation. Once the Hunt museum artefact was chosen as a starting point, the first ideas and designs bore a close similarity to the original artefact - a near replica, see Figure 4.2. As the requirements develop, the design is adapted, similar to continuously applying a filter to a filtered image. The changes reflect the emulation process. The final design contains the core ideas of the original artefact but is able to do tasks required by the maker, e.g. if ants are the original artefact then the Dod’s design embodies the behavioural and physical capabilities of an ant but its form and extension mechanisms can complete tasks that ants cannot, such as morphing interfaces, programmable matter, real-time 3D representation of digital data, etc.

To further define the design process itself, the following subset of guidelines focused on the most important qualities that emerged from the literature and what the design should ideally encompass, i.e. the essence for the physical design of a MAS agent:

1. A semi-spherical shape with an irregular, cratered surface.
2. Non-hierarchical chain of command: autonomy to function as individuals
3. The ability to morph: surface topology and fundamental form
4. One material make-up and scalability – structural affordances and inherent material qualities
5. Bi-directionality – the ability to assemble and dis-assemble
6. Behavioural simplicity

The requirements and their application aim to emulate individual features from the systems that inspired them. They are not listed in any order of importance because each feature is interdependent on the other. From a physical design perspective however, a crucial aspect for this design is the characteristic of self-assembly and dis-assembly. In a system that functions because of many small agents working to create an overall structure, intent-full or dynamic self-assembly is an efficient and necessary method of construction. The counter-behaviour of self-assembly, dis-assembly, is not as often mentioned in literature even though for a system to be flexible, reusable and programmable in real-time it is a vital characteristic. The ability to dis-assemble
reflects the bi-directionality that is a core component to haptics and tangible interaction.

The design of the Dod attempts to fulfil the requirements derived from the literature but it also aims to resolve issues that can be problematic by the inherent qualities current computing technology. If specific components of a laptop are broken beyond repair, the entire laptop is usually scraped by the average user. This approach is wasteful and detrimental to the environment. Society can no longer afford to be wasteful with respect to materials that are currently being used to manufacture computing technology. Designing technology that can be reusable even if several components or mechanisms fail, aims to help change the attitude to technology whilst creating a more robust and efficient system, e.g. if the Dod’s extension mechanism experienced a complete mechanical failure it could still be usable because of its overall shape, see Chapter 4, section 4.4. Considering issues such as the longevity of technology, the ability of systems to self-repair efficiently or the connection between technology and user are important even though they may seem at this point removed from the design process.

Table 1 aims to summarise the design parameters, which will be explored in the following sections, as well as illustrate from which field of research (e.g. biology, engineering, design, etc.) they originated from.

<table>
<thead>
<tr>
<th>Desirable attributes</th>
<th>Domain</th>
<th>Inspiration</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi spherical shape with irregular surface topology</td>
<td>Fluid dynamics</td>
<td>Non-Newtonian, MR and ER fluids</td>
<td>These areas help determine what role the particle has in contributing to rheopectic behaviour</td>
</tr>
<tr>
<td>Material sciences</td>
<td>Liquid crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid and semi-solid behaviour</td>
<td>Fluid dynamics</td>
<td>Non-Newtonian, MR and ER fluids</td>
<td>Exploring what other elements can contribute to rheopectic behaviour aside from the particle itself.</td>
</tr>
<tr>
<td>Biology</td>
<td>Solenopsis Invicta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi agent communication</td>
<td>Biology</td>
<td>Ants and bees, Virus behaviour</td>
<td>Exploring a variety of communication techniques (audio, movement, chemical) as well as transmission methods can influence physical aspects of the agent design.</td>
</tr>
<tr>
<td>Software engineering</td>
<td>Program fragment, seed particles,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy manipulation</td>
<td>Biology</td>
<td>Plants, lichen and algae, energy gradients, bacteria</td>
<td></td>
</tr>
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<td>---------------------</td>
<td>---------</td>
<td>--------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>These areas address the idea of the Dod design becoming self-sustaining or alternative creating a symbiotic relationship with another energy source. The primary aim is for the Dod to become autonomous and not exclusively depend on an energy middleman.</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>Trionoelectric generators, piezoelectricity (cellular or other natural forces, sound, heat, light, etc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>Sensors, facet function, wearable technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>Reactive to environment: light, water, pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly and dis-assembly</td>
<td>Gecko, ant claws</td>
<td></td>
<td></td>
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<tr>
<td>Natural forces</td>
<td>Magnetism, capillary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>Velcro, polymagnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ability to morph shape and texture, bidirectionality</td>
<td>Haptic sense, blowfish, cat claw, octopus, hair</td>
<td></td>
<td></td>
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<tr>
<td>Technology</td>
<td>Pushpin computing, SMA, multiagent systems, Hoberman sphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineering</td>
<td>Structural exploration: spring, origami</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Art</td>
<td>Material study: texture, conceptual process, application exploration, philosophical approach, behaviour through structural</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. The Dod

| Scalability and one material make-up | Technology | 3D (multi-material) printing, one-piece bots (e.g. Octomag), external actuation, micro origami | Using many small parts to create a large whole, in particular to create intricate interfaces ideally requires a high resolution of agents. All aspects of the agent must therefore be able to reduce to the required scale. |
| Biology | Cellular adaptability and flexibility, moth caterpillar, Pharaoh ant, phage, electrospinning, DNA manipulation |
| Material sciences | Smart or custom designed polymers |
| Motion | Biology | Nastic motion, plants | To aid the quality of autonomy a degree of ability to move is required, in a variety of environments, (e.g. space, liquid) |
| Technology | Modular hydraulics, microfluidics |
| Behaviour | Math | Simplest ruleset, ideal condition concept | The structural shape defines what behaviours were possible for the Dod agent design. Considering a variety of perspectives aids in shifting the focus so that it is possible to determine the true requirements and those that emerge from the interaction of a ruleset. |
| Art | Error and imperfection, perspectives |
| Technology | Karel concept, creative coding, awareness model |

Table 1 Design parameter summary - the design parameters used to inform the agent design and their origin in related research.

4.2 Prototypes

An important part in the design methodology has been the process of creating prototypes. As mentioned in Chapter 3 the development of 3D printing has enabled the process of testing and developing ideas in 3D more accessible. The following descriptions of prototypes are centred around the design of the dodecahedron itself. There are four prototypes before the final design was established and each of them
focuses on an element of research that progresses the design from the replication stage to the emulation stage. Magnetism is the mechanism chosen to simulate self-assembly. For this study, it has proven to be the most versatile and accessible medium with respect to design functionality. However, it is not the final envisioned mechanism by which the agents would be able to attach because in the long-term magnetism is inefficient and difficult to predict its behaviour accurately, particularly when several magnetic fields interact with each other.

4.2.1 Replication: Prototype A
The first exploration of the dodecahedron with respect to determining its viability as a MAS agent is a close replica of the original artefact (Figure 3.1). This prototype remained solid with concave, semi-spherical depressions on each facet as opposed to being hollow with different sized holes located on each facet as per the original. As a bar magnet (4.6cm x 2.2cm x 1.5cm) is used for this prototype, it is printed in two halves with a slot in the centre for the bar magnet, Figure 4.1.

The spherical depressions aimed to reduce the amount of material between the magnets to improve the effectiveness of the magnetic field. Another feature in the original artefact are the nodes on the corner of each facet. These nodes were also modelled to test their capacity to act as surface irregularities to aid the interlocking of several dodecahedra, see Figure 4.2a. Whilst it supported the interlocking of two dodecahedra, it proved to be a hindering feature when more than two dodecahedra come together.
The magnetic effect could be felt however due to the size of the prototype, it was weak. Of interest, a second print of this prototype resulted in a semi-permeable and delicate structure, rich in textural quality. Whilst it was a malfunction in the printing process the resulting effect is a worthwhile consideration regrading semi-permeable constructs, Figure 4.2b and 4.2c. To improve the strength of magnetic effect experienced by other dodecahedra and for the purposes of testing the self-assembly behaviour, a solid, plain faceted dodecahedron was also modelled around the dimensions of the bar magnet so that the poles of the magnet had no more than 4mm of material between them at any given point, Figure 4.3a and 4.3b. Removing the depressions allowed the overall dodecahedron to be scaled according to fit a bar magnet.

4.2.2 Smart Fluids MR: Prototype B
The second and third prototypes are based on the principles underlying magneto- (MR) and electro-rheological (ER) fluids. These types of fluids are considered smart fluids as they experience a change in viscosity depending on an external actuation source, see Chapter 2. These fluids operate with particles that are in the nano to micro range.
4.2 Prototypes

Since scaling is an important and recurring requirement for man-made multiagent systems, the following prototypes explore how well the dodecahedron can be scaled and still maintain its structural shape working with the 3D printers available to this study. The design illustrated in Figure 4.4a and 4.4b, were printed with the Form1 printer using clear resin and are approx. 2mm in diameter.

**Figure 4.4 Resin dodecahedron** - (a) The original structure before being coated with iron filings, (b) the dashed line highlights how well the structure is maintained via FORM1 printing.

These dodecahedra were coated in ferrous particles averaging approx. 6.25µm² in size (ranging in total from 4.167µm² to 9.315µm²), see Figure 4.5b. It was difficult to achieve an even coating of ferrous particles and generally the faceted structure of the dodecahedron was lost. The design became spherical in shape and the surface topology was rough and irregular similar to cornstarch particles see Figure 4.5a.

**Figure 4.5 Prototype B** (a) the agent covered with iron filings, (b) the average size and shape of iron filings used 6.25µm², (c) Neubauer counting chamber dimensions (Celeromics 2018).

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The grid used in Figure 4.5b is a Neubauer hemocytometer counting chamber. The counting grid is comprised of 9 squares with subdivisions of 1mm. Each individual square is 3mm x 3mm. The central square is divided again into 25 squares, 200µm in width. This is further subdivided into 16 smaller squares, see Figure 4.5c (Celeromics 2018).

These designs were originally intended to be implemented into a Magnetophoretic Display (MD) based testing rig, to experiment with the viability of the design being able to create 3D structures in a liquid environment. The concept of a MD is used in the toy MagnaDoodle™. Micro-sized ferrous particles are suspended in a white, cloudy liquid in the shape of a rectangular display. The balance between particle size and viscosity of the liquid is such that the particles remain suspended, can move freely through the liquid (top to bottom) and are not affected by gravity. The liquid and particles are contained between two thin sheets of clear acrylic. A honeycomb lattice separates the sheets of acrylic, is 0.8 - 1.5mm in depth and ensures that the ferrous particles and liquid remain evenly distributed. To draw on the display a small magnet is contained in a stylus that attracts the particles to the surface. To erase the drawing, a width-sized strip contains a magnet behind the display and is free to run the length of the display – this attracts the ferrous particles to the back of the display clearing the front (Igawa 1992).

For testing of the design, the viscosity of the liquid was increased in order to compensate for relative size of the particle. Honey was used with a centipoise rating of 10,000. It became clear that the balance between liquid viscosity and particle size had become unstable. The dodecahedra were too large and the increase in viscosity was A) not enough to support the position of the agents and B) hindered the movement of the particles. The effect of gravity and friction began to have a greater influence and after a time the agents continued to sink to the bottom as soon as the external magnetic force was removed.

Considering the perspective of Butera’s proposition of a paintable computer (computer particles contained in a liquid), the forces these particles experience is largely influenced by their size (e.g. Brownian versus gravity). Other characteristics such as absorption, solubility, saturation, temperature, viscosity, etc. play a critical role in the overall complex behaviour of particles in liquids. For example, introducing a computer
4.2 Prototypes

particle made from man-made materials may require the liquid to be also man-made, like a smart-polymer. In contrast, it may eventually be possible to 3D print biological computers, which in turn may have more success in integrating organic and artificial particles into existing smart fluids.

4.2.3 Smart Fluids ER: Prototype C

The previous prototypes focused on the MR fluids and the type of particles that contributed to the fluid’s behaviour. The following prototypes explored the ER fluid concept. To maintain a better rendering of the dodecahedra, shape these prototypes reversed the process by containing the attractive material on the inside as opposed to the outside. All the designs were printed in two halves and glued together. Two different types of magnetic material are used in these designs: ferrous powder and 3mm ball magnets.

The 1st design consisted of a hollowed-out dodecahedron. A spherical hollowing is used which served the purpose of giving strength to the completed design but also to ensure an equal spread of the magnetic material contained therein. This design was printed several times with varying wall thicknesses ranging from 3.4 to 3.8mm, to test the minimum thickness whilst still maintaining structural cohesion but also at which point the magnetic material appeared to be least effective, see Appendix A. The design which contains the ferrous powder is approx. 2mm in diameter. Filling these dodecahedra was inconsistent and the magnetic effect was reduced as it was difficult to fill the cavity efficiently, see Figure 4.6a and 4.6b.

![Figure 4.6 ER Particle 1](image)

*Figure 4.6 ER Particle 1* – (a) the dodecahedron filled with iron filings, (b) 3D model of dodecahedron container, (c) illustrates the magnetic effect with respect to stacking and attachment ability.

These designs require an external source to incur a reaction, i.e. a magnet. Therefore the 2nd design is modelled around the dodecahedron containing a 3mm ball magnet. This increased the overall diameter to 3.5mm but also improved the magnetic self-
assembling effect\textsuperscript{17}, Figure 4.7b. The 3mm ball magnet fills the entire cavity and is more efficiently processed in the assembly of each agent. Whilst this design was also solid, it developed into a design that incorporated holes in each of the 12 facets. This is again to allow maximum exposure of the ball magnet and to reduce interference of the resin container on the magnetic effect, Figure 4.7a. As with the 1st design, several prints were tested in relation to wall thickness for structural cohesion but also for the method of modelling the hole in each facet (i.e. with rim or without). Figure 4.8 illustrates two approaches used for creating the holed facets.

\textbf{Figure 4.7 Prototype C} – (a) The adapted casing to accommodate a 3mm ball magnet, (b) an assembly of particles.

The casing in Figure 4.8a had a defined wall thickness into which a hole was cut. In Figure 4.8b the size of the casing was reduced until the inner cavity began to protrude through the facet areas. Since this inner cavity would be filled with a 3mm ball magnet, the maximum exposure with minimum material interference was envisioned. The latter design was prone to structural failure because the material became too thin. For further details see Appendix A.

\textbf{Figure 4.8 ER particle casing} – (a) Casing with defined wall thickness, (b) hole achieved via reducing the casing until the inner capacity emerged.

In maintaining the inherent structural form of the dodecahedron, the ability to create structures when assembled was greatly improved when compared to the ferrous coated

\textsuperscript{17} This style of design very closely models a form of water based magnetotactic bacteria (Frankel et al 1979). Their spines consist of Nano-sized magnetic particles, which enable them to orientate to Earth’s magnetic field lines in order to move in their environment.
4.2 Prototypes

design but also when compared to the ball magnets in their original spherical form, Figure 4.7b and 4.6b.

4.2.4 Toys: Prototype D

For the final prototype before choosing the final Dod design, the work of Walter Hsiao was reviewed. Hsiao created 3D printed bisymmetric hendecahedrons whereby each facet contains a 3mm ball magnet (Hsiao 2015). This mechanism of assembly was replicated to test the validity of the dodecahedron’s ability to create structures.

In this iteration of testing, dodecahedra and tetrahedrons were 3D printed using the Ultimaker printer and compared to each other. The tetrahedron was chosen as a comparative design possibility, because it is the most basic platonic solid and like the cube, its dihedral angle (70.5˚) ensures that tetrahedrons can fit together exactly without separation: facet on facet.

The two platonic solids were each modelled to accommodate 3mm and 5mm Neodymium ball magnets accordingly. The shapes are solid and modelled such that the ball magnets are positioned in the centre of each respective facet, Figure 4.9. The opening for the magnet is slightly smaller than the diameter of the magnet so that the magnet can be firmly pushed in. With this method, the magnet can still freely rotate when inside but cannot be extracted even when experiencing opposing magnetic forces (see Appendix B). Eight samples of the design configurations were created to explore the size to magnet force ratio for the design:

- Tetrahedron: 5mm ball magnet, modelled close together and far apart,
- Tetrahedron: 3mm ball magnet, modelled close together and far apart,
- Dodecahedron: 5mm ball magnet, modelled close together and far apart,
- Dodecahedron: 3mm ball magnet, modelled close together and far apart

18 Even though Hsiao used 3mm ball magnets in his own designs he had initially stated that the 3mm ball magnets were potentially too weak and did not exhibit the required attachment force.
Close and wide in Table 1, refer to the positioning of the ball magnet in the facet of each shape. Close indicates that there is a minimal amount of material separating each ball magnet, i.e. the tetrahedron and dodecahedron’s size is determined by the magnet’s size. At this distance, the ball magnets experience magnetic interference from the neighbouring magnet, however they are able to orientate themselves to the most stable polar position possible since the cavity that contains the magnets in the facets is approx. 3.18mm and 5.17mm, respectively, in diameter (the degree of printer accuracy also had to be considered). Wide indicates that the ball magnets are separated over a larger distance and that there is more material between them. This has the added advantage of reducing the magnetic interference between neighbouring magnets. The values in Table 1 indicate the distances between the ball magnets and the dimensions around which the platonic solids are modelled. The 3mm magnet has a holding force of approx. 1.27N and the 5mm magnet has a holding force of approx. 3.92N.

The minimum distance by which the ball magnets could affect a notable change on each other, i.e. cause the other to move via the attractive force in a linear direction is approx. 3.1cm for the 3mm ball magnet and approx. 4cm for the 5mm ball magnet. In the wide models, the ball magnets to not experience an interfering magnetic force from their neighbours, only that of the magnet to which they connect to. The data relating to the inscribed circle in Table 1 relates to the size around which the polygon is based and thereby the resulting polyhedron, (for a visual representation see Appendix B).
4.2 Prototypes

<table>
<thead>
<tr>
<th></th>
<th>Distance between magnets in mm</th>
<th>Diameter of inscribed circle in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wide</td>
<td>Close</td>
</tr>
<tr>
<td><strong>Tetrahedron</strong></td>
<td>6.61</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>5.93</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>Dodecahedron</strong></td>
<td>11.16</td>
<td>4.54</td>
</tr>
<tr>
<td></td>
<td>7.47</td>
<td>3.74</td>
</tr>
</tbody>
</table>

Table 2 Magnet distance - The values of toy prototypes printed to accommodate 3 and 5mm ball magnets.

The 5mm ball magnet was considered because of Hsiao’s recommendation that the 3mm ball magnet may not be strong enough and that the macro structures created through the individual pieces may benefit from a stronger magnet. Whilst both magnet diameters were tested and considered in the described prototypes, it was decided that the 3mm ball magnet in the close configuration was sufficient in providing a suitable attachment force for the purpose of this study. The close configuration is chosen for several reasons:

- despite the magnetic interference, the larger prototypes have more weight, and distance between magnets,
- scalability has a high priority because programmable matter is orientated towards the micro scale. This means that reducing the scale of all the components of the design has a high priority,
- even though the 5mm ball magnet is stronger, it is also heavier and bulkier therefore it was not considered in further iterations of the final design. See Appendix B for further details regarding 3D models of large and small tetrahedra and dodecahedra.
4.2.5 Prototype Summary

The greatest disadvantage of magnetism with respect to this study is the need for an external source of actuation. As discussed in Chapter 2: section 2.4, magnetic assembly is not dynamic self-assembly and must rely on external changes in the magnetic field in order to react. For shape-shifting or morphing interfaces the general desire (from the user) is to direct it into what it should assemble into (final goal) but the main internal self-assembling process should be accomplished by the agents themselves (internal autonomy).

It has also become clear through these prototypes that to scale a design to the micro-scale and still have the desired features to fulfil self-assembly, learning, adaptation, etc. requires such sophisticated technology that it is still beyond current capabilities. Considering what type of efficient agent design nature can create at 2mm – the Pharaoh ant (Monomorium pharaonis), is an indicator of the current state of MAS and the technology available for a human-made agent.

Geometric shapes are very popular to trial various approaches regarding self-assembly, communication (signal transfer or contact transmissions), coping and learning strategies and to date the most successful / commonly used geometric shape is the cube. Due to its 6 sides, it is possible to maintain an overview of the complex behaviours that can emerge. It is a shape with which people are familiar, i.e. digital 2D pixels or 3D building materials – it is a shape about which a significant amount of knowledge already exists. In contrast, the dodecahedron offers a more complex design space due to its increased number of facet but also because of its existence in a combination of planes via its dihedral angle. It encourages the process of designing in 3D rather than starting from a 2D basis (Ishii et al. 2004b, Follmer et al. 2011). An alternative to the traditional sketching is demonstrated by projects that use malleable materials, like clay, and use them to manipulate digital data, in essence 3D sketching.

4.3 Current Prototype – the Dod

The final prototype of the dodecahedron design is the Dod. Its design reflects the influence of art and creativity because the last consideration in developing the design is based on aesthetics.
This was a turning point in the project’s development and to an extent demonstrates the effect of control described in Chapter 1. Rather than exert complete control and develop one conclusive design, the Dod is representative of a change in perspective. Instead of only focusing on the functional and practical elements, the incorporation of aesthetics meant relaxing control and allowing the design to take shape, i.e. being able to see the potential of the design and the directions it could take.

It connects a man-made construct, the dodecahedron, with a long-established natural mechanism, the spiral (Holman and Vertegaal 2008). This is the first instance where the design indicates potential to move from a replicative process to that of emulation. As with many of the shape-shifting, morphing interfaces proposed in research it is difficult to clearly define an actual application. These interfaces predominantly exist in a lab setting therefore the aim of the Dod is to provide a blueprint that can be adapted to suit the development of future applications.

### 4.3.1 Physical Appearance

The Dod is based on a geometric solid: the regular dodecahedron. The shape belongs to the group of platonic solids of which there are five. Platonic solids are polyhedrons that have inherent symmetry and the most commonly used platonic solid in existing projects exploring multi agent self-assembly is the cube. The dodecahedron is semi-spherical in nature and harmoniously balances the curved fluidity of nature and humans desire for controllable, accurate geometry. It can flow or move freely, within or outside of a potential transport medium, whilst still offering support in a scaffolding capacity due to its flat faces and defined edges. The alignment of dodecahedra is such that a curved line can be represented and created more easily than is possible with the cube. This characteristic provides an alternative perspective in relation to building 3D structures.

The dodecahedron is used but is designed with the ability to extend arms via a spiralling twist i.e. an outward rotation. This ensures that the plates do not interfere

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19 Plato associated the basic elements of water, fire, earth, air and aether to the platonic solids. The dodecahedron represents the aether, which is a suitable analogy for this shape linking human thinking with nature’s design (Critchlow 1969).
with each other, as they do not rotate in place. Rotation may however also provide the option to be used as a mechanism to aid in disassembly of each arm or the reverse to act as a locking mechanism for self-assembly (Chapter 7 - Polymagnets).

The arms are an inverted pentagonal frustum whereby the small, narrow end is located at the inner core dodecahedron. The full extension consists of two full rotations of the outer plate (5mm in diameter). When all arms are retracted the outer plates meet forming another dodecahedron, essentially creating two dodecahedra: the inner or core dodecahedron and an external dodecahedron that encases the inner one. The inner core can be either solid or hollowed out – the computational parts would be located here, Figure 4.10.

![Figure 4.10 Retracted Dod](image)

**Figure 4.10 Retracted Dod** - Split view of a closed Dod and a cutaway revealing arm attachment in retracted position.

When all the arms are extended, the maximum gap between the plates is 0.6mm, Figure 4.11a and when the arms are retracted the gap closes to approx. 0.04mm, Figure 4.11b. The arms extend up to 12mm and can be retracted by 5.92mm. If the distance between the inner dodecahedron face and outer plate is smaller than 6.08mm, the outer plates will interfere with each other and the overall structural configurations.

![Figure 4.11 Gap detail](image)

**Figure 4.11 Gap detail** – (a) Detailed view of gap when arms are fully extended, (b) gap that is present when arms are fully retracted

Magnetism is still used as the mechanism to represent self-assembly therefore the Dod design is based on the previous prototype regarding the insertion of 3mm ball magnets into each facet. The size of the Dod is reliant on the minimum printable material around the magnet when the arm is retracted, see Figure 4.12, detail B and C. Whilst there is inevitable interference of magnetic field lines, creating areas of strong and weak
magnetic connection, this behaviour can be used for demonstration purposes, illustrating how the weaker magnetic fields lend themselves to allow the Dods to break apart more easily. This is an important consideration. The majority of interfaces explore attachment mechanisms, whereas the ability to dis-assemble with similar ease is necessary to facilitate the reuse-ability of such an interface.

*Figure 4.12 Ball magnet position* - Current version of the Dod: detailed views illustrate how the ball magnet remains in the facet and is free to rotate. Split views also highlight that this is the minimum size possible with full enclosure of the magnet in a retracted state.

It is currently proposed that each arm would be able to extend individually – whilst this contributes to an overall behavioural complexity, it makes the design flexible and adaptable to a variety of requirements or its environment. As the research continued to progress it became clear that maintaining structural cohesion may become problematic should all arms extend at once. These concerns are explored further in Chapter 6 whereby it is also a possibility to have pre-configured Dods, either physically or through the Dod’s behavioural coding (e.g. assignment of relative and static IDs, see Chapter 5). Figure 4.13 illustrates the Arm ID pattern on which the behavioural coding is based. This makes it possible to identify opposite arms which is important for creating specialised construction elements such as straight lines or curves (e.g. Arm1 is opposite to Arm12, Arm 2 is opposite to Arm 10, etc.)
4. The Dod

To demonstrate the potential of the extending arm mechanism, eight configurations of the Dod were 3D printed in different colours for easy identification. The arms are rigid and cannot extend/retract due to the material used (PLA), however each configuration illustrates a potential state of the Dod. Configuration in this instance refers to the number and manner of arms extended. The arms were arbitrarily chosen yet it is feasible to manipulate these states to be orientated in any fashion, e.g. like an octopus whose eight legs may have fixed neural connection but are not locked to always preforming the same task. The following colours identify the arm configuration of that particular Dod and will be seen in the images throughout this study.

- White: All arms extended
- Pink: All arms retracted
- Blue: 11 arms extended
- Red: 10 arms extended
- Yellow: 6 arms extended
- Green: 5 arms extended
- Black: 3 arms extended
- Orange: 1 arm extended

Scalability is a requirement that re-focuses the design on every iteration. An issue with current mechanically based MAS systems is the non-linear relationships between components, (Korvink and Paul 2006, Uhrmacher and Weyns 2009, Bergbreiter 2014) The earlier prototypes demonstrated that the dodecahedron can be scaled to approx. 2mm in diameter and still maintain its faceted structure, a similar test was carried out on the current Dod design. In maintaining the magnetic effect for self-assembly, the Dod was remodelled so that a 3mm ball magnet could be located in the centre of the
structure rather than in each facet, i.e. the limiting factor in this case is the 3mm ball magnet Figure 4.14.

Figure 4.14 Scaled PLA Dods - The current Dod is remodelled so that a 3mm ball magnet is encased in the centre thereby still exhibiting an assembly behaviour.

It was possible to print various Dod configurations, that are also presented at the macro scale, with sufficient accuracy at the reduced size with the Ultimaker 3D printer. This indicates that with smaller attachment mechanisms and a high-quality 3D printer it may be possible to reduce the physical Dod design even further reaching the target of an agent sized in the range 2-6mm or smaller.

Removing the magnet from within the Dod design, made it possible to scale down the design even further. These studies primarily tested whether the structural stability of the extended arm could be maintained. Only two states were printed for this test (all arms retracted and all arms extended), see Figure 4.15a and 4.15b, as they represent either extremes with respect to available configurations. The Form1 3D printer was used for these prints because of the higher degree of accuracy possible. See Table 2 for measurements.

Figure 4.15 Scaled resin Dods –(a) Form1 printed Dods with all arms retracted, (b) with all arms extended.
<table>
<thead>
<tr>
<th>Diameter</th>
<th>Retracted Configuration</th>
<th>Extended Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>8.5 mm</td>
<td>14 mm</td>
</tr>
<tr>
<td>Medium</td>
<td>6 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Small</td>
<td>5 mm</td>
<td>8 mm</td>
</tr>
</tbody>
</table>

Table 3 Scaled Dods - The size of each agent is noted in mm, according to its diameter.

To date the most viable means to create micro or Nano-sized agents is to construct them out of one piece of material (Kummer et al. 2010) and with as few complex, moving parts as possible, e.g. joints and cogs, etc, as possible as these may suffer from strain and wear (Gilpin et al. 2010, Hawkes et al. 2010, Kummer et al. 2010, Christensen et al. 2015). Considering these aspects, the Dod has the potential to embody this design concept. The design is such that the arms are connected to the inner and outer plate and that the whole structure is of 1 mechanism. Even the rotation and twist of the arms is designed to be a smooth motion that incurs minimal levels of friction and resistance.

**4.3.2 Spring**

Whilst the exact mechanism, by which the Dod will function mechanically i.e. the expansion & retraction of its appendages, is still speculative the current mechanism used for the Dod artworks is an origami based pentagonal spring, Figure 4.17 (sphere360 2014). Either ends of the spring connect to the facets of the inner dodecahedron and the outer plate respectively. The advantage of using this type of spring is that A) origami is very versatile (form, structure, strength, size, etc.), B) there is a wide choice of existing and accessible materials, C) this spring design is pentagonal in its fundamental structure and D) it is scalable. The rigidity of the extending arm is dependent on the choice of material used. This quality is elaborated on in the section describing the Dod’s development from an artistic perspective.

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20 Issues such as scalability, stress & strain, material design are under continuous development. Research into wearable technology may be of interest with respect to energy conversion or communication (fiber optics, copper filament), biologically inspired organisms may yet provide the key for more efficient and effective physical mechanisms for movement, self-assembly, etc.
There are other methods of extending the Dod’s arm (pneumatics, hydraulics ref, motorised actuators, etc) but origami was chosen as it lends itself well to scaling whilst maintaining strength and an obvious yet important characteristic of the spring is its reversibility so that it can be reused consistently. Whilst the pentagonal base of this spring design is optimal with respect to fitting the inner dodecahedron, another octagonal spring was also tested, see Figure 4.18.

Origami is a relevant that informs individual aspects of projects as well as the being the primary focus of a systems design (Hawkes et al. 2010, Lv et al. 2014, Silverberg et al. 2014, Filipov et al. 2015, Li and Wang 2015, Miyashita et al. 2015, Reis et al. 2015, Malkinski and Eskandari 2016). The materials used to produce origami inspired designs are as diverse as the artform itself, ranging from smart memory alloys & polymers, temperature & light actuated materials to electromagnetic waves (Liu et al. 2003, Tolley et al. 2014, Miyashita et al. 2015). Its application is also evident in Nano-technology in the form of micro-origami (Malkinski and Eskandari 2016). The characteristic of morphing size and /or shape is of keen interest with respect to designing autonomous robots (Gilpin et al. 2010, International 2014). Research into origami based designs is not limited to an overall form but also includes the materials used to achieve new and unique results as well as behaviours, e.g. rubber membranes (Py et al. 2007), polymers: polypyrrole PPy and gold (Liu et al. 2003), thermo-reactive sheets (Corina 2014) and bond or foil paper (Hobbyists). The advantage of using lightweight materials that through various folding patterns are able to support or resist larger forces is invaluable with respect to designing agents that exist on the micro level\textsuperscript{21}. The versatility of origami creates an interesting solution space for challenges such a current waste management of devices such as computer, laptops, phone, tablets, etc and the raw materials used therein.

A spring is envisioned to be the central structure of the extending arm. To provide more support but also to potentially fulfil other functions (e.g. contributing in the creation of energy gradients, creating boundaries between the Dod and its environment, see Chapter 7). A skin or flexible membrane encases this spring creating a more natural connection from edge to edge of the inner dodecahedron to the outer

\textsuperscript{21} Using the Pharaoh ant again as a reference point as to what already exists in nature, this creature is not only small but weighs between 1-2 milligrams and its queen has a lifespan between 4-12 yrs. Resource and material management must become active design considerations.
pentagonal plates, Figure 4.16. In the Dod design when the outer plate has completed two rotations, it is fully extended and the skin is taut creating a flat surface, (see supplementary material 1: Arm Skin).

![Image](image1.png)

**Figure 4.16 Arm Skin** - An illustration of the skin (cling film) connecting the outer facet to the inner dodecahedron.

### 4.3.2.1 Pentagon spring

A pentagonal spring can be folded from 1 sheet of ordinary A4 paper and the pattern is illustrated in Figure 4.17

![Image](image2.png)

**Figure 4.17 Pentagonal spring** - (a) Folded segment of the spring, (b) folding pattern.

Through this pattern five parallelograms are created, with the edges folded outward, on each horizontal level. The diagonal, which is folded inward, ensures that the whole structure can be flattened – this is equivalent to the inward taper as seen in the octagonal spring. Instead of vertical lines being created, the lines running the length of the spring are slanted defining the direction of twist. It can only be twisted in one direction unlike the octagonal spring.
4.3.2.2 Octagonal spring

An octagonal spring can be based on modular origami, i.e. it is composed of many individually folded components that are interlocked to create the overall structure. This method uses more material when compared to the pentagon spring. As is illustrated in Figure 4.18 each level consists of 8 cubes that taper inwards towards the centre of the spring. Each cube consists of four folded components. Vertical lines are generated as a result of the cube alignment throughout the spring.

![Octagonal spring images]

**Figure 4.18 Octagonal spring** – (a) Origami octagonal spring based on modular components, b) illustrates the dual rotation afforded by the square structure.

An interesting feature of this spring is the ability to twist and compress in both directions, as is indicated in Figure 4.18b, by the slanting of the vertical lines in both directions. This is clearly visible when comparing the top and bottom rows with the middle section. The behaviour is possible due to the symmetry of the cube / square being used as the basic modular component in contrast to the parallelogram of the pentagon spring.

Both springs were made using ordinary paper (80gsm). Table 3 summaries the most relevant characteristics defined in this study.
4. The Dod

Of interest is that when the pentagonal spring is twisted slightly beyond the full extension length, the spring can withstand extra force without requiring any additional scaffolding or supports, considering that the thickness of the paper used is 0.1mm. The strength is due to the combination of folds forming parallelogram segments on each level, as well as specific structural qualities such as buckling, explored in the next section. The parallelogram structure can deflect downward forces more effectively because of the diagonal fold, in comparison to a vertical line deflecting the same type of force.

Due to the specific folding pattern, when the pentagon spring is depressed, it will always fold in the same direction. The octagonal spring can be unpredictable because of the higher state of instability that the vertical lines represent. It is very sensitive to weight distribution during the compression process as it will contribute in determining to which side the vertical lines will fold.

### 4.3.3 Buckling and tensegrity structures

The zone of demonstrating extra resistance, experienced by the pentagon spring is conditional. From a structural engineering perspective, this point of resistance occurs shortly before an outward buckling of the material within one or more of the segments (along the diagonal fold) depending on where the greatest pressure is being felt. The point at which buckling occurs are inherent qualities in the material and the structure.
it forms, but it need not necessarily be considered a negative consequence (Hunt and Ario 2005, Filipov et al. 2015). The concept of buckling is a yielding or giving way of an object or material under strain or pressure. There is a significant build-up of potential energy up to the point at which buckling actually occurs, essentially a point at which order and entropy are nearly side-by-side. This balancing between states can be prolonged (tensegrity structures) or used as a means to create something new (e.g. 3D mesostructures).

When considering buckling from an alternative perspective it is possible to create controlled and predetermined 3D structures, by bonding 2D planar shapes, such as spirals or leaf shapes, onto a pre-strained elastomer at specific anchor points. In the easing of the strained elastomer the 2D planar constructs experience out-of-plane buckling and thereby create unique and interesting 3D geometries. Applying the existing understanding and knowledge of how buckling functions (leveraging, length, width, material, curve, strain, shearing, etc.) contributes to achieving reliable & repeatable results (Xu et al. 2015). The potential energy from the strained elastomer is channelled into the 2D planner shapes and enables them to maintain the new 3D state. To date in this research, single 2D layers resulted in predominantly hollow and limited 3D mesostructures. A development from this level is the use of multi-2D layers. The advantage of this layered approach opens opportunities of the forces of each layer acting upon the next at specified locations. This provides a new range of unique 3D mesostructures and an improved inner supporting framework. The next stage of development of this technique is the bonding of the individual 2D layers at specific locations (Yan et al. 2016).

An important result from this research is the potential for new approaches to designing existing mechanical devices, e.g. springs, force actuators and micromanipulators. Currently the predominant application lies with antenna design for near-field communication technologies and materials experimented with are silicon, polymers and metals (Yan et al. 2016). Similar to the Dod design, the resulting 3D mesostructures resulting from the compressive buckling state resembles 3D fractals, as many of the 2D planar structures/shapes are scaled replications of an original design.

Kirigami, the art of paper cutting, and origami, the art of paper folding, design principles are applied in the researched described above. It is the ability to create usable
3D structures through the reshaping and redefining of the original material without the need for additional elements. Reversibility from 2D to 3D states is a useful quality, among others, of these techniques although in this instance constant energy is required in maintaining the pre-strained state. A characteristic that is a common thread in much of the research conducted for the study of compressive buckling as a construction method, is the requirement for external manipulation of the pre-strained elastomer. The technique is currently best suited for once off activations for the construction of 3D mesostructures however it may yet prove interesting to potentially combine this method with MAS systems in future. The reason for exploring such a technique is predominantly to examine the potential of viewing a negative behaviour from an alternative perspective and attempting to use it as a means to enhance the overall system or the design of an individual aspect of the system. This technique is also applied to the Dod in an attempt to provide a wholistic analysis of the design.

4.3.3.1 Tensegrity Structures
Tensegrity structures maintain a fascination with respect to the nature of their construction. The term itself is an amalgamation of tensional integrity (Sieden 1989) and is generally represented through sculptures. They are 3D structures consisting of mixture of elements that are in contact with another (e.g. rod to cable) which enable elements that are not in contact with each other (e.g. rod to rod) to maintain their position via a tensional force. These structures undergo constant compression, pressure and tensional forces however the structure, if assembled correctly, can exist in complete, stable equilibrium. In 2012 this technique was explored by NASA, for its potential to be implemented as an alternative to the traditional rigid robots used for planetary exploration. “Small, light-weight and low-cost missions” (Agogino et al. 2013) are the requirements for more frequent exploratory space missions. Tensegrity robots are designed to move along unstable and irregular terrain but can also withstand impact forces by distributing the load equally over the entire structure and cope better with single-point failures (SunSpiral 2012, Agogino et al. 2013). These types of robots can alter their shape, size and location whilst still being based on elements that are undergoing tensional and compressive forces. Similar to considering the validity of buckling with respect to using it to an advantage, tensegrity structures provide a unique
insight into using forces that are often seen as a destructive or negative when building structures.

4.3.4 Surface
Surface topology is a property that plays a central role in the haptic aspect of this project as well as the functional. The following section describes the ability of the Dod to change its size and surface topology and how its design helps it cope physically in its environment.

4.3.4.1 Dod surface
Since the Dod is based on the dodecahedron, which has clearly defined facets, the surface topology of each facet is not designed to change shape or texture. It is the extending arms that create a variety of different surface topologies, by altering the overall shape and size of the dodecahedron, (from compacted dodecahedron to expanded or gaped dodecahedron). The design of cornstarch particles is such that it can move easily through water when slowly stirred (semi-spherical) and then when a sudden agitation occurs the particles can lock into each other temporarily (irregular surface topology and variety in size) and generate the rheopectic behaviour. The cornstarch particle incorporates both seemingly opposite qualities which the Dod design also reflects. The advantage of the Dod is the ability to control the surface topology by defining specific arm configurations or behaviours (e.g. form clusters, dense and smooth or semi-permeable mass, etc). This greatly effects the textural quality of each individual Dod and as a result the overall MAS. The following example relates to this textural characteristic of a changing surface topology and highlight some interesting interactions that could be possible.

As mentioned previously achieving an agent design approx. 2-6mm (Gilpin et al. 2010), in size would be a desirable goal. At this scale, the agents would most likely be perceived as a whole rather than individually. The material from which the Dod design may eventually be constructed not only has an impact on its physical and behavioural constitution but also on how an interface will be perceived in its entirety.
Texture is an integral component of tactile haptics and is influenced by material and its behaviour in the specific environment as well as the physical shape of an interface. If a user completes a process incorrectly the surface texture may become rough. If unable to solve the problem, the user can be guided through the correct steps by the texture becoming smooth in the specific areas required. Texture could also resemble reacting to the emotional state of a user - depending on the force applied to the interface or the current noise levels around the interface, these elements could be reflected haptically through a change in surface topology.

While texture can be perceived in isolation (e.g. Braille) it has been shown that multimodal interfaces are more successful at reducing the occurrence of errors or mistakes, provide more information upon which users can act and the potential for greater correlation of information from different sources. The better these sensory inputs are mapped or aligned with each other, the more integrated a system can become. In the development of interface design, vision has been established as the primary modality through which a user may process information. It is a versatile sense because of its direct and peripheral functions and has received much attention through research. Considering the aesthetic quality of texture would extend the repertoire of design features that can be employed. As much as elements such as colour, movement, design and detail, can be used to grab and hold the attention of users when considering an interface’s design, texture is an element that adds dimensionality to an interface and can be just as effective. e.g. liquid aesthetic of ferrofluid.

In the prototypes made to date, different coloured PLA plastic was used because it was the most convenient and accessible material available. The quality of the prints could be varied slightly by adjusting the density and temperature - it is possible to get rough or smooth surfaces. However, of interest were the prints that emerged via a mistake, e.g. filament not being fed through continuously. This resulted in a very porous, light and rough texture, see Figure 4.2c and 4.19. Whilst its current value lies in its aesthetic potential it could have a function worth considering for future projects, see Chapter 7. For example, if the agents were to be liquid based then if the inner core and the skin surrounding the arms are of a porous material, whilst the outer plates and spring structures are denser, a filtering process could be envisioned similar to perfusion and diffusion principles in biology or sea anemones and sponges found in nature.
4.3 Current Prototype – the Dod

Figure 4.19 Material permeability - A semi permeable Dod due to printer malfunction.

4.3.4.2 Environmental Surface
Many agent designs have the advantage of learning and/or moving in design spaces, i.e. the environment - whether the surfaces are large, flat, confined, irregular, different densities, temperatures, smooth, etc. Even in its prototype state printed in PLA, the Dod demonstrates an ability to find equilibrium on smooth or irregular surfaces see Figure 4.20a and 4.20b. Depending on the attachment mechanism it is also capable of facilitating top heavy structures, Figure 4.20c. Its faceted construction and extending arm mechanism are adequate coping features but could be further improved upon depending on the facet function and material choice. Chapter 6 and 7 discuss the various facet functions among which alternative attachment mechanisms to magnetism are considered.

Figure 4.20 Irregular surface topology – (a) agents building upon an irregular and soft surface, (b) a top-heavy cluster held at the base by tweezers.

The semi-spherical nature of the Dod allows it to move with greater ease than a cube, and the planar nature of the facets ensure that states of equilibrium can be achieved more easily and maintained. For example, a marble experiencing an angled, pushing force on a flat surface will not be able to maintain a stable position without boundaries. In contrast the Dod in the same situation would be able to maintain its orientation, and
be subject to friction and strain forces as it would be moved across the surface on one of its facets.

4.4 Artistic Approach

The Dod artworks are a type of abstract prototyping that has been invaluable as a means of continuously adding creative approaches to the Dod’s design. The experimentation with materials and direct form manipulation, through the practical process of building the artworks, involves applied lateral thinking, spatial exploration and haptic contextualisation. Expanding the materials and themes under which the Dod can be interpreted, not only provides interesting insights but also works towards maintaining an accessible link between research and the public through art (Ausareny et al. 2014). Newly emerging professions such as Science Communicator highlight the importance of bringing highly abstracted concepts to accessible levels. This process stimulates discussion, though and further ideas outside of a research lab environment. It crucially contributes to widening the perspective through which research such as this study is viewed (British Council 2015).

Another valuable contribution these artworks make is to demonstrate the ability to draw similar conclusions to those achieved through a scientific route, e.g. mathematics and computer modelling. Although mathematical modelling and simulations may provide a larger, more robust data set from which to draw conclusions, in this instance the comparison can aid in the proof-of-concept process. This will be discussed further in the following section. The contributions resulting from the artworks created as part of this study support the validity of the science, technology, engineering, art and mathematics (STEAM) movement more so than the former STEM movement. In the continued development of this approach, it is necessary to develop studies and researchers that are capable of positioning themselves and their work at the midpoint of these domains (ideally without bias for a particular domain). Similar to the need for professionals that have a singular expertise in a particular field, it is necessary to train professionals that have an expertise in encompassing a variety of fields.
4.4 Artistic Approach

4.4.1 Steampunk Dod
The first Dod made in the series of Dod artworks is a Steampunk interpretation. Steampunk is a style that uses technology from the Victorian era and juxtaposes it alongside modern applications and materials. It appropriates materials for purposes that it was not initially designed or planned for. There are certainly many aspects and descriptions to this style however this is most apt in describing the approach used for the Steampunk Dod. The materials used are copper and Perspex. There are three layers of dodecahedra of increasing size; they consist of turned copper wire, crocheted copper wire, and embossed copper plates, see Figure 4.21.

Figure 4.21 Steampunk Dod - Finished artwork.

4.5.1.1 The inner dodecahedron
The core of this artwork, is constructed using a Bronze Age decorative technique; two interlocking spirals. There are several methods that can be used to create this effect. In this instance, a spiral was created at each end of a length of copper wire, coiled in opposite directions. When they met in the middle one spiral was twisted to face the other direction creating a figure of eight. Three sets of these spiral shapes were used to construct one pentagonal face, Figure 4.22a. Once the twelve faces were completed they were sewn together to create a dodecahedron, Figure 4.22b.
4.5.1.2 The middle dodecahedron
The middle dodecahedron is made up of 12 crocheted pentagons. Four different patterns were used and were sewn together once the inner dodecahedron was suspended inside, see Figure 4.23. Whilst the material itself (0.15mm copper wire) is quite fragile and delicate on its own, by being crocheted it gained strength and malleability through the process.

4.5.1.3 The outer dodecahedron
The outer layer consists of 6 panels of Perspex and 6 panels of embossed copper plates. The hollows in the copper plate are designed to incite textural exploration and to enhance the dispersal of light on the copper plates, Figure 4.24. The clear Perspex aided the viewer to look inside and see into the other layers contained inside. The outer dodecahedron’s cohesion is dependent on the fact that all plates were sewn together with copper wire; there is no internal force that binds them together. The inner layers are suspended throughout, see Figure 4.21.
4.4 Artistic Approach

4.4.2 Origami Dod
The second Dod in this series is a flat-pack paper interpretation. This concept reflects the ability of paper to change size, shape and strength depending on the form it is in. This is the basis of origami and like the copper wire in the previous project, taking these materials beyond their original designed function can lead to new applications but also improvements to the material itself. The paper used in this project is inherently 2D however it is possible to transform it into 3D structures.

This render of the dodecahedron uses stencil cut-outs and iris folding. The focus as a result of the techniques used in this project is A) the interplay of light through the coloured paper and B) the art of framing the composition as a whole, as well as each individual facet of the Dod. Similar to the Steampunk Dod, there are two layers of dodecahedrons and the materials used are blue & red card (200 gsm), coloured tissue paper and transparent acrylic sheets, Figure 4.25a.

Figure 4.24 Outer copper layer - Embossed bronze plates.

Figure 4.25 Origami Dod - (a) Finished artwork from an external perspective, (b) the inside of the Origami Dod with suspended perspex Dod.
4.5.2.1 The inner dodecahedron
The inner dodecahedron is constructed by fitting together two halves. These halves are created from one template and through specific folds and slits can be fitted together without the use of glue or tape, (see Figure 4.26). The main function of this dodecahedron is to enhance the interplay of light but also to reflect the transparency of a structure despite its definite presence. Its construction echoes certain qualities of tensegerity structures regarding a finely tuned balance between tension and form. In this artwork the tension is created through the material and the shape into which it is formed.

![Figure 4.26 Inner Perspex dodecahedron](image)

**Figure 4.26 Inner Perspex dodecahedron** - the halves are held together via slits on opposing hemispheres where quilling decorations mark the top and bottom halves.

4.5.2.2 The outer dodecahedron
The outer layer consists of a two-card template in the shape of a pentagon, which creates the overall structure. The iris folding is sandwiched in between the card templates, see Figure 4.27.

![Figure 4.27 Outer templates](image)

**Figure 4.27 Outer templates** - Card stencils front and back views.

The iris folding is done via tissue paper because when light is shone through or it is viewed against natural light, it has the effect of stained glass. This effect allowed for experimentation with respect to colour compositions, layering and shading. It was also
possible to alter the size of the strip used in the folding process this allowed for patterns to be incorporated that would be visible only when viewed with a light source, Figure 4.28a and 4.28b.

**Figure 4.28 Iris folding** – (a) Template for iris folding, (b) the effect of light through the iris layering.

The inner dodecahedron is suspended inside the larger dodecahedron and one panel is left open so that it is possible for the viewer to look inside and through the stained-glass panels, see Figure 4.25b.

### 4.4.3 String Dod

This Dod reflects the latest prototype with extending arms and the origami spring. The dimensions are centred around the origami spring and the inner dodecahedron and outer plates are scaled according to the magnetic attachable Dods accordingly. Whilst it is possible to scale the origami spring to 25% of the original size, for practical reasons an A4 sized sheet is used as reference point.

The aim of this work is to A) demonstrate the functioning extending and retracting arms and B) illustrate that it is possible to have an outer ‘skin’ surrounding the spring without too much interference. This ‘skin’, as mentioned in section 4.3.2.1, may be useful in furthering the development of the Dod’s design in relation to the arm structure. It may act as a boundary between the inner arm structure and the external environment, Figure 4.29.
4. The Dod

4.5.3.1 Inner dodecahedron
The inner dodecahedron is 3D printed in white PLA with a slight inset into each facet so that the spring is securely positioned. The edges of this dodecahedron are perforated in order to facilitate the sewing of the outer plate to the inner dodecahedron, see Figure 4.30.

![Figure 4.30 Core Dod](image)

Figure 4.30 Core Dod - The inner dodecahedron to which the outer plates are sewn.

4.5.3.2 Outer dodecahedron
The outer pentagonal plate has a thickness of 2mm and is also 3D printed PLA. A flat circular magnet is located in the centre of each plate so that when the viewer holds a magnet over this plate it will extend the arm, Figure 4.31a. Reversing the polarity of the magnet will cause the arm to retract, although it emerged that gravity also aids the arm to retract to the closed position.

![Figure 4.31 Outer plates](image)

Figure 4.31 Outer plates - (a) The outer plate containing the disc magnet, (b) illustrates how the outer plates are sewn to the inner dodecahedron, (c) the Perspex springs for retracted arms, (d) the card spring for extending arms.
The outer plate is attached to the spring which is secured to the inner dodecahedron. The seven retracted arms were sewn to the inner core as well as to neighbouring plates, on the outside. This provides the overall structural cohesion. The arms that are free to move were chosen arbitrarily however they are still capable of sufficiently demonstrating the line and curve state.

Strands of coloured thread are threaded from the outer plate to the inner dodecahedron. This creates a semblance of skin, Figure 4.31b. Other materials such as cling film and tissue paper had been tested previously, in order to gauge the effect of an outer skin on the retraction of the spring. Since the arms are never completely retracted (due to the larger outer plates) a hollow space is created between the outer plates and the inner structure whereby the potential exists to use denser possibly bulkier materials for the skin. There is sufficient space to accommodate the excess material when in a retracted state. Considering the behaviour of the Dod each arm has its opposite, which is indicated by the matching colours. The concept of opposites is elaborated on in Chapter 5 with respect to coding the behaviour of the Dod.

The retracted arms have springs that consist of clear acrylic sheets whilst the springs in the extending arms are made up of white card (120gsm), see Figure 4.31c and 4.31d. The rigidity of the clear acrylic sheet provides an outward force on the outer plates because they do not compress as efficiently as ordinary paper (80gsm). This internal, outward force acts, to an extent, against the external force of being sewn together in an attempt to help the inner dodecahedron maintain a centralised position. The card used in the extending arms provides stability yet is supple enough to retract and extend easily under a magnetic force.

4.4.4 Latch Dod
This Dod is a development of the design from the perspective of game or toy design which will be elaborated on in Chapter 7. The artwork aims to illustrate the user behaviour envisioned for a Dod used in this capacity: to press a facet of the Dod and that it extends smoothly, Figure 4.32.
4. The Dod

Figure 4.32 Latch Dod - Finished art work highlighting the inner structure.

An origami pattern for a pentagonal frustum spring made it possible to maintain the concept of facet and arm rotation. The sole purpose of this origami spring is to provide lateral stability for the whole arm structure. Hidden spring latches like those used in furniture (cabinet doors) are the extension mechanism used for this design. They are strong, rigid and their length allows for 1 rotation of the outer plates. The size of this design, like its predecessors, accommodates the spring latches used, see Figure 4.33 and 4.34a.

Figure 4.33 Latch Dod arm - An arm from the Latch Dod in retracted and extended position.

4.5.4.1 Inner dodecahedron

The inner core for this design is a dodecahedron with all arms extended. It was 3D printed in two halves and modelled so that the latches are set into the extended arms. The inset distance was calculated to ensure that the effect of the extension is still visible but also that the minimum distance exists between the ends of the latches. This distance ensures that the inner core is as small as possible but still able to accommodate the latches, see Figure 4.34a and 4.34b.
4.4 Artistic Approach

Figure 4.34 Latch Dod core- (a) inner dodecahedron core with rigid extended arm each of which contain a latch spring, (b) the bottom half of outer facets attached illustrates the construct in context.

4.5.4.2 Outer dodecahedron
The outer dodecahedron consists of larger pentagonal plates similar to that of the String Dod. They are colour coordinated to make it easy to identify arm opposites. In the centre, on the inner side of the plates, is a 10mm diameter, raised platform. A thin circular magnetic cap is placed on this platform and attaches the outer plate to the extruding spring latch. The inner core is once again connected to the outer plate via the origami frustum spring. Since the magnetic cap is larger in diameter than the head of the spring latch there is some degree of flexibility. The origami springs acts as a securing boundary to keep the outer facet orientated in the correct plane, Figure 4.35.

Figure 4.35 Latch Dod configuration - Various configurations of extended and retracted arms in the Latch Dod.

For this design it would not have been necessary to maintain the rotational aspect as this design demonstrates there is no between faces even if the extension mechanism is straight out.
5. Dod Behaviour

5.1 Introduction
Since the primary focus of this study, this chapter explores the behavioural qualities of the proposed agent. Creating a detailed and extensive blueprint of the Dod is valuable in defining its existence. Research on communication is an ongoing, rich study and in relation to self-assembly inspiration is taken most often from natural systems. Whilst this project does not aim to present a new or fully documented communication protocol to be used in MAS, it proposes a fundamental rule set that can be potentially applied to the Dod design. Projects exploring distributed sensor networks (Butera 2002, Lifton et al. 2004, MIT Media Lab 2018), self-organising multiagent systems (Gilpin et al. 2010, Rubenstein et al. 2014, Le Goc et al. 2016), multiagent coordination (e.g. drone flight) provide protocols that emulate swarm or hive behaviour. Even though these systems often rely on an external perceptor in order to transmit localisation data to the individual agents, it is possible to determine valuable insights. For example, running several iterations of the Zoooids assembling into a specific shape, the packing order emerged as being random. It does not have an adverse effect on achieving the end goal nor did it effect the Zoooids ability to recreate the desired shape.

The fundamental question of whether an agent is aware of its position in relation to the larger group remains unanswered. Perhaps this kind of knowledge acquirement is possible only through biological mechanisms whereby the storing and processing of data is flexible and interchangeable. For example, a human is capable of learning and acquiring new knowledge, from mistakes, others’ experiences, static or dynamic sources (e.g. books / teachers) and in a variety of mediums and formats (e.g. song, text, drawing, dance, etc.). It is also possible for a human to forget but still retain the essence of an experience or knowledge of consequences of certain behaviours. This means that the mind is not clogged with excessive information. A person can approach each
situation as new but working from a solid foundation of experiences. In contrast, the hardware of computers does not yet encompass this flexibility.

Communication and degrees of awareness are explored in the 1st section of this chapter. Their relevance informs the Dod design at a fundamental level but also provide insight into how the Dod should ideally behave and function. Since applications for this type of technology remain largely hypothetical considering the Dod as a unique entity, as opposed to a puzzle piece predetermined for a specific purpose, is favourable. With respect to the Dod’s behavioural rule set, two main concepts were considered and used as guidelines: Richard Feynman’s idea that complexity is built upon many simple rules working and interacting with each other and Kristinn Thórisson’s awareness model to simulate an autonomous artificial agent (Thórisson 1996). As mentioned in Chapter 2 communication is an essential quality for self-assembling, swarm systems (Le Goc et al. 2016). Defining attributes that are essential to communication may influence specific aspects of the Dod design, e.g. creating a common knowledge base or encouraging an individualistic approach to sharing knowledge, sensor distribution, and information processing. As a result, this could free certain channels or bandwidths to aid in more precise data manipulation as opposed to being used for standard communication aspects. For example, consider the scenario that the Dod determines its position through IR sensors. With the ability to extend arms, like the tentacles of sea anemones or an octopus, the Dod can stay in place and send out ‘feelers’ to scope out its surrounding thereby using energy more efficiently. Multi-modal sensing and the bi-directionality of the haptic sense in relation to their application in communication are valuable qualities that can enhance the Dod design.

Following from the discussion of communication models, it is important to detail the observations and results of Rubenstein’s work in the Kilobot project as well as Le Goc’s work in developing Zoooids (Rubenstein et al. 2014). Creating a detailed and extensive blueprint of the Dod is valuable in defining its existence. These projects detail successful demonstrations of hundred circular robots communicating, moving, and self-organizing to recreate user-defined shapes. In future developments, the Dod would ideally be able to build upon the programming that has been achieved in these
projects with respect to communication and environmental sensing, adding the ability to determine itself amongst the other agents.

In the next section, the verification of the Dod design will be explored. The rule set for the Dod will be presented, i.e. how it can create a straight line, a curve or create porous or solid structures. The aim was to develop the most basic rules required for the Dod to function mechanically. Each individual rule set has been tested in relation to isolated occurrences/applications, i.e. the ideal condition set. The implementation and testing of the emerging behaviours in a large group will require further exploration. The second part of this exploration is a simulation in which the Dod is programmed to exhibit the two extreme configurations: all arms fully extended or retracted. The aim of this simulation is to demonstrate the viability and the potential advantage of the Dod design with respect to handling an irregular terrain and interactions between agents. The functionality of the configurations and their effect on possible future applications will be explored through simulations. The finding from these simulations is discussed in Chapter 6.

To close this chapter, reference will be made again to the importance of error or imperfection. A significant counterpoint to the building of structures and the creation of order is the release of entropic energy back into a system. In the proposed MAS, the aim is to achieve 3D self-assembled, known or newly imagined, structures – generating order from a mass of disorganized and chaotic agents. Error is an integral part of this process: in chapter 4, it is discussed in relation to the physical qualities of the Dod design. In this chapter, it will be explored with respect to its suitability to be considered a creative or mutative force in the self-assembling process. Rather than retain the negative connotations associated with the concept of error, it will be explored from the perspective of control and equilibrium.

5.2 Awareness Model

As illustrated in Chapter 2, the concept that self-assembly is dynamic or self-directed, is an important distinction from the existing interfaces and systems that claim to be self-assembling. The majority of systems require continuous external observation (e.g. projector) or physical intervention (e.g. picking up and relocating individual agents), which is a significant obstacle in creating truly autonomous self-assembling and
organising systems. Ideally external initiation should be the main or only input considered, in order to start the process of self-assembly. This is how the user will eventually define what he/she requires of the interface.

Despite copious research being carried out into self-organizing and assembling systems both biological and inorganic, little is still truly understood regarding dynamic self-assembly (Whitesides and Grzybowski 2002). It is one of the core concepts that is evident at nearly all stages of existence (from cells to individuals to societies, and inclusive of biological and inorganic materials). However self-assembly can be considered a higher-level, complex behaviour, which results from the interaction of agents and / or with its environment.

In the process of developing and conceptualizing how the Dod should eventually function, the enormous potential complexity that could emerge became apparent. Richard Feynman’s interview (Dallas 2015) and Doughlas Hofstadter’s micro-domains (Hofstadter 1995) are a vital influence regarding this aspect.

Feynman’s response to complexity highlights the fact that, usually, complex systems are comprised of very simple rules. There is a hierarchy of complexity that builds upon the layers of variables that affect the system and the reason it appears complex is the distance of understanding between the simple rules and the final product or system (Dallas 2015). For example, in a system that has four independent variables acting on it, it is possible to understand the system in its entirety but also to potentially predict future behaviour dependent on the changes in those four variables. In contrast consider if the same system was now exposed to 25 variables, 10 of which are independent, 2 are dependent on 6 others, 8 are interlinked with 11 (3 of which belong to the group of 6) and 5 occur only when there is a change in 4 of the other variable (3 of the interlinked group and 1 of the dependent). It becomes clear that as the simple rules become more complex within themselves, it becomes harder to model the system accurately as the number of variables that affects the systems grows significantly and the ability to predict its behaviour is significantly decreased. (Univerisity of Groningen 2016). Whilst this is only a fictitious example it offers perspective into the task of defining fundamental rule sets for autonomous man-made agents that will eventually be able to interact with their environment and act on it and react to it.
Despite the quantity of simple rules and the resulting quantity of interactions, it is the complex behaviour that is perceived. To reduce the knowledge gap between the simple rules and how they make up the final system, Hofstadter’s micro-domains are explored and considered in the development of behavioural rulesets for the Dod. Essentially Hofstadter emphasises the usefulness of magnifying a single aspect of a system to reach the most rudimentary state. Eventually the system loses its context and the issue to be solved becomes abstract. For example, saying a familiar word too many times changes how it sounds and the perceived meaning of it or the process of slowing down a song or tune in music, until the overall cohesion and structure is imperceptible. Focus shifts from the overall melody structure to the tonal quality of each note, etc. The passing of one note to another is brought to the attention of the player as well as all the factors that effect this transition both technically and biologically. Very often musicians lose the ability to continue the piece of music because they ‘forget’ what comes next, instead a new piece is reassembled. The benefit of taking a system out of context by zooming in to a greater detail is the shift of perspective by which it is examined but the ability to retain the natural variables that act on it (Hofstadter 1995). This abstraction shares similarities with the concept of the ideal condition. As illustrated in Chapter 1 the ideal condition set is a setup in which the studied system is designed to function in its most ideal form. This precludes external forces that act upon a system, e.g. gravity, boundary conditions, temperature, etc. In most cases this ideal condition set cannot exist, e.g. fluid dynamic study of a water droplet. The ideal condition set may be considered an abstraction of the real-world system whereas the micro domain is an intense focus on one specific variable of a system that is exposed to its natural environment (Hofstadter 1995). The procedure of exploration in both methods is similar: altering one variable in order to see its effect on the system and which other variables are linked or dependent on the studied variable.

In conjunction with the knowledge gained through the above-mentioned perspectives, the model presented by Kristinn Thórisson is also used as a method of structuring the task of creating a fundamental rule set for the Dod. In summary, he highlights three distinct layers of awareness in an autonomous agent (Thórisson 1996):

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22 The Dadaists were a group of poets, artists and makers from the early 20th century. Dada is described as being everything and meaning nothing. It was often said that the closer one tried to accurately define what Dada actually was, the more elusive it became.
5.2 Awareness Model

- The inner or bottom layer refers to the agent’s rudimentary functions, i.e. how it fundamentally works: the system mechanisms, the rules and coding that characterize it. This layer of awareness functions even if the incoming sensory information is not being processed.

- The 2nd or middle layer refers to the behaviours of the agent. These behaviours emerge and are defined as a result of the interactions between the 1st level rules. This encompasses the variety of combinations in which the rudimentary mechanisms can function together.

- The 3rd level and what can possibly be considered the topmost level, is one in which the agent behaviour interacts with the environment in which it is in, i.e. its surroundings and the objects therein as well as other agents. This is the boundary between internal and external environments.

Once the process of awareness begins, each layer is interlinked and appropriately informs the next layer. This model indicates the bi-directionality of awareness but also the balance between ‘hardcoded’ behaviours found in the innermost layer and the flexible, adaptability of the remaining layer in their participation of information exchange. For example, consider an agent whose 1st level, basic rule set consists of moving, talking and collecting. The 2nd level behaviours that could emerge from this are moving, talking, collecting, foraging (moving + collecting), storing information (talking + collecting) and spreading of information (talking + moving). The behaviour of an agent is continuously being informed by its basic rule set and in the 3rd level, the agent acts and communicates outside of itself, i.e. in the environment. Factors such as stigmergy may become relevant as well as contact with other agents and whether or not they have similar or different behaviours. This is an example of a purely mechanical rule set and can be considered to have relatively predictable variables. The introduction of emotions as an unpredictable and undefinable ruleset clearly indicates the complexity of interaction that begins to emerge.

In future MAS developments, the depth of autonomy required for agents will predominantly define the refinement of the basic ruleset. For this study the Dod is considered to function on a purely mechanical level. Therefore, as Chapter 4 describes the research and physical attributes that are conducive to adaptable self-assembly and
self-organization, the following sections aim to provide 1st level of awareness for the Dod design.

5.2 Communication
The previous section delineated a path that contextualised the need for a basic ruleset to be determined.

As mentioned in Chapter 1, MAS are most commonly encountered in the digital domain. Developing communication protocols and models used in MAS are valuable because they can be used to model scenarios such as traffic control, city growth, human or animal migration (Uhrmacher and Weyns 2009). The task of creating an autonomous agent, that is capable of learning, living, dying and making choices, is easier when compared to creating the equivalent agent in 3D (e.g. Conway’s game of life). The process of abstraction has the greatest impact at this stage. The biological coding that is present in living organisms is replicable, to an extent, via digital programming in terms of algorithms. Using ants as an analogy, it is possible to assume that the worker ants do not possess knowledge of the whole concept: the big picture. For example, the queen of a hive or nest does not delegate to each individual ant what jobs must be done or where to be, rather she relies on the biological programming that defines each worker ant and gives it a specific function or task. By adding communication concepts, such as frequency of interaction or strength of a chemical signal, it is possible to combine these behaviours to achieve larger goals, e.g. build a nest or hive. Being able to replicate these systems not only provides insight into the variables that affect them but also how much change in the variables is necessary to make an impression and what the results are from each variable change. Whilst sources in nature have proven to be good guidelines, and despite the copious research into these domains, it is still only possible to speculate as to how the systems truly transfer information. Intrinsic and extrinsic communication methods are reflective of interactions between the awareness levels, e.g. intrinsic suggests that the 1st and 2nd levels awareness are primarily being applied and that communication is focused inwards.
5.2 Communication

5.2.1 Intrinsic communication
Communication based on an intrinsic level would indicate that each agent receives the same knowledge to begin with but after initiation, is responsible for sensing, storing and analysis of any extraneous information that is gathered. The agent communicates within itself more so than with its neighbours in order to make sense of its surrounding. These types of agent could easily lead, particularly if placed among agents that have less knowledge. This setup creates individualistically orientated, valuable agents because of the resources required to facilitate each agent with learning capacity, memory storage, energy to transmit and direct, knowledge processing, decision making. More energy is consumed by individual agents but the potential exists that these agents can make decisions based on the information collected.

5.2.2 Extrinsic communication
Communication based on an extrinsic level would indicate that the external environment, like stigmergy, controls each agent. Such a setup would require very precise and definitive instructions from the environment to achieve specific goals. Aside from environmental influences, this type of communication requires a greater proportion of agent-to-agent interaction. In this setup it could be possible to pool information together, collected by each Dod, such that the common knowledge base of the MAS is maintained. While the potential exists for memory storage to be used up quicker, it would ensure that each Dod is aware of the system. This is useful for determining system states or if the Dod based MAS is applied in a sensor network application, see Chapter 6.

Following from these concepts, consider the following example: a group of 50 adult humans is asked to link together in order to create the shape of the letter ‘B’. Each person understands the concept of the letter. One solution is if people link hands and follow one person who walks out the shape. By being linked everyone not only knows the state of the system (i.e. how many people there, how far to spread out, when to move, etc.) but they also learn more about their environment. The people following do not always know where or when the shape ends because they are part of a linked chain.

Alternatively, people can also arrange themselves individually by realizing where they are needed and what needs to be done to complete the structure. Each person takes the
responsibility to be aware of the overall goal as well as their individual place. This ability means that the people are not tied to a specific place in the shape and can adapt to or compensate for unforeseen events.

The example highlights the strengths and weaknesses in both approaches of communication and the behaviours that can emerge as a result. The ideal case would be a combination of intrinsic and extrinsic influences. Each agent should be influenced by its environment, i.e. be aware of surrounding Dods and the environment in which they move, enabling them to make informed decisions, but also information should be passed from one agent to another to foster a collective awareness. Despite the application of these types of behaviours falling outside the scope of this study, the application of learning algorithms is an important aspect of future work. Such algorithms would enable a Dod to communicate effectively and contribute to designing the 2\textsuperscript{nd} level of behaviours necessary for a higher level of awareness\textsuperscript{23}.

An advantage in testing communication protocols, such as the ones in the example via simulated MAS is that it is possible to manipulate the variable \textit{Time}. Whilst it is possible to observe patterns and development of communication in real-time, the timespan for such observations potentially precludes any useful application of the collected data. This is also a contributing factor as to why communication models have received continuous interest and research. The development of communication and the means to embody it are usually symbiotic-ally interlinked within a system. In the domain of man-made agents, it is sometimes necessary to consider one characteristic over the other, e.g. the physical appearance before communication technique or vice versa, choosing a specific communication style that delineates the resulting physical design (Gorbet \textit{et al.} 1998, Lifton \textit{et al.} 2004, Richardson \textit{et al.} 2004, Nakayasu 2010).

The method of communication can also influence the style of self-assembly\textsuperscript{24} (static or dynamic and therefore several different approaches for programming these methods have been developed as a result (Butera 2002, Rubenstein \textit{et al.} 2014, Romanishin \textit{et al.} 2015, Le Goc \textit{et al.} 2016, Roudaut \textit{et al.} 2016, Özgür \textit{et al.} 2017). They will be

\textsuperscript{23} This includes being able to prioritize knowledge through active learning, forget irrelevant information, pool knowledge between agents and pass on or receive knowledge gained from past experiences.

\textsuperscript{24} There is a subtle divergence between self-organization and self-assembly. To organize does not necessarily incorporate the ability to create structures as is indicated by self-assembly.
briefly described in the following section. Determining which approach is most efficient, with respect to a computer-based system, is still being experimented with.

- In his proposal of pushpin computing, Lifton (2002) describes information travelling from one agent to another via programming fragments. These fragments pass on the commands to their next nearest neighbour until the require task is completed. In analysing the graphical data of this work, it is possible to draw an analogy between the spread of commands amongst the particles to the propagation of a viral infection, i.e. an exponential growth. The potential exists for this to be achieved through physical contact or defining a sensory range.

- Another suggestion detailed in the project Proteo is to have several seed agents dispersed throughout the system. These would act as core points around which the other agents can gather and orientate themselves. They would have slightly different coding and be able to make more managerial decisions (Bojinov et al. 2002, Le Goc et al. 2016).

- ‘Ghost’ trails (Uhrmacher and Weyns 2009), which are very similar to the pheromone trails left by ants and other insects, have been developed to indicate location and type of message (food: energy, danger: obstacle, etc). Depending on how many agents use the trail, it strengthens and an initially chaotic field of trails eventually becomes ordered into the optimum paths (Tero et al. 2007).

- Organisation according to stigmergy is another approach and is based on the mechanism by which agents can organize through commonalities in the environment (Tummolini et al. 2009) and is very closely linked to the ghost trails approach. The main principle is based on the fact that a single ant can lay a trail that indicates a good food source. This anomaly of difference in the environment influences the next actions taken by the same ant or others that find the trail and strengthen it (Tummolini et al. 2009). It is also possible to alter the environment to influence the behaviour or reaction of the agent.

Considering these approaches will influence the development of the Dod design since a fundamental difference exists between an internally driven motivation or environmentally driven motivation to self-assemble or self-organise. For example, it emerges that the lack of a singular hierarchical chain of command ensures that a system
can expand and maintain optimum flexibility (Gordon 2010). Alternatively, the concept of seed particles could be translated into representing the seed particles as being physically different - slightly larger, or have a different configuration, etc. to provide a structural initiation marker instead of digitally communicating its significance.

To provide a wholesome blueprint of the Dod the following section explores two systems that have demonstrated the combination of communication and active self-assembly. It is envisioned that when the Dod is further developed that a variant of this communication protocol may be adapted and applied. The projects encompass important concepts that inform the behavioural design of the Dod, similar to how ER and MR fluids influences the physical features of the Dod.

5.3 Existing Platforms
Adaptability, flexibility, stability, endurance and robustness are desirable qualities of a MAS communication protocol. This type of protocol should ideally be able to handle Thorisson’s three stages of awareness model, which is communication within the agent itself and with its environment. Most biological life forms utilize multimodal sensing. As mentioned in Chapter 2, section 2.5.3, it involves receiving information from multiple sources. Whilst it would increase the computational requirement it would be an advantage in multiagent communication. Tangible progress has been made in the area of MAS communication by the work accomplished by Rubenstein (Kilobot), le Goc (Zooids) and Ozgur (Cellulo), although the projects are still reliant on external influences to inform the agents (e.g. an overhead projector). The following discussion details the valuable insights of each project, with the aim of eventually defining the Dod’s higher level behavioural characteristics.

5.2.1.1 Kilobot
Rubenstein details the effective swarm communication of robots numbering in the hundreds (approx. 1024 Kilobots\(^{25}\))(Rubenstein et al. 2014). The challenges that arise from increasing interactions between agents indicate that the probability of error and

\(^{25}\) Circular robots based on IR sensing for distance & position and vibration motors for locomotion.
in turn error propagation need to be accommodated. In support of the concept of relinquishing a degree of control, regarding the method in which self-assembly is applied, Kilobots is based on defining the boundary rather than the placement of each agent. As mentioned previously there is an amount of system flexibility, with respect to packing patterns, that can occur and this reflects a more natural approach to organic assembly (Rubenstein et al. 2014). It highlights that there are numerous possibilities for efficient and practical assemblages and that similar to nature, being adaptable and responsive to changing circumstances can be beneficial in the survival of a particular design or behaviour.

Whilst the robots illustrated by Rubenstein’s work are not orientated towards 3D self-assembly (i.e. along the z axis) the following observations he has made can be applicable and relevant for any multiagent system (Rubenstein et al. 2014).

- Variation in ability of agents due to component (motion, extension, learning, transmitting, etc).
- Rare or unpredictable events causing errors either from within or external environmental influence (e.g. internal influence: short circuit, external influence: poke)
- Message corruptions – multiple message per channel, chatter between agents, random noise. This can have a domino effect on other dependant factor, e.g. failing to sense boundaries
- Anisotropic boundary measurements

Being able to sense or recognise boundaries is a crucial skill for an autonomous agent, especially in the process of adapting to specific, complex, prescribed boundary conditions such as a keyed interface. Rubenstein demonstrates successful assembly into a quasi 2D planar shapes, the next challenge requires defining boundary conditions that contribute to constructing 3D volumes. Boundary conditions can help define distance and aid in collision detection between agents (see also Chapter 7).

Distance is defined by the communication between agents, i.e. the update of messages. Localization in contrast is defined by averaging the distance samples between the sensing agent and its surrounding neighbours. This value is used in the process of triangulation. Maintaining a list of sampled distances ensures that behavioural
adjustments can be made based on the comparison of values. For example, in the case of Rubenstein’s robots – if a robot was pushed aside by other edge following robots, then the pushed robot would realize from the sudden change in several distance values that its position had changed suddenly and not as part of the self-assembling process. Similar to the example relating to intrinsic communication, each Kilobot only registers its nearest neighbour and immediate environment. It is not aware of the overall system state.

5.2.1.2 Zooids

Zooids is a project based on swarm user interfaces. The main aim of this research is to close the gap between actuated tangible table-tops whereby solid materials can be manipulated or shape displays that use the method of physical deformation to manipulate digital data. With respect to Le Goc’s definition of swarm user interfaces very little difference between such a system and a MAS exists. Similar to Kilobots, Zooids make use of an external guidance mechanism: an overhead projector that tracks the position of each agent. Like a natural ant hive, this project has a centralised control system to coordinate the Zooids. Qualities that the authors highlight, which are essential in a swarm UI and also indirectly for the individual agent, are A) autonomy, B) self-propulsion - without external manipulation, C) collective motion via information exchange or one central coordinator, and D) reaction to direct user’s input, i.e. a bidirectional sensing behaviour. Of interest is the conclusion that to be considered for real-time applications, a MAS or programmable matter based interface must be able to execute any function or motion or shape change in ‘the order of one second’ (Nielsen 1995, Le Goc et al. 2016). This relates to the user’s expectation, focus and need for feedback regarding system states.

Each individual Zooid moves via motor driven wheels and is battery powered. Its motion is limited both directionally and topologically. It utilises capacitive touch for sensing and it communicates through a radio receiver. Overall, the physical Zooid agent represents only a quarter of the entire MAS: an application sets the goal, then a simulation is responsible for path planning, proceeding to a server that sends commands to the Zooids, who carry out these instructions under the observance of a projector. The authors opted to have the server send instructions to each individual
5.3 Existing Platforms

Zooid. A similar approach is used by the authors of the project Cellulo (which is discussed in the following section) (Özgür et al. 2017). It is questionable whether this is the most efficient methodology of transmitting or even maintaining a swarm interface. Once each Zooid receives its instructions specific predefined algorithms are initiated and executed as required.

The following qualities are described by the authors which merit careful consideration.

- **Continuous versus discrete positioning**: the advantage of swarm computing is the possibility of availing of continuous positioning. Continuous values contain more information, provide greater accuracy and resolution, and possibly even render a more faithful representation of physical matter. Discrete values are most often used in the digital domain and represent values that have been interpolated in order to convey the essence contained within digital data, e.g. an image that is converted into square pixels.

- The concept of a system being able to adapt to a fixed number of elements or one where the agent count differs, i.e. active and inactive agents. This is true to natural systems. A MAS must be capable of dealing with agents that malfunction or, if for example a shortage of energy is detected, function with a reduced capacity of agents.

- Defining agent identity is an important consideration. Le Goc suggests that in interfaces where specific agents have a task or role, e.g. a handle or controller, these should ideally avoid being interchangeable as it would only confuse the user. If the application is more generic, e.g. forming a line, agent identity is not as pertinent.26

- The ability of agents to change their roles is a quality that is also echoed in certain ant species (Gordon 2010). Whilst this is a desirable trait it is possibly better suited to a system in which each agent has a greater level of autonomy and is not reliant on receiving commands or instructions from a centralised source. The ability to decide which function is appropriate to the current task

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26 It should be noted that if it is possible to achieve a system with agents approx. Scaled to 2mm the issue of one agent representing one entire controller is redundant as a controller will then be comprised of many smaller agents.
contributes to the awareness level, enabling the agent to determine the next course of action with greater independence.

5.2.1.3 Cellulo

The last project worth considering with respect to inter-agent communication is Cellulo. Cellulo is a tangible table-top based interface whose main objectives are to be robust, reliable, affordable and versatile within a classroom or educational setting. As these are their main aims, the communication protocols have not reached the level of sophistication required for the envisioned autonomous agents of a MAS. However, it is possible to consider elements that can be used to create a robust foundation ruleset. This system is also based on an external guidance mechanism: a microdot pattern printed on sheets of paper. Cellulo agents communicate via Bluetooth and have a downward facing camera to read the printed microdot patterns. The agents are capable of holonomic movement due to an omnidirectional ball drive (Özgür et al. 2017). Each agent communicates, via Bluetooth, with a ‘master’ tablet. Bluetooth technology limits the number of agents that can be active at any given stage. The inefficiency of the system becomes apparent in that each agent is told what to do individually as opposed to presenting the agents with the final goal and allowing them to achieve in their own means. An important quality in this project, that may seem secondary, is the ability of the Cellulo agents to cope with unexpected events, e.g. kidnapping: when a child removes an agent from the table top, or physical manipulation: pushing an agent against the designated direction, etc. This is due to the relative simplicity of the system with respect to its movement and environmental localisation capabilities, i.e. a camera reading a microdot pattern and following an instruction. The simplicity of its ruleset means the Cellulo agents exhibit predictable behaviour. As a result, it is possible to focus on apparent collective behaviour: the final, perceived behaviour versus the actual, inner functions.

These are functioning projects that achieve effective communication in physical MAS, ranging from 7 to 1000 agents. Whilst the core issue of awareness is not yet fully solved, it is possible to see the potential of using such systems as basic templates. The following sections explore the basic movement-based mechanisms that are available.
to the Dod design, with the aim of eventually leading to defining which communication protocol is best suited for future developments of a Dod MAS.

5.4 Dod Ruleset
The Dod’s fundamental ruleset emerged from the affordances of its physical design. Existing systems that have a similar shape or mechanisms also helped inform possible behavioural rules and patterns. For example, octopus and anemones explore their surrounding via appendages that can extend or retract, are flexible and are essential in completing everyday tasks such as environmental exploration, foraging, protection, defence, camouflage, etc. An important differentiation is that these rulesets do not automatically ensure an innate awareness. In the Dod’s case they currently cater for the mechanisms that are possible through its design (e.g. extending arms, semi-spherical nature, etc). This means that if the Dod develops further, e.g. construction material, sensory ability, application - this ruleset should remain unaffected, the equivalent to default factory settings. As similar analogy is that humans are designed to walk upright placing one foot in front of the other, regardless of human size, age, clothing, shoes the mechanism of walking remains the same.

5.4.1 Basic Mechanisms
This section details how a Dod physically functions on its own and it includes the description of how features such as lines, curves and clusters are constructed. The following points are deemed as being necessary components for the basic level of Dod awareness, from which fundamental rules can be formed.

Body Mechanisms
- Extend and retract arms
- Connect & disconnect to other arms
- Orientate to any 12 arms (see 5.4.2)
- Sense next closest Dod
- Sense the immediate environment
Computational Mechanism

- Emit ready to connect tag = attachable
- Emit connected tag = attached and # of arm
- Emit not functioning tag = arm failure
- Emit standby tag = waiting for use
- Send and receive command messages
- Memory: the ability to store past, present and future tags in command line
- Memory: the ability to remember and forget (once a command has past or a goal has been achieved)

Fundamental rules:

1. An arm can go in (0) or out (1),
2. Any arm will always have 5 surrounding it.
3. The decision on which arm is extended or not will eventually depend on weighted probability. This is based on which configurations are most advantageous given the different states.
4. When exploring the environment, a Dod extends its arms like the feelers of an insect. When it encounters a solid boundary, it determines that it is either a surface meaning it can potentially move in that direction or it is another Dod. The concept of awareness must be considered at a very primeval level particularly when considering scalability. Dods are designed to feel rather than see therefore in order to check whether a Dod is connected they must either emit a connect tag: like a pheromone or must receive force feedback such as resistance when pushed.
5. To construct a line or curve only two arms are required by each Dod and in a cluster a minimum of three Dods are required with a vast variety of arm states possible.
6. It is currently envisioned that commands are passed from one Dod to another via contact.

From these basic guidelines, it is possible to construct a set of rules, e.g. tags that determine specific actions and behaviours. The term tag is symbolic of the piece of coding that the Dod would work with and act upon, similar to the program fragments
as described in Lifton’s thesis on Pushpin Computing (Lifton 2002). To date three rules have been established in this study: line, curve and cluster tag. The curve and line can be viewed as basic structural components for 2D and 3D structures.

The root position is one in which the Dod rests completely on one facet. When the arm connected to this facet is extended, it will be defined as the standing arm for ease of visualisation. Another stable configuration is when all arms are extended and the standing arm and its mirror arm are retracted: the edges of the surrounding extended arms support the Dod.

Due to the inherent symmetry of the dodecahedron it is possible for any facet to become the root position. This is what is meant by the Dod being able to orientate to any of the 12 arms, if the sensor ID remains static for each Arm, then Arm ID is relative to the sensor value, e.g. Arm 1 can become Arm 7, (Appendix C, Line and Curve tag). Therein lies great flexibility, because it is possible for the Dod to reposition and orientate itself irrespective of the task, location and orientation.

For the following example, the Arms will have static designations. The 1st Dod will start in root position with 1 as the centre arm in the lower hemisphere and 12 as the centre arm in the upper hemisphere. When a 2nd Dod connects to a first it will always be 1 (of 2nd Dod) to 12 (of 1st Dod). Figure 5.1a illustrates the root position and highlights both standing arms, Figure 5.1b) indicates the lower hemisphere, showing arms 1-6 in white and the grey shaded area indicates the upper hemisphere, showing arms 7 – 12. Figure 5.1b illustrates the mapping of the remaining arms when in the root position configuration whereby Arm 1 and Arm 12 are designated as the default standing arms in root position. For the line and curve states the standing arm in the bottom hemisphere will be the reference point and is always in use throughout these states. The cluster state is based on four fundamental anchoring states described as Case A-D. The physical arm identifier and the allocation of sensors may often vary.

Arm 2 is directly opposite Arm 10,
Arm 3 is directly opposite Arm 11,
Arm 4 is directly opposite Arm 7,
Arm 5 is directly opposite Arm 8,
Arm 6 is directly opposite Arm 9.

Figure 5.1 Root position – (a) root position with standing arms retracted & extended indicated by the red lines, (b) Facet / Arm allocation, (same as Figure 4.13)

5.4.1.1 The Line tag
Line tag (LT): In the line state, the fundamental rule is: opposite arms always engage or activate together. The arms can A) both extend, B) retract or C) have one extend and one retract. It is possible to adjust which arms are retracted or extended, resulting in straight-lined structures of varying heights, see Figure 5.2.

Figure 5.2 Line heights - Varying heights due to the configuration of arms that are retracted or extended

5.4.1.2 The Curve tag
This tag is the opposite of the Line tag. Rather than activating opposing arms, the first arm is identified and then another arm either on the upper or lower hemisphere of the dodecahedron can be activated. This creates acute or obtuse angles without much strain
on a mechanism such as a joint or lever. Due to the semi-spherical but faceted nature of the Dod, the facets between upper and lower hemisphere are offset to each other. This influences the dimensionality of the circle or line formed with this tag, i.e. instead of a flat circle, there is a slight twist or wobble because of the offset facets.

It takes a minimum of 6 Dods to form a circle using obtuse angles Figure 5.3a. Applying this tag to a line, creates a spiralling curved line because the obtuse angles are formed through both hemispheres of the Dod. This twist does not interfere with the overall structure because of the inherent symmetry of the Dod, Figure 5.3b.

Curve tag (CT): In the curve state, the fundamental rule is: opposite arms never engage or activate together. If it is necessary to construct a line at a different angle then the curve state applies to the Dod that acts as a corner agent. The Dod is capable of two types of angle positions. There is the AcCurve tag (AcC) for an acute angle (root position + arm from lower hemisphere, Figure 5.4) or the ObCurve tag (ObC) for an obtuse angle (root position + arm from upper hemisphere).

CT: new Arm activation for a line at a different angle
- AcC: new Arm activation on hemisphere surrounding the active standing arm
- ObC: new Arm activation on hemisphere opposite the active standing arm
The following example is based on Figure 5.4 and demonstrates how the Line and Curve tags could be applied and it will be assumed that all arms are active and involved in the building of structures.

The first instruction is a line tag (LT). Assuming the 1st Dod rests in the stable root position, the standing arms are activated. Arm 1 emits a connected signal and Arm 12 emits a ready to connect signal. The next closest Dod connects to the standing arm (Arm 12), emits a connected signal and receives the instruction package minus the first instruction. It checks whether there is a deviation or curve required for the next agent (CT) else LT applies. A third Dod connects to the appropriate arm and executes the same procedure. In this instance, there is a deviation therefore CT applies. Next the sub value of CT is checked to see whether a AcC or an ObC is relevant. In this instance, the AcC tag is activated, therefore a new Arm on the lower hemisphere of the Dod is activated. The Dod closest to this Arm will connect and emit a connection tag as well as receive the instruction package, etc. This time the LT is called and the connected arm and its opposite are activated to create a line. This procedure is continued until the structure is complete.

When an arm is extended it emits a marker signal that is receivable by the surrounding Dods. By sensing which arm is closest to the currently transmitting arm the next Dod can react by creating the next link in a configuration. It will receive the next stage of the instruction package via transmission and if there is no deviation or curve of the line at that point then a LT applies.

These two states provide the basic two arm functionality. Once the Dods connect and attach it is possible to fix or identify arm numbers. Using the example above, the starting Dod A activates Arm12 and Arm1 (Figure 5.3a). The second Dod B that attaches connects its Arm1 to Arm12 of Dod A and activates its Arm12. The third Dod C attaches and connects its Arm1 to Arm12 of Dod B. However, because Dod C received a curve and AcC tag it activates Arm10, instead of Arm 12 etc.

If it is necessary to connect 2 Dods or more Dods to one, (e.g. creating a line and a junction via a curve) it may be more efficient to list the specific Arm numbers required for the task. In relation to relative and static IDs, consider that each facet of the Dod contains a sensor correlating to that specific arm - Sensor 1 is on Arm 1. Once the first Dod is orientated in root position on a level surface it is possible to define Arm12
(standing arm) even though it equates to sensor 4 (i.e. it once was arm 4 but is now reassigned). This algorithm enables the arms to be reassigned accordingly. Therefore, it is possible to recall where each arm is and thereby potentially activate specific Arms that may need to be activated.

Once there are more than Dod-to-Dod connections involved in structural tasks, i.e. two+ Dods to one it becomes a cluster state. It also requires the Dods to be more autonomous. For this state four cases have been explored, see Chapter 5, section 5.4.2.

5.4.1.3 The Cluster tag

The last rule relates to the Cluster tag. A cluster is comprised of Dods with specific arm configurations. A configuration in this instance is defined as the position of the arm states (extended or retracted) such that another Dod can attach to these active arms and form an anchor. The main usage for this tag is to fill space, thereby creating a variety of texture and emulating material density. This can be achieved via three options:

1. All arms retracted = a dense, compact filling of Dods
2. All arms extended = a porous filling of Dods
3. Via configurations = a starting point of three Dods connected in one of four specific patterns. These connections each in turn provide the opportunity for a wide variety of configurations to which other Dods can connect and continue to build structures. In this manner, it is possible to juxtapose areas of dense and sparse clustering of Dods.

It is possible to define or code the line and curve tag with greater accuracy. The challenge arose in attempting to define the Dods behaviour to enable them to cope in a state of greater uncertainty. The rule had to instruct the Dod in how to behave (what arms to extend and / or connect) but then also to allow for further interactions to evolve independently according to each Dod’s decision. In the cluster state, there is still scope for many adaptations. Enabling the Dod with the capacity to learn the most often used configurations, when emulating specific materials, might only for example require 3 and 7 armed Dods as opposed to all arms retracted or extended, etc. This latter point precedes the possibility that whilst the current suggestion highlights that all arms are
extend-able it may emerge that only a certain number of arm configurations are necessary. Superfluous configurations may be eliminated thereby creating a more efficient Dod. A method of determining the most successful configurations could be through evolutionary algorithms. Once a Dod modelled in such a way, the potential exists to define which configurations would be best suited for specific applications.

A cluster consists of a minimum of three agents connecting and attaching with each other and a *cluster anchor* is comprised of the six arms (2 from each Dod) being arranged in specific configurations. When a cluster anchor is generated, two craters are formed on either side of the anchor via the adjacent arms, into which other single Dods can attach. This enables two sides to be delineated: Side A and Side B, Figure 5.5.

![Figure 5.5 Craters](image)

The craters on either side determine the arm configuration necessary for another Dod to attach - this configuration is defined by three arms: 3 arms extended (3E), 3 arms retracted (3R), 2 extended arms and 1 retracted arm (2E1R) or 2 retracted arms and 1 extended arm (2R1E). The number and variety of craters formed is dependent on the state of the arms adjacent to the anchoring arms. For example, as stated for Case C when ADod1 (Anchor Dod1) has 2 extended arms, ADod2 has 2 retracted arms, ADod3 has 2 retracted arms then on side A the following configurations are possible:


<table>
<thead>
<tr>
<th>Crater</th>
<th>ADod1 2E</th>
<th>ADod2 2R</th>
<th>ADod3 2R</th>
<th>Resulting configuration</th>
<th>Required config for connecting Dod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>extended</td>
<td>retracted</td>
<td>retracted</td>
<td>2R1E</td>
<td>2E1R</td>
</tr>
<tr>
<td>2</td>
<td>extended</td>
<td>extended</td>
<td>Retracted</td>
<td>2E1R</td>
<td>2R1E</td>
</tr>
<tr>
<td>Side B</td>
<td>extended</td>
<td>retracted</td>
<td>Extended</td>
<td>2E1R</td>
<td>2R1E</td>
</tr>
<tr>
<td>3</td>
<td>extended</td>
<td>extended</td>
<td>extended</td>
<td>3E</td>
<td>3R</td>
</tr>
<tr>
<td>4</td>
<td>retracted</td>
<td>retracted</td>
<td>retracted</td>
<td>3R</td>
<td>3E</td>
</tr>
<tr>
<td>5</td>
<td>retracted</td>
<td>extended</td>
<td>Retracted</td>
<td>2R1E</td>
<td>2E1R</td>
</tr>
<tr>
<td>Side B</td>
<td>retracted</td>
<td>retracted</td>
<td>extended</td>
<td>2R1E</td>
<td>2E1R</td>
</tr>
<tr>
<td>6</td>
<td>retracted</td>
<td>extended</td>
<td>extended</td>
<td>2E1R</td>
<td>2R1E</td>
</tr>
</tbody>
</table>

Table 5: Crater formation - Sample of the craters that are formed in a Case C cluster connection.

It is possible to extrapolate that a single connecting Dod must form the opposite configuration to the one formed on the sides of an anchor cluster in order to connect or attach correctly. In Case C due to the symmetry of ADod2 and ADod3 some craters are mirrored on side A and B and therefore these configurations are not counted. It is possible to get differing craters for Side A and Side B at the same time, however this effect is more pronounced in Case D.

The fitting error that is potentially disadvantageous as is illustrated in Case A & B can now be quite useful for two main reasons. Firstly, it is not always necessary for all arms to connect to create larger configurations. For example, in Case C two anchoring agents are not connected to each other but are linked via the third agent. In this case it is still possible to form further craters on either side of the anchor cluster. This is relevant in instances where it may be advantageous to define: A) the arm extension length, whether it should be extended or retracted and thereby defining density of a Dod cluster, 2) if a Dod is malfunctioning it does not mean that the Dod is ineffective, i.e. material optimisation or 3) if the angle of connection is not planar, i.e. if the facets meet at an angle as opposed to surface to surface). Secondly the orientation of connecting facets does not always have to match, i.e. it is possible for Dods to be connected despite difference of a 180° facet rotation. This allows for flexibility.
regarding attachment mechanism and Dod material regarding what the arm and facet will eventually be made of. Case C also demonstrates the potential to emulate more efficient methods of connecting and building configurations like the nature equation of maximum function through optimum material used.

Case D creates the most stable anchor clusters because all three Dods are connected. Due to the specific arm configurations, this anchor cluster has the greatest probability of being capable of dealing with the packing error caused by the dihedral angle of a dodecahedron. This Case has the greatest variety of crater formation into which single Dods can attach to. Similar to Case C craters are formed on both sides of the anchor cluster. As the cluster builds around the cluster anchor it is possible to add further Dods so that an entire hemisphere of either one of the anchor Dods can be engaged. The last agent to be connected in such an instant would have greater restrictions, as it would fit into a configuration composed of 4 arms, a situation comparable to 3D Tetris.

The following section summarises the four Cases and highlights the number of craters that produce varying configurations are formed.

5.4.2 Cases
This section describes the four cases that are evident in the cluster state. They refer to the types of cluster anchors that can be formed between 3 Dods. On a local level, these cases have an effect on the types of craters are formed on either side of the anchor and on a larger scale they effect what kind of material density can be emulated, see Appendix D.

Abbreviations

- 3E = three extended arms
- 3R = three retracted arms
- 2E1R = 2 extended arms & 1 retracted arm
- 2R1E = 2 retracted arms & 1 extended arm
- ADod = Anchor Dod
5.4 Dod Ruleset

5.4.2.1 Case A and B
The state of all arms retracted (Case A) or all arms extended (Case B) will generally become unstable if similar state Dods come together. This instability is due to the fitting error caused by the dihedral angle. The Dod design enables packing to continue despite not being a perfect fit (Teich et al. 2016). These cases (and thereby the configurations) should ideally have the lowest probability weighting, alternatively they can be implemented primarily for generating dense or porous masses

**Case A**

When all arms are retracted, craters are formed on side A and B that generate configurations to accept totally retracted Dods or Dods with three adjacent arms retracted (3R).

**Case B**

When all arms are extended, craters are formed on side A and B that generate configurations to accept totally extended Dods or Dods with three adjacent arms extended (3E).

5.4.2.1 Case C and D
These cases present clusters that have more variety with respect to the configuration possibilities. They can be implemented in the construction of materials that require a mixed density.
5. Dod Behaviour

*Case C*

When ADod1 has 2 extended arms, ADod2 has 2 retracted arms, ADod3 has 2 retracted arms, it is possible to generate approx. 34 craters with different three-arm configurations in this setup (some configurations are mirrored through symmetry and therefore not counted)

*Case D*

When ADod1 has 2 extended arms, ADod2 has 2 retracted arms, ADod3 has 1 extended & 1 retracted arm it is possible to generate approx. 40 craters with different three-arm configurations in this setup. See Appendix D for the code that indicates which configurations are viable.

The first part of this section illustrated precise rules involving individual Dods (line and curve) and focusing in on the specific connections to be able to achieve defined features. The second part of this section demonstrates the ability of the Dods to create larger structures through building around an anchor cluster. This behaviour is more closely related to the behaviour exhibited by the solenopsis invicta in raft or bridge building, see Chapter 2. For example, in order to bridge gaps and/or create larger structures with less agents, retracted configurations are favoured e.g. 3R or 2R1E so that Dods with extended arms are supported. In contrast to create dense clusters, to fill gaps or support more weight, extended configurations are favoured e.g. 3E or 2E1R this will support Dods with retracted arms. Appendix D contains a simple program written in java that aids in determining which type of configurations are created via the specific Cases.
5.5 Error

The difference between other agent designs developed to date (cube, rhombic dodecahedron, Zoids, Termes, etc.) and the Dod design, is the ability to incorporate and make use of flaws or imperfection. As a designer rather than attempting to account or provide a solution for every possible error it is possibly more important to enable the system to cope with error. Qualities such as self-repair and being able to function despite minor system failures can have substantial advantages not only for the system itself but on the scope of resources, energy efficiency and sustainability. This concept is one of the guiding principles that influenced the development of research and fundamentally, the design process.

One definition of tolerance is a maximum level of foreseeable errors that a system is designed to cope with. Similar to a margin of error, it enables a system to keep functioning despite these errors. It can be interpreted as boundary condition because it is the scope between the safe zone and the limits of a system or material. In contrast to tolerance, errors or mistakes are necessary components for learning and for change but can also be detrimental to a systems normal operation. Generally, error is considered to be unacceptable predominantly because it introduces an element of unpredictability. However, the smallest errors can have a lasting effect both in duration but also in magnitude, due to error propagation. An interesting and simplified example can be gleaned from the ways in which metal can break. Snapping a piece of iron in half requires significant force as it means breaking apart the molecular structure. In contrast if there is a gap or hole in the molecular link, it is possible, over time, that this hole moves along the link. Once it has reached the edge there is a displacement. Since the hole has left another gap behind it, along its path, this second hole also moves through the link until it reaches the end. Eventually the displacement becomes so large the piece of metal breaks. This example highlights the importance and effect of Time: in the first example a large burst of energy may be able to break apart the metals molecular structure in a short amount of time whereas in contrast with more time and less energy it is possible to achieve the same result, making use of an inherent flaw in the material.

In the case of any life form it is possible to consider there being two main types of system error relating to the internal and external elements of the system respectively.
For example, an internal error may be that the ‘brain’ of the agent no longer functions correctly and therefore cannot transmit any more data. An external error would relate to a physical mechanism of the agent, e.g. an arm can no longer extend and / or retract. In many designs, these errors may prove detrimental not only to the individual agent but to the overall system. In traditional computing devices, it often occurs that if one piece of hardware is damaged and non-replaceable, the whole device is unusable, even though the other components may still function. In the case of the Dod its structural design enables it to be relatively versatile despite internal or external errors. If a Dod can no longer pass on information - it may not be able to actively contribute to the building of a structure but through its physical shape it can still be part of a possible foundation which can be built upon. Similarly, if an appendage should fail, the fact that there are 12 appendages altogether ensures a greater probability that the Dod can still contribute to the overall system albeit at reduced functionality. Naturally there is a point at which there is no possibility of coping with error (complete system failure) but this is also a natural occurrence in biological life-forms and is to an extent a necessary element to complete the life-cycle of an agent.

5.5.1 Clusters
The relevance of error increased, particularly with respect to the development of the cluster tag. It became apparent that the ruleset could quickly grow too complex. Creating specific rules for when, where and how each configuration should be applied is unrealistic because as the cluster becomes larger, the number of connections also increases. If too much focus is placed on one part of a system, the potential for other areas of the system to come apart or fall subject to more detrimental error is increased. The challenge was to simplify the behaviours in this state so that the number of predictable variables in the system could counteract some element of randomness which would inevitably be larger, when compared to the line or curve state. It is clear, that this state requires more agent autonomy. Once again it is comparable to ant behaviour: in normal circumstances they build structured nests based on their inherent, biological ruleset but in exceptional cases (e.g. floods) they can create structures with a defined, external form but and random internal composition. This is the point at which the potential for error could be increased, not necessarily a system relevant error.
but the error perceived by the user themselves in relation to the system. Relinquishing control and providing a system with a greater level of autonomy means that it can make its own decision. These decisions may not always align with those of the controller. It will be a consideration for the future implementation of learning algorithms, i.e. the 2nd level of awareness, as to how much autonomy and awareness does a self-assembling interactive system need to be imbued with. As mentioned in Chapter 1 the desire to have control is predictable but the fear of losing it can lead to irregular behaviour. This in turn can affect interactions with an interface that is trained or designed to react to its environment and the entities in it.

As mentioned earlier a unique quality of this agent design is the ability to assemble curves as well as straight lines, i.e. it is possible to build domes and spheres of a higher particle resolution. It is possible to represent a curve using cubes however the semi spherical nature of the dodecahedron lends itself for this type of structure. The flaw in the Dod is inherent in its shape, specifically in relation to filling a space, i.e. when three Dods are placed so that three facets touch it becomes clear that the dihedral angle does not allow the three faces to make a flush connection, see Figure 5.6.

![Figure 5.6 Filling error](image)

**Figure 5.6 Filling error** - Rendered and line illustration of a clusters of closed dodecahedra. The gap illustrated can propagate throughout the cluster as it increases in size.

Whilst this error could cause problems if allowed to propagate throughout the system, it could also be used to aid in dealing with randomness, particularly when considering packing efficiency. In the Kilobot project, the author indicated that it is possible for the same number of agents to self-organise into the same shape but have different packing order each time (Rubenstein *et al.* 2014). There is no obvious disadvantage to this behaviour and it demonstrates that the system is flexible and capable of coping with uncertainty. It is reminiscent of biological systems that demonstrate an overall pattern but when this pattern is magnified, highlights the wide variety and seeming randomness from which it is constructed, e.g. ants being swirled in a beaker (GeoBeats News 2015). Even though it is counter intuitive to the desire of maintaining maximum control, the margin of uncertainty that randomness contributes to self-assembling
systems may be worthwhile embracing, especially when such a system is required to be autonomous.

The potential exists in the Dod design, to regulate this fitting error, to an extent, through the shape and mechanism of the extending arms. This is evident in the interactions between Dods: A) the facet-on-facet connection, B) facet rotation and C) circuit breakdown. These errors to an extent relate to the affordance of the physical design of the Dod. The project inFORM described in Chapter 2 highlights the need for creating vocabulary with respect to haptic affordances (Leithinger and Ishii 2010, Follmer et al. 2013). Like many biological systems there is a chink in the armour of every organism which enables food-chains to exist in a continuously shifting balance. Rather than seeing the error as a flaw in the design, it is possible to use the error as a means to enable a different type of behaviour.

5.5.2 Facet-on-facet connections
Using the cube as a control or reference point, in order to build stable structures, it is necessary that each facet connects to another facet. Corner-to- or edge-to-facet connection create unstable connections and if this propagates through a design it can potentially create weak links. Whilst the 90° dihedral angle of the cube makes it vulnerable to vertical & horizontal shearing forces, once it is built by overlapping a percentage of the surface area, cubes can create a wide variety of stable structures. Even though in this configuration each cube would support two others, the area upon which another cube can rest is halved. The concept of the square shape and in turn the cube, is familiar, widely used and researched and therefore it is relatively well understood. The pixel is an important aspect of image technology, computer games such as Minecraft utilise the cube as a fundamental building block. It is however also a good indicator of what a curve-less world would look like (as is Lego®). The cube is attainable to manipulate both physically and digitally because the geometric planes upon which it operates are not as intricate.

In contrast, the dodecahedron adds complexity by the addition of 6 extra facets but also its semi-spherical nature. In a comparative study between the plantonic solids, regarding packing efficiency, dodecahedrons came second to icosahedrons (Teich et al. 2016). This is supportive of the bridging role that the dodecahedron shape fulfils.
There is no bias towards one geometrical extreme, i.e. straight line versus curved geometries. The dodecahedron has an advantage with respect to a greater probability of withstanding or deflecting shearing forces because of the slant of the facets at a dihedral angle of 116.56°. In its rounded form overlap is an intrinsic aspect of its shape, despite it not being as clearly defined as with the cube. It semi-spherical nature lends itself to dome constructions, which proven by Buckminster appears to be the more efficient and stable method of construction (Fuller 1975, Sieden 1989). He demonstrated that tension and pressure is spread evenly through a dome structure which enables it to endure longer than traditionally built buildings based on 90° angles. Like the cube, corner-to- or edge-to-facet connections are also not desirable however, the design of the extending arms lend themselves to guiding other extended arms or accepting retracted arm positions. For example, in the situation where 1 arm is retracted and surrounded by 5 extended arms, a spacial, conical funnel is created focusing inward (decreasing in diameter) towards the retracted arm. This configuration acts like a crater or cradle that can help straighten and guide the extended arm of another Dod or contain a closed Dod, Figure 5.7.

A method of reducing this error is through the facet function: either through the physical connection mechanism or by sensor feedback which is linked to the extensional rotation of the arm. Facet functions will be discussed further in Chapter 6.

**5.5.3 Facet rotation**

This type of error is related to the facet-to-facet connection. If two facets from separate agents are connected but misaligned by 90° this could lead to weak links and disrupted structures where these connections should ideally be flush and properly aligned. With the Dod design the rotation of the arm itself lends itself to coping better with this type of error. Similar to the example above, the configurations described create lock-and-
5. Dod Behaviour

key situations where the orientation of each Dod does not have as strong an influence. The crater configuration allows sufficient space so that the locking or extending arm does not interfere with the other extended or retracted arms. In relation to a cluster of Dods, a slight facet misalignment would also be corrected by the connection of other arms to surrounding Dod\textsuperscript{27}.

The dodecahedron’s facet is based on the pentagon and the angle of misalignment is naturally smaller than that of a cube, which again is an advantageous quality inherent in its shape. The square face of a cube must rotate 90° until the current vertex fills the next vertex position, whereas the pentagon must only rotate 76.6° to complete the same action. The inverted frustum design of the extending arms also assists in reducing interference, such as snagging, between active facets due to its shape and placement. This error like the facet-to-facet connection error can be reduced through the capacity of facet functions, such as attachment mechanisms

5.5.4 Circuit Breakdown

This error is in relation to when the computational mechanism of the Dod should malfunction or reach the end of its lifespan. Butera envisioned a paintable computer by which a person could technologically enhance any surface and increase or decrease the computing capacity by simply adding or removing more paint (Butera 2002). This incorporates dealing with a percentage of particles that break down, stop functioning after a time, etc. Since it is not possible to extract the individual broken particles it may be more efficient to make use of them through their psychical design, which is the last element of usability remaining.

The versatility of Dod, enriched by the extending arms, is advantageous in the consideration of reusability and material management. Taking the example of creating a straight line with three Dods it is possible to encounter three states: both arm retracted, extended and one retracted / one extended, see Figure 5.8. This also aids in creating different lengths of lines.

\textsuperscript{27} In this instance, an example of stigmergy defining the behavioural condition of a Dod.
5.5 Error

![Figure 5.8 Arm configurations](image)

If a Dod should break and no longer have the capacity to extend arms then it is still possible for the broken Dod to be part of the line link. Using the error of a broken or malfunctioning agent and turning it into an advantage is a relatively rare quality in nature as it inherently requires intent and perspective, i.e. approaching a problem from alternative angles. Whilst certain animals (crows, octopi, etc) have demonstrated problem solving abilities, applying these strategies and creating a new solution involves a degree of creativity. In the case of the Dod, the error of breaking down is offset by the affordance of its shape, e.g. if the arm extension mechanism no longer functions its facet functions may still be used, in a sensory or constructional capacity. Whilst facet functionality may not be unique to the dodecahedron, the facet functions may also be applied a cube, the extension of the arms enables a greater variety of shapes to be created and thereby provides more potential affordances.

Generally, error is considered to be unacceptable predominantly because it introduces an element of unpredictability. The error described in this section relates to physical attributes of the design itself (pentagon facet, configurations created via extending arms, etc). Each Dod design that emerges aims to fulfil a specific need or research requirement but also deals with the errors that arise from the design. It is important to reiterate that some errors are final and non-negotiable. However, by designing a system to be adaptable and capable of dealing with uncertainty is an approach that reduces the impact of the less extreme errors.

The margin of error is a guideline by which the results or behaviour of a system can be measured. If this margin is too large it indicates that the results are inaccurate and that the system is highly unpredictable. However, if the margin is moderate, i.e. like
the optimum nature of the dodecahedrons dihedral angle, then it can also be interpreted as having an element of flexibility within the system, as is demonstrated in the Zooids project. Whilst randomness adds an element of unpredictability into the system it also contributes to the robustness of the overall system because the agents are capable of finding different paths to complete the final goal: flexibility and adaptability. In future, constructive error may be used as an indicator of the creativity within a system.

A design that is too focused on fulfilling one particular task may inevitably fall prey to the fallacy of bastardization. Designers and researchers engaging with user centred design methodology often encounter the fact that users don’t always use the product in the manner for which it is designed or intended.
6. Discussion

6.1 Introduction
This chapter brings together the contributions this study has made to the field of interactive interface design. Concepts such as energy, flexibility, adaptability, scalability, communication, application, shape-shifting, etc have defined the core of this domain. Designing these types of interfaces requires a multidisciplinary approach. Through this approach it is possible to find inspiration and use existing systems to adapt them for new uses. Recalling the concept of emulation rather than replication from Chapter 1 it has been important to maintain this guideline throughout the design process. Whilst it is possible to use existing mechanisms and structures it would be better to define the essence of what that mechanism does and find alternative solutions that are possibly better suited to a new system.

In the domain of shape-shifting interfaces or programmable matter an interesting challenge that arises is bridging the gap between imagination and reality. Throughout this study research has not only included existing systems and prototypes but has also considered similar systems that can only exist through pen and paper. The latter systems are an important counterbalance to question research that has begun to focus or isolate and then specialise on specific issues such as communication, physical design, behaviour, etc. This method is not uncommon: in medicine, it is advised not to have a diagnosis without a differential diagnosis. Parameters that these imaginative systems contribute to research are aesthetics, fun, new applications and interaction styles and an alternative perspective. The importance of these parameters is their unboundedness to reality and the laws that govern it. The majority of adults lose the ability to imagine without limits therefore subjects incorporated by the arts are important to maintain a flow of creativity, even in science. The design of the Dod and the research supporting it are inherently rooted in this gap between disciplines, being
influenced by reality, conceptualised through art and explored and supported through science.

It is an example of the interplay between inductive and deductive reasoning and how the equal application of both methods is essential in defining certainty. As mentioned in Chapter 3, section 3.1.1 intuition is an integral element of the artistic methodology. Art provides the scope and space for a person to work on and implement this sensation, and as a result inductive reasoning comes more naturally in this field. The premises are defined by observation rather than factual theory. They help inform the hypothesis and theories that can eventually be tested further through deductive reasoning. For example, in section 6.6, comparisons are made to a project that avails of similar mechanical structures (e.g. extending prismatic arm) and mechanisms (e.g. origami). For the purposes of this study, i.e. creating a blueprint as opposed to a high-fidelity prototype, it was inferred that if such a peer-reviewed and published project was accepted by the general academic community, then the design proposed in this study, which has similar features, has the potential to be a viable alternative to existing man-made agent designs. The inference in this instance, has generated a valid hypothesis that is the basis for being subject to deductive reasoning in order to determine the validity and truth of the hypothesis. Generating these hypotheses is an important contribution of this study. They demonstrate the need to consider art and the STEM subjects as inseparable. The fact that the process of interchanging inductive and deductive reasoning is as evident in art as it is in science is also supportive of this consideration. It is clear that both of these styles of reasoning come naturally, depending on context, because they accommodate two aspects of human nature: creativity and logic. Once a theory has been postulated through the observation of certain behaviours, it becomes necessary to deduce the truth of that theory.

The prototypes created throughout this study have encouraged a greater emphasis on haptic exploration of the material as opposed to using a purely intellectual or visual based method. This is an important approach because as this study aimed to contribute to the design of interactive interfaces in a tangible user interface domain, it is important to consider haptics as a core property. Parameters such as texture, weight, force, etc are nearly incorporated by default which makes the design more natural and intuitively orientated towards a user’s sense of touch. The most interesting quality of the haptic
sense which has also been a guiding element in the design process is the ability to sense bi-directionally: this means a person can receive information (temperature, pressure, shape, force, etc) about an object (sensing) and can then exert a force or action on that object (reaction) using the same mechanism that was used for sensing. The other senses, vision, hearing tasting, etc, do not have the ability to alter the state of what has been sensed. The most beautiful part of this sensing process is the tool that has developed to make this process literally considered child’s play (see Chapter 1) and that is the human body. The speed at which sensing, perception and action occurs, the ability to filter information and to recombine information from other sensory inputs are just some elements which highlight what a tangible interactive interface, particularly one based on MAS, swarm or hive computing, must be able to cope with. It is the authors belief that with the current state of technology it is impossible to surpass the biological mechanisms and that any attempts to replicate these mechanisms should be purely considered for understanding and gaining knowledge about the mechanism itself.

The reoccurring issues in existing literature that provided a focus for the Dod design are A) scalability, B) the ability to shape-shift, C) haptic sensation, D) to self-assemble and dis-assemble and E) complexity through simplicity. The findings from the exploration into these concepts will be detailed in the following sections and based on these results it is possible to propose that the Dod represents a potential improvement on some of the existing and most current designs. As is the nature of multidisciplinary research, there are usually several strands of research occurring simultaneously, nevertheless the presentation of the findings are as sequentially as possible, with each section defining how design choices were explored and progressed. Section 1 addresses the ability of the Dod design to be scaled appropriately whilst still maintaining structural integrity, and section 2 explores an alternative attachment mechanism to magnets. In evaluating the suitability of the dodecahedron as a basis for the Dod’s physical design, section 3 studies and compares the remaining platonic solids with the addition of the extending arm mechanism. Section 4 details the observations made through the artistic exploration of Dod renderings exploring materiality, functionality, aesthetics and haptic qualities resulting thereof. Section 5 is another comparison of the most recent and published work regarding metamaterials.
6. Discussion

using a combination of geometric polyhedrons and origami. This comparison is important to validate specific design choices made for the Dod despite not actually creating a fully functioning prototype. The last section explores the Dods ability for motion and an attempt to demonstrate the behaviours that are envisioned for the Dod as described in Chapter 5. This study was carried out via a computer simulation resulting in videos that provide a visual demonstration of Dod crossing irregular terrain and moving in a forward rotatory motion via the arm extensions, see supplementary material 4 - 7.

6.2 Scalability

This is a recurring concept that is envisioned for the majority of MAS systems but which is still very difficult to implement. Projects such as Bergbreiter’s rocket powered microbots (Bergbreiter 2014), and DARPA’s magnetic origami tugers (International 2014, Christensen et al. 2015) demonstrate how various mechanisms and materials can be scaled to the desired microscale. The problem with adapting human-made mechanisms into the realm of what nature is capable of (2mm Pharaoh ant and the Cyclophora albipunctata capable of repetitive acute angles (Wagner 2005)), is to a large extent the inflexibility of material. Smart polymers and 3D printing are advances that may enable microbots to be constructed from materials that are more durable and still provide the performance required. Since certain mechanical constructs are not suitable when reduced in scale, e.g. joints, gears, switches, it was important to consider designs which yielded the same effect but were better able to cope with the stress and strain of repetitive use.

Scaling to the micro domain also allows for design ideas to be gathered from the other end of the spectrum: nanoscale. For example, in the study of platonic solids regarding packing efficiency, Teich highlights that, in the domain of nanoparticle growth, faceted geometries have advantages over the completely smooth or spherical geometries with respect to thermodynamic properties (Teich et al. 2016). Exploring how nanobots are envisioned to function in the medical domain, particularly for targeted drug delivery systems, provides valuable insights (Leong et al. 2009, Breger et al. 2015, Ghosh et

28 It is possible to reproduce such mechanism on the nanoscale but it is questionable whether they provide the same efficiency as their macro sized counterparts.
6.2 Scalability

*al. 2017*) regarding design. Research into this field brought the study back full circle regarding the initial concept of man-made particles interacting with naturally occurring particles in liquid environment (i.e. from cells to Non-Newtonian fluids).

Despite the originally described design having movable arms that can extend, the Dod used in the exploration process is a rigid prototype printed in PLA. The primary question from this exploration was whether it was possible to maintain structural integrity and shape accuracy. This includes the outer facet structure and the arm structure both in a twisted and extended state. At a scale of 15% of the current prototype structural cohesion was no longer maintainable, see Figure 4.15 in Chapter 4, section 4.3.1. Whilst it is possible to generate surfaces or materials of one atom in thickness (e.g. graphene) it must be applicable for the context and application required.

Chapter 4 describes how the previous iterations of the Dod could easily be scaled to 2mm in diameter, see Chapter 4, section 4.2.2 and section 4.2.3. There was little functionality, only that provided by the physical affordances inherent to the dodecahedron itself. Once the Dod design was established, it was similarly tested and was scaled to 50% of the original size, see Figure 4.14 (Chapter 4, section 4.3.1). One set of prints attempted to maintain the simulated assembling behaviour and was therefore scaled to fit around a single 3mm ball magnet which is contained in the centre of each facet. The retracted Dod is 11mm in diameter and the expanded Dod is 17mm in diameter. These prints were produced using the Ulitmaker 2 and were of an acceptable resolution. The final prints of the Dod were produced using the Form1 resin printer as it was possible to achieve a higher resolution and accuracy. In this instance, it was deemed sufficient to print a Dod in either extremes (all arms in and all arms out) since the other configurations would only be variants of these two extremes. This was the limit of reduction that this design could endure using 3D printing as a production method. If the scale is reduced further structural integrity and resolution suffers greatly. The retracted Dod measures 5mm in diameter and the expanded Dod is 8mm in diameter, Figure 4.15a and 4.15b in Chapter 4, section 4.3.1.

Printing these prototypes has demonstrated that the design, even with the extendable arms, is suitable to being scaled down. The question of how the functionality is maintained needs further investigation. Considering the possibility of micro-origami, it may be possible that even the spring mechanism proposed in Chapter 4 is feasible.
The current state of technology prevents projects such as rock pebbles (Gilpin et al. 2010), Cubli (Gajamohan et al. 2012), Proteo (Bojinov et al. 2002), Cubimorph (Roudaut et al. 2016), Termes (Petersen et al. 2014), etc. from reducing further in scale than their current description. Considering the hardware required to imbue an agent with the intelligence required to fulfil the tasks mentioned or imagined throughout this study and in related work, reducing the scale of an agent is currently limited. With the advances in 3D printing and the medical sciences a viable alternative for future construction materials is biological matter: instead of being made, a Dod could potentially be grown, see Chapter 7.

The following section explores an alternative attachment mechanism to ease the process of self-assembly and dis-assembly.

### 6.3 Gecko

In the current prototypes, the Dod utilised 3mm ball magnets in each facet to simulate the attachment mechanism. While dynamic self-assembly is achieved through an aware communication process, the magnets provide a visual aid in illustrating this process. The disadvantage of magnets is the uni-directionality of the force, i.e. they assemble with ease but sometimes require forcible separation by an external force. Alternative mechanisms were considered such as polymagnets (see, Chapter 7) and Gekko tape. The criteria that had to be considered were the A) surface area available (would reduce when scaled), B) easy to attach to, C) easy to detach from and D) robustness with respect to stability of attachment and reusability of the sticking components. The Velcro effect, suction and capillary action were methods also considered. Whilst these techniques did not fulfil all the required criteria it inspired the use of Gekko tape which is similar to the concept of Velcro with the combination of suction (Binderband 2016), Figure 6.1.
Geckos are extremely efficient and skilled climbers and can stick to hydrophilic and hydrophobic surfaces, of various topologies and materials. Gekko tape technology is inspired by this ability but also by the fact that a Gecko can support its own bodyweight in any orientation and release this strong grip in an instant. Geckos achieve this grip as a result of the accumulative force of numerous small components acting together as a whole (Chen 2015). There are two main components to this mechanism: the external forces (van der Waal forces) and the internal design (the structure of the gecko’s feet). The gecko has 5 spade-shaped toes on each foot. Each toe is covered in millions of Nano-hairs called setae (10 micron in length, 5 microns in diameter) in the formation similar to overlapping scales, lamellae. At the end of each hair are 100-1000 triangular-shaped spatulae (200nm at the widest point) (Autumn and Peattie 2002, Dickerson 2014) and the entire structure is made of β-keratin.

In conjunction with biological design, intermolecular forces play a critical role. The most prominent of these forces is the van der Waal force, which is an electric force. It describes how molecules are temporarily polarized creating momentary dipoles that exhibit attractive and repulsive forces. This occurs between the spatulae and the surface. In isolation, van der Waal forces are very weak. It requires numerous occurrences of this force to generate an attachment force strong enough to hold more than the body weight of an average gecko (approx. 70g). It is the biological design of the branching spatula from each seta that provides the increased surface area, which increases the van der Waal effect. The ability of geckos to stick to hydrophilic surfaces is dependent on the higher humidity levels, reducing the elastic modulus of the setae thereby making them softer and more pliable.
The ability for rapid attachment and detachment is due to the positioning of these setae and the orientation of the spatulae. The setae are parallel to each other but are angled in relation to the toe itself. Therefore, to activate adhesion requires the setae to be pushed downward, perpendicular to the surface and then dragged slightly backwards in parallel to the surface (Autumn and Peattie 2002).

The resulting adhesive product that is tested in this study was Gecko® Nanoplast®. It is approx. 0.34mm thick and has 29,000 gripping elements per cm² (Binderband 2016). It is said to work very well on smooth surfaces and is not affected by moisture. It has the advantage that it can be pressed together with relative ease, held in place firmly, but released with a slight rotational force. It also works when taped to itself, therefore it is possible to maintain the maximum usability for each Dod facet.

Comparative tests were carried out regarding the attachment ability of the Gekko tape versus the ball magnets. Three Dods were used in each instance, white, red, and yellow and were connected at points where both arms of each Dod were extended to exert the maximum leverage force on the connected facets. Throughout the testing the order of the Dods 2 (red) and 3 (yellow) changed while Dod 1 (white) remained constant. Three Dods were used because both magnet and Gekko tape were successfully able to maintain the connection between two Dods throughout a 360deg rotation. The Dods used in both instances were printed from PLA and have the same dimensions. The magnetic Dods had the magnets inset into the facet of each extended arm and each weigh approx. 9g (white Dod), 7g (red Dod), 6g (yellow Dod) and the Gekko Dods were printed at 30% fill density, with the Gekko tape adhered to the facets of the Dods each weighing approx. 8g (white Dod), 5g (red Dod), 5g (yellow Dod).

### 6.3.1 Observations

The Gekko tape is better suited to sticking objects to smooth surfaces such as glass or computer displays (see Figure 6.2). Whilst it can attach to itself, a comfortable range is 2 Dods, Figure 6.1.

When three or more Dods were configured to create a long line and then tilted to a position of unstable equilibrium under the force of gravity, the connection usually failed between Dod 1 and 2. The connection was unable to take the added weight and
the shearing forces became greater than the adhesion force of the Gekko tape. The equivalent magnetic Dods experienced the same behaviour, however, the breakage point would occur in places where magnetic interference created a weaker zone.

In the tests with three Dods 5 attempts were carried out for the tape and magnets. The Gekko tape could hold the connection to an approx. average of 29.16deg from the perpendicular, before the weight of each Dod and the shearing forces caused it to disconnect, see Table 4. This frequently occurred between Dod 1 and Dod 2 (regardless of which Dod was occupying this position, i.e. red or yellow Dod.). Very little force was required to connect two Dods to each other which has the advantage that the disconnection, and thereby the disassembly, process is easily accommodated. With Gekko tape the Dods would have the added capability of building up along smooth containers using the boundaries as a building aid. It would enable a collective of Dods to build structures using themselves and the support provided by boundary of the container. In contrast, the magnetic Dod would only be able to use themselves to build structures, regarding a container as a confining element or a non-contributory boundary condition, rather than a constructive factor 29.

![Figure 6.2 Tape strength](image)

Figure 6.2 Tape strength - Dods sticking to a computer screen (single Dod: white and two together: yellow and red).

The ball magnets provided a better connection along three Dods, in some instances being able to maintain the connection for a full 360deg rotation. However, this is directly dependent on the orientation of each ball magnet. If all the ball magnets achieve the correct polar orientation, the connection is secure and stable. If the magnet’s polar orientation is not favourable (e.g. the ball magnet is not free to rotate) it leads to weak links and breakages on average around 65.18deg angles from the

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29 Unless of course the container has magnetic qualities.
perpendicular, due to magnetic interference, see Table 5. The primary difference between the Gekko tape and magnets is consistency. It is difficult to clearly determine, in this design, if a magnetic connection will be stable. With the Gekko tape a consistent and repeatable connection is established between two Dods, see supplementary material 2: *Gekko Tape Test.*

<table>
<thead>
<tr>
<th>Attempt</th>
<th>Gekko Tape</th>
<th>Ball Magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attempt 1</td>
<td>34.0°</td>
<td>90.0°</td>
</tr>
<tr>
<td>Attempt 2</td>
<td>29.5°</td>
<td>60.5°</td>
</tr>
<tr>
<td>Attempt 3</td>
<td>14.0°</td>
<td>66.0°</td>
</tr>
<tr>
<td>Attempt 4</td>
<td>25.8°</td>
<td>40.4°</td>
</tr>
<tr>
<td>Attempt 5</td>
<td>42.0°</td>
<td>69.0°</td>
</tr>
<tr>
<td>Average</td>
<td>29.2°</td>
<td>65.2°</td>
</tr>
</tbody>
</table>

*Table 6 Gekko tape comparison* - The results for each attempt of both tape and magnet Dods.

The next study carried out on the Dod relates to the dodecahedron itself and the use of the arm extension mechanism. The remaining platonic solids were compared and examined regarding their ability to create similar or potentially better structures.

### 6.4 Comparison of Platonic Solids

There are five platonic solids, tetrahedron, octahedron, cube, dodecahedron and the icosahedron. These solids are regular convex polygons in which symmetry of the angles and edge length is uniform throughout. Three of these solids are unique in that they are based on a single 2D primitive (triangle, square and pentagon) whereas the other two solids are comprised of a combination of two 2D primitives. The tetrahedron is based on an equilateral triangle, the cube is based on a square and the dodecahedron is based on the pentagon. Each edge of the shapes is attached to the edge of another shape until the 3D polyhedron is completed.

The octahedron’s centre is square with two equilateral triangles connected to each edge of the square. The triangles form two square pyramids on either plane of the square. The icosahedron is based on two pentagons separated by a band of connected
equilateral triangles. Triangles are connected to the edges of the pentagon that connect to form a five-sided pyramid.

In past studies, the cube and rhombic dodecahedron have been chosen as agents for multiagent systems to embody specific behavioural attributes, i.e. simplicity of design but predominantly because of their ability to assemble and move independently. In order to further explore the validity of the dodecahedron as a design base, a comparison study was completed between the platonic solids but with the added application of the extending arm mechanism.

- The cube is suitable for definite structures, clear and easy assembly and is a natural choice in the concept of building blocks\(^{30}\). It is accessible for coding behaviour due to its resemblance of a 3D pixel, and that its facets can be more easily described using the x-y, y-z, and x-z planes, in contrast to the other platonic solids. The dihedral angle is 90°, which gives the cube a unique ability to exist in higher dimensions and is an indicator that the cube also copes well with additive as well as potential fractal construction methods. The cube is not efficient in creating curves – it would require a high resolution to achieve the appearance of a curve and it cannot withstand large shearing forces due to its vertical facets and resulting assembly method. As the cube is reduced in size this surface area is also reduced providing less area and resistance.

- The rhombic dodecahedron (RD) was primarily chosen for its improved degree of rotation 120° (dihedral angle); in comparison to the cube (180°) i.e. it requires a shorter turn in order to present the original symmetry. It has twelve facets and is a Catalan solid indicating that it is based on an irregular 2D primitive, in this instance a rhombus.

These two geometric shapes were and are currently still being explored with respect to creating a multiagent self-assembling system (Roudaut et al. 2016). Each concept has attempted to make every facet of the structure capable of attaching to the facet of another. Magnetic attachment is still the most common form of achieving this effect. The rhombic dodecahedron presents a greater complexity in comparison to the cube

\(^{30}\) It is interesting to consider that had building been based on concepts such as the geodesic dome it may be possible that the basic building block shape would be completely different, e.g. triangular or spherical, etc.
because it has 12 facets as opposed to the 6 facets of the cube. The aim of this comparison study is to highlight why the Dodecahedron may be the better design choice on which to base a multiagent system.

6.4.1 Testing parameters

The natural stability and equilibrium of each solid is when it rests on an entire facet. The following tasks are explained and the comparison between each solid is illustrated in Table 5. 3D paper prototypes were created to analyse the tasks and the suitability of each solid with the added arm extension mechanism.

- **Edge Support**: this is to check for stability when the resting face or root position is retracted and the surrounding arms are extended – the agents rest on the edges of the extended arms.

- **Form configurations**: the ability to create clusters that contribute to overall structural integrity. The capacity to form a variety of configurations aims to enable the agent to build in specific directions as well as different shapes. It also enables the agent to adapt to its surroundings and other agents. The configurations emerge as a result of the interaction between two or more agents and are defined as functional when the potential extension or retraction of arms does not interfere with each other, e.g. configurations ideally result in facet to facet connection not facet to arm, etc.

- **Form a straight or curved line**: It is important for an agent to be adaptable in order to build either of these fundamental structures. This is where emulation rather than replication is applied. The agents designed to date can currently only do one or the other.

- **Build upon a flat or irregular surface**: Similar to the previous condition, being able to adapt to the environment is crucial for such an interface. Current technology requires specific environmental conditions. Machines like laptops and tablets are an attempt not to be strictly confined to specific locations and setups.

- **Same shape via alternative configurations**: Adaptability is again a key consideration. In this instance, it is important to consider the possibility of agent failure or disruption. For example, if only 1 or 2 arms no longer extend /
6.4 Comparison of Platonic Solids

retract it should still be possible for the agent to function. This attitude to technology ensures that its re-usability potential is increased and that, even if a component is not working at full capacity, it can still be used before being discarded.

- **Agent locomotion mechanism through the arm mechanism**: the ability to move is important whether the agent is contained in a transport medium or not. Whilst the key object is not for the agents to travel distances it is important to incorporate a sense of mobility, to be able to manoeuvre or rearrange according to requirement.

Another interesting quality that arose in the exploration and comparison of these structures is the formation of flat, concave or convex craters via specific arm configurations\(^{31}\). This indicates that whilst the other platonic solids can combine and assemble to each other, they cannot necessarily create workable (practical) or usable craters. As illustrated in Chapter 5 the Dod creates concave craters in its cluster state: the central vertex of the crater lies below the outer vertices and tending towards the centre of the structure.

### 6.4.2 Observations

In the case of the tetrahedron, this solid can combine with other tetrahedrons without creating a gap. However, because of its shape and dihedral angle, when the arms extend they do not create viable craters. They form convex craters, i.e. the centre vertex is higher than the outer vertices and tends away from the centre. This solid is similar to the cube and would be better used in its original unaltered state (no arm mechanism).

The octahedron faces similar challenges to the tetrahedron as it is based on equilateral triangles. It can form both convex and concave craters due to its centre being based on a square. It is limited in the number of usable craters that can be formed because when the arms are extended interference occurs due to the larger outer facets.

The cube creates flat configurations because each facet is perpendicular to the other. The arm extensions are not of significant use because they would not interact or meet

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\(^{31}\) *When two or more agents cluster together, depending on the arm configurations, craters are made that can accept further agents in order to build up a structure, see Chapter 5, section 5.4.*
each other unless facet-to-facet contact is being made. The cube can fit perfectly with other cubes without generating gaps however when the arm mechanism is applied and is in an extended position the probability of facet to arm connections are greatly increased because the distance or space between arms is too large. This is due to the fact that the cube has 6 faces and when arms extend, they spread too far apart. To prevent this type of connection would require the outer facets to become larger. This would be that the inner core would stay quite small in relation to the outer cube that is created via the outer facets and there would be a greater volume of unused space inside the structure.

The icosahedron is closer to the dodecahedron by the shared semi-spherical nature and used of the pentagon as a 2D primitive. However, the larger dihedral angle of 138.19° means that when the arms extend there is again interference of the outer facets but also the crater into which another icosahedron could fit is too small.

Table 6 presents an overview of this information. The orange/thin ticks represent the ability to complete the task but with significant instability or specific usability restrictions. For example, curved lines formed by a tetrahedron or octahedron will curve through all the planes depending on direction, i.e. it is not possible to build a curved along a static 2D plane combination (e.g. x / y plane). Another example is the ability to initiate movement via arm extension. The dodecahedron and icosahedron excel at this task because of their semi-spherical nature, due to the increase in resolution of combined edges. In contrast, the triangle and square do not lend itself to this type of motion.
6.4 Comparison of Platonic Solids

<table>
<thead>
<tr>
<th></th>
<th>Tetrahedron</th>
<th>Cube</th>
<th>Octahedron</th>
<th>Dodecahedron</th>
<th>Icosahedron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Edge Support</strong></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Form configurations</strong></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✔</td>
<td>X</td>
</tr>
<tr>
<td><strong>Form a straight line</strong></td>
<td>X</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Form a curved line</strong></td>
<td>✔</td>
<td>X</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Flat surface</strong></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Irregular surface</strong></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Same shape, alternative extension</strong></td>
<td>X</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Rotational motion through arms</strong></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Table 7 Platonic solid comparison - A comparison of the platonic solids according to an extending arm mechanism.

Unlike the cube or tetrahedron the dodecahedron does not completely fill the space when forming a cluster (see Chapter 5). This gap can propagate through the structure and increases with the addition of more dodecahedrons and may be viewed as a fault. It is argued in this study that instead of regarding this quality as a fault it may be the element that provides the optimal degree of unpredictability necessary for the structural aspect of self-assembly. The dodecahedron’s dihedral angle ensures that the configurations are optimally angled to avoid facet interference and most reliably generate craters into which other dodecahedrons can fit into. Although the complexity of programming twelve facets as opposed to six is an element of consideration, from a design perspective the dodecahedron is an optimum starting point in the domain of using polyhedrons as a basis for agent design in a MAS, more so than the cube.
Following this exploration of structure, the next section explores the Dods functionality from an artistic perspective in which material, form and structure are varied.

6.5 Artworks
The artistic renderings of the Dod are an important part of the haptic exploration of shape and form regarding the Dod’s design. The most valuable contribution these artworks made to the study is the possibility to imagine new interaction methods, functionalities and applications beyond the lab setting. It brings the concept of an agent into the public realm with the potential to spark further inspiration. Making complex concept accessible to the public allows ideas to spread further and reach a wider audience, thereby also potentially preparing the market for the uptake of new ideas. Each artwork evolved with the current research and contributed important knowledge to the study. The following observations are a result of direct handling of materials and construction of the artworks. The concept of structural cohesion emerged as the underlying design consideration and is addressed in various methods throughout all the artistic prototypes. It is an important aspect particularly considering that the Dod’s design is based on the ability to extend all or some of its arms but also because it is environment and context dependant. For example if a Dod is to be used in space it may be constructed from ceramics, or special fabrics designed to be lightweight, heat-resistant, etc (Landau 2017) or if it is used in liquids it can potentially use the liquid as a power source and use its arms as manoeuvring or sensing aids (Parmar et al. 2016, Vilela et al. 2017).

6.5.1 Steampunk Dod
For a full description of the artwork see Chapter 4: section 4.4.1. The spiral is used as the main decorative element in this instance. It is physically reflected in the final design of the Dod through the twisting nature of the arm extension as it rotates through 3dimensional space as well as being used in the adaptive facet allocation algorithms in the Dod’s behavioural coding. The spiral is a naturally occurring structure and it represents a strong link between aesthetics and mathematics. It can also contain
potential energy in the form of a spring and has proven to be a diverse and adaptable structure.

The textures of each layer vary depending on their fabrication method: twisted wire is smooth and cool, the crocheted layer is coarse but fragile and delicate, and the embossed layer is smooth, heavy and solid. The information contained in texture is rich and largely underutilised especially in the majority of user interfaces even though the potential for new and intriguing materials is expanding due to the research into materials science (Wang et al. 2013). Texture is a useful and easily applicable haptic quality and its diverse range can be used to represent various states particularly in relation to haptic experiences. These can be linked to emotional responses, e.g. sharp, needle-like texture is associated with pain or caution, whereas soft and furry is soothing and comforting.

The inner two dodecahedrons are held in place via suspension, each being linked in series. This concept is similar to the final design in that the dodecahedron is self-repeating in a fractal nature but contained within itself. Translating this to a potential adaptation of the Dod’s design may include suspending the inner core through magnetism. The outer plates would seem to be suspended a distance away from the inner core and could be slightly depressed by the user. This could provide a unique approach to haptic interaction; experiencing a force that is not visible and can only be felt (Lee et al. 2011). In this type of design, force feedback would be a valuable quality and it would ultimately embody the bidirectional nature of the haptic sense.

**6.5.2 Origami Dod**

For a full description of the artwork see Chapter 4: section 4.4.2. This artwork is made of paper and as origami has been a vital part of this study it was useful to explore other aspects of paper and the forms of manipulation that are available. The fragility of paper is often transformed by the art of origami which simply involves folding techniques. It is possible to alter the method of manipulation to achieve different effects, e.g. strength and /or functionality through layering. This type of layering is common but not limited to wearable, smart fabrics (soft sensors, the printing of solar panels and integrated circuits onto fabrics as well as fibre optics integrated into fabrics and conductive inks). This artwork also indicates that certain materials often belie their
true capabilities which emphasises the importance of multi-modal sensing. This is a consideration worth applying to the Dod as an autonomous entity. The material from which a Dod is made may help in establishing a multi-modal functionality like human senses. For example, considering the material aerogel. This material is most often used in space to collect comet dust because of its highly porous nature. It is aesthetically pleasing with a cloud-like appearance, often known as ‘frozen smoke’, and is very brittle. However, it has excellent insulation properties as well as compression strength. A Dod made of this material would be highly sensitive to its particulate environment (sensing or retrieving information) as well as robust and durable, suitable for exploration and / or blending into the environment.

6.5.3 String Dod
For a full description of the artwork see Chapter 4: section 4.4.3. Several interesting insights emerged from this prototype with respect to design considerations relating to the localisation potential of the inner dodecahedron. The outer plates that were sewn together provided a basic shell structure, which aided in determining the retracted length of the acrylic springs. However due to the flexible nature of the overall structure (i.e. the plate flexed slightly in the sewing process due to the minimal thickness and varying tension on the threads on different sides), the height of the retracted arms is varied, i.e. some arms are retracted a little further than others. This meant that although the outer plates maintained the cohesion of the dodecahedron structure, inside some of the springs flexed from their original position. They are no longer exactly perpendicular to the outer facet and the core. The resulting consequence for the overall structure is that the inner dodecahedron has the scope to move, to an extent, within the space created when the outer plates are in the retracted position. Since the Dod is semi-spherical in nature, the core also has the possibility of altering position along any plane required. This type of mechanism enables the Dod to exhibit weighted behaviour, the closest analogy being like a weighted dice. In addition, if the core is constructed from a dense material, it can increase the probability for the Dod to land in a particular orientation. This becomes relevant when defining specific arm configurations. Since only specific arm will be active and the others static, this weighted behaviour will ensure that the Dod can consistently and reliably land in the correct orientation to make
use of these configurations. Weighted behaviour could also influence the assembly mechanism by A) increasing or reducing pressure on specific connection points by creating stronger or weaker connection points according to the applications, and B) help to balance a structure of Dods should it be built upon an irregular surface by lowering the centre of gravity of each Dod causing them to be bottom heavy.

Returning to the concept of structural cohesion, an interesting behaviour that emerged from the materials used in this artwork is the bending and flexing motion of the spring structure and skin design. Even though it is proposed for the Dod to have all arms extending, practicality may be a defining boundary condition. The ability to extend all 12 arms relies on the strength and rigidity of the spring structure as well as the skin material connecting the outer plates to the inner dodecahedron. The combination and relationship between the skin and spring material remains undecided as it is primarily application dependant. For example, a soft, elastic skin and a flexible spring structure enables the Dods structure to become more malleable, like that of an octopus or the domain of soft, squishy robots (Cheng et al. 2014, Galloway et al. 2016, Wehner et al. 2016). In this state, the Dod would be malleable and more adaptive to different sized environments. To achieve a certain level of structural cohesion it is necessary to have a minimum of 6 arms, ideally 7, permanently connected to each other as well as to the inner core. The closed facets would span the circumference of the Dod, see Figure 4.31b in Chapter 4. Having six arms connected ensures that both hemispheres of the dodecahedron are linked, (like peeling an orange in one go). The addition of a 7th arm creates a corner which provides the stability for the Dod’s structure. This configuration is established as providing the Dod with the optimal structural support without interfering with the behavioural abilities of the Dod: forming a line, curve or cluster.

The design of pre-set configurations, i.e. which arms stay retracted or extended, may be explored in future work using evolutionary algorithms (Mitchell et al. 1992, Mitchell 1996). In conjunction with this it may also be possible to determine the optimum structures that can be achieved through that specific set of configurations.

As stated in Chapter 4, the initial concept of the Dod’s design is that all twelve arms can extend. Maintaining this feature despite applying the pre-set configurations with static arms can be accomplished through the assignment of relative arm identifiers in the Dod’s behavioural coding. Each arm has a unique / original identifier that is
hardwired into the inner core, e.g. sensor IDs, depending on the orientation of the Dod it is possible to assign new temporary identifiers to each arm (see Chapter 5). A simple analogy to clarify this concept is that people know the function of their arms (balance) and legs (motion), when walking on a handstand the roles of these appendages temporarily reversed even though their fundamental identifiers remain the same (arm / leg). Whilst it is possible to physically design the Dod to maintain a pre-set configuration so that it can no longer change, the advantage of achieving this state through the behavioural aspect is that a Dod can maintain its flexible and adaptive nature.

In this artwork the origami spring also exhibits an interesting behaviour. The springs are based on an A4 sheet of paper card; however, the full extension is not required. The outer facet rotates twice and delineates the maximum extension height. This process means that there is surplus material in the spring structure itself, i.e. compressions of the spring can occur in different locations, see Figure 6.3.

![Figure 6.3 Spring displacement](image)

*Figure 6.3 Spring displacement* - The varied location of surplus material in the spring is highlighted in the green insets.

In the yellow spring there are two segments fully extended from the top, in the red spring the is only one segment fully extended with the surplus material folded directly underneath. This feature can be potentially advantageous when considering issues such as material strain and wear particularly in the corners of the origami spring. Being able to adjust which segments of the spring are extended could contribute to prolonging the lifespan of the material and the overall agent.
6.5 Artworks

6.5.4 Latch Dod

For a full description of the artwork see Chapter 4, section 4.4.4 In the phase of research considering possible applications of the Dod design, the Latch Dod was the final artwork to emerge. This design demonstrates the potential for the Dod design, when the arm and spring structures are rigid. Depending on the requirement, the design itself is flexible enough to accommodate a variety of different arm configurations but it does not exhibit bending or flexing behaviour as seen in the previous Dod-work. In this design, the spring structure itself is the supporting element in the extension mechanism and there is no need for a skin membrane to connect from the outer place to the inner core. This type of Dod would be suitable for creating semi-solid constructs for structural or support purposes as it offers greater resistance. In contrast to soft materials, if the spring structure is strong and rigid, it can be used to create porous or dense structures, like coral. The density of the skin material adds another element of functionality as it may aid in the creation of energy gradients (like in biological systems) or aid the Dod to move within a liquid, etc.

This artwork exhibited an interesting motion-related behaviour before all the outer plates were attached. Before the Latch Dod was completed as envisioned, see Figure 4.34a, it was dropped onto a hard surface. The spring in the latch itself is quite strong therefore it can incur a bouncing behaviour as is evident in the supplementary material 3: Latch Dod Motion. Whilst similar toys already exist (Lanard Toys Ltd. 1994, Chuckle Ball 2016) their appendages are stationary and the bounce or jiggle come from within the spherical ball provided by an internal motor. In the instance of the Dod there is no power source required, i.e. the energy for motion, bounce, topological and form change is provided by the potential energy contained in each of the 12 springs.

When the inner core with the inset latches (all in the retracted position) was dropped, onto a latch, from a height of approximately 10cm the spring of the latch on which the Dod landed extended providing sufficient energy to propel the whole construction up and onto another latch. This essentially initiated a chain reaction causing the Dod to jump around an area until most latches had been activated. This behaviour was still possible when all the outer plates where attached however it was not as accurate a movement and slightly less forceful as the larger area of the outer facet absorbed some of the impact energy.
The insights gained from these artworks are valuable contributions and sources of inspiration for future development of the Dod. The next section is another comparison to the most current development of metamaterials based on geometric polyhedrons and a prismatic extension mechanism. The comparison of an untested design to similar elements of a model / design whose results have been published and accepted is a valid method of determining the viability of the untested design. Whilst it is not a guarantee, it is a step towards proving the probability of success.

6.6 Metamaterials: Proof by comparison

As this study developed, terms like metamaterials or architected materials are being applied to interfaces, surfaces and structures that are made from smaller parts or a juxtaposition of unusual materials, to essentially highlight a new phase of materials for which a specific application is potentially not yet available - materials that are consciously constructed. Despite there being nuances that can determine specific differences or unique attributes to one or the other term, each term encompasses the same general idea. In the same way that MAS usually refers to digital, computer simulated agents rather than physical, 3D entities, hive or swarm computing, and programmable matter are some alternative descriptors that can be used to describe MAS. These nuances are important for discerning alternative approaches or perspectives with respect to design or problem-solving. For this reason, it is important to be aware of the variety of terms that are generated in and around the domain of shape-shifting interactive interfaces, so that it is possible to maintain an overarching awareness for how the domain is developing.

The following section describes the development of a new type of metamaterial which is based on the combination of a variety of polyhedra and the effect of extending specific facets. A program was developed that can run the various combinations and provide simulations of the most successful designs, which in turn could be recreated as a 3D prototype. In this instance, the metamaterial refers to the construct of a future material and not the material from which the prototype is made.

Considering the work done in MIT and Bristol, regarding self-assembling cubes, and the latest work by Overalde, with respect to creating shape-shifting architected materials (Overvelde et al. 2016, Overvelde et al. 2017) positions the Dod firmly in
line with the research being presently pursued. The structures (or interfaces) that the Dod would eventually create would be considered meta- or architected materials. The latest work in architected materials is supportive of some of the features implemented in the design of the Dod, i.e. extruding arms, fixed configurations, and geometric polygons as basis for creating larger macro structures. In conjunction with these factors reviewing the resulting macro structures that emerge from the various agent designs or micro-structures indicate the increasing degree of complexity and richness of solution space for new construction techniques. For example, as mentioned in section 1.3, and 4.4.1 the game Minecraft demonstrates a world consisting of cube assembly, or the dodecahedron being spherical in nature encourages the construction of curved or domed features (Teich et al. 2016).

### 6.6.1 Origami

Through the work published by Overalde it is possible to determine that even though an official mathematical model does not yet exist for the Dod, there is a significant possibility of proving its viability through comparison. Overalde’s work is based on origami, which in recent years has grown as a topic of research interest with respect to its ability to change shape, structure and strength (Cheng et al. 2014, Lv et al. 2014, Silverberg et al. 2014, Reis et al. 2015, Overvelde et al. 2016). There are several characteristics that make this art form very appealing in the robotic and interface domain.

- Changeable surface topology
- Ability to morph shape & form
- Auxetic quality
- Strength transformation through structural rearrangement

There is also an appeal in origami from a material sciences perspective. The materials used in origami can be made to react to heat, water, electricity, etc. as well as dissolve when a task is completed (Christensen et al. 2015). For these reasons, there is substantial interest to use the concepts of origami in the development of medical Nano-bots. An advantage of origami is its ability to exist as micro and macro structures and that its strength, which is material related, remains relative to the size of the structure.
In the most recently published work by Overalde, they demonstrated a mathematical model that allows them to input simple polyhedra and as a result create complex, adaptable metamaterials or architected materials. They reflect the origami inspired quality in that the resulting metamaterials can be folded into several states depending on their physical connectivity and degrees of freedom (DoF). By changing the microstructure (i.e. the simple polyhedra) it is possible to gain a vast scope of reconfigurable macrostructures. Their work also highlights that these architected materials have a greater degree of complexity and it effectively demonstrates the scope of geometric shapes to build a wide variety of new and aesthetically rich structures.

6.6.2 Comparison
The complexities emerge through the configurations and the combinations thereof. The Dod creates configurations through the retraction and extension of specific arms. However, the basic shape remains the same: the pentagon. In contrast, Overalde’s metamaterials are configurations created A) via the combination of polyhedrons (e.g. a tetrahedron attached to a facet of an icosahedron) and B) via the extrusion of specific facets of this ‘new’ structure, i.e. the microstructure. When a microstructure is initially determined, new configurations emerge through the extrusion of specific facets. When the extruded facets are altered, i.e. when different facets extrude from the original microstructure and the number of extruded facets changes; it is possible for new configurations to emerge.

Returning to the microstructure level, if the relative position of the original polyhedrons is altered, this effect will cascade through the levels and creates new sets of configurations. Whilst there is inevitably a certain level of overlap, it demonstrates the vastly increased test space for configuration viability. It also illustrates the scope of configurations that are possible through just two shapes. Whilst the mathematical model developed for this project is capable of analysing the wide range of possible configurations, the degree of complexity is thereby also increased because of the number of variables that affect the system and require consideration.

Similar to the analysis of the platonic solids illustrated in Chapter 5, the number of polyhedral combinations that result in usable and effective architected materials are also defined by core factors such as the dihedral angle, structural cohesion, interference
of extruding facets, etc. Therefore, discovering which configurations are most beneficial will require further study. The main difference between the Dod and the described metamaterials is the basis on which the microstructures function. For example, in the architected materials the microstructure is repeated and each additional microstructure replica is attached to a specific part of the original microstructure, like a tessellation pattern. In this instance the replica must be an exact copy and is limited with respect to the attachment points. In contrast the Dod, as demonstrated throughout the three artworks produced, is a replica of itself within itself, like an infinity mirror. The following conclusions are summarised between the two design approaches

The Metamaterials described by Overalde:

- Based on polyhedra: predominantly the cube, hexagon, tetrahedron and octahedron.
- Extrusion – perpendicular extrusion of facets
- Rigidity – the fixture of specific facets in order to maintain the reconfigurability of the macrostructure.
- Macro-Units ‘grow’ from a microstructure, i.e. replications of the microstructure

The Dod as described in this thesis:

- Based on one polyhedron: the dodecahedron
- Extrusion – a conical extrusion of the facets
- Rigidity – the fixture of specific facets to maintain stability of the agent
- Through self-assembly of multiple agents, macrostructures are created.

### 6.6.3 Bi-stability & changing states

Throughout this study the primary challenge which still exists is that of energy and in particular the question of how to imbue man-made constructions with the ability to process and procure energy independently. This procedure is complicated further by the need to reduce the scale of the components for creating micro or Nano sized robots. Whilst current methods of energy generation on these scales will be discussed further in Chapter 7, this section explores the issue of bi-stability. Bi-stability signifies that there are two states in a dynamic system that can exist alternatively, in equilibrium.
This is an important characteristic of an agent if it is to be part of a system that creates larger structures comprised of many individual parts.

In the work on metamaterials, Overalde describes how these origami based materials are capable of morphing into several different states or configurations and thereby creating new structures (Overvelde et al. 2017). Even though the primary focus of his work are the algorithms that are used to enable a vast variety of polygon based metamaterials to be modelled, the resulting structures provide large scope & potential for creative implementations.

The main issue with these new structures is the manner in which energy must be utilized. Instead of using energy to perform specific functions (e.g. sensing, actuation, motion, etc), a certain amount of energy is required to maintain a change in state. If energy is diverted to complete a fundamental function (i.e. a change of state), it can be argued that the overall structure cannot reach its full potential other than in its initial starting state or configuration, i.e. the original macrostructure created through the replication of the microstructure which is stable. Whilst a system or structure can function in this manner, it is potentially inefficient and self-limiting.

The Dod design can potentially avoid this limitation depending on the final user requirements and construction materials (e.g. a rigid skin & spring material or rigid spring with a flexible skin membrane, etc.) it is possible for the Dod design to provide varying degrees of stability in both retracted and extended configurations. The Latch Dod is in equilibrium in either retracted or extended configuration and furthermore energy is required to achieve a configuration change but not to maintain it.

To reiterate, the design briefs or research questions are very different for both of these projects however if shape-changing structures are the end goal, it is necessary to at least consider possible implementation scenarios. For example, if Overalde’s metamaterials are purely artistic, e.g. a moving sculpture, then the focus is on the change of state and the energy required to temporarily achieve this is the energy’s primary function. In contrast, the change of state in the Dod is aimed to aid it in the construction of larger structures through the interaction with other Dods, e.g. the primary energy use would be in the assembly mechanism.
Another advantage of the Dod design is the potential load bearing capacity even during transition states. If a rigid skin membrane and spring structure are used in conjunction with a control mechanism for the spring structure (e.g. hydraulics, pneumatics, flywheel & torque) it is feasible to propose that the arms can maintain their functionality despite not being fully extended. As discussed in Chapter 4, section 4.4.3, Figure 5.2 and 5.8 demonstrates three different ways in which the Dod could form lines – depending on requirement, the possibility exist for the arms to only partially extend, etc thereby offering options in height variance. The load bearing capacity of the arm is subject to engineering principles of leverage versus length, resistance versus thickness, etc. It is possible to define the optimum balance between these parameters and attune them to the requirements and implementations of the Dods (e.g. whether they will be implemented to construct flexible sponge-like materials or stiff, hard materials).

**6.7 Simulation**

The final stage of exploration focused on implementing some of the behaviour stipulated for the Dod in Chapter 5 as well as exploring the validity of the Dod design being based on the dodecahedron and the mechanism of extending arms in the shape of an inverted pentagonal frustum ending in a large pentagonal facet. Two simulations were created to achieve this (see Appendix E) and due to the nature of the software used for creating the simulation, the Dod is represented in 2D profile. The view of the Dod in this instance also reflects the manner in how the 3D Dod prototypes were printed and assembled: four arms are directly affected, i.e. cut in half (numbered 1, 2, 4, 5 in Figure 6.4a), and two arms are visible but remain unaffected (numbered 3, 6 in Figure 6.4a). The two unaffected arms extended into the Z-plane. The edge length is shorter because it represents the edge of the pentagon shape as opposed to a vertex to edge measurement, seen in number 1.
6. Discussion

Figure 6.4 Simulation Dod – (a) 2D profile of Dod used in the simulations with visible arms numbered 1-6, (b) the slight difference in extension length to represent the planar difference of arms 3 and 6.

The extension into the z-plane has also been accommodated for in the simulation in that these arms do not extend as fully as the four main arms, Figure 6.4b. Whilst the four main arms represent a complete facet connection (plane-to-plane) with the environment, the smaller arms represent an edge connection (edge-to-plane) with the environment. The Dods do not actively communicate with each other and the interactions visible are based solely on a mechanical basis, i.e. how the motion and arm mechanism affects neighbouring agents. Two types of Dods were explored, one with a shorter overall arm extension and one with a longer one, to observe which extension length performed the best over the range of obstacles.

6.7.1 Terrain

The first simulation explores how multiple Dods interact with each other over a varied terrain with gaps. The design of the arm ensured that accidental snagging with other agents was greatly reduced and supports the design of an outer membrane to contain the spring structure. The spring of the Dod, as it interacts with the environment, is portrayed in the simulation via the motor force of the prismatic joint used to demonstrate the arm extension mechanism. The actual rotation of the spring as described in Chapter 4 is not visible due to the profile view of the Dod. This simulation is design as a course which is divided into three sections: upper, middle and lower. The upper section contains two shallow gaps of varying width: in the 1st, three closed can fit and into the 2nd, two closed Dods can fit. The middle section contains an undulating terrain with a large deep pit which the Dods must pass over. Since it was not yet possible to simulate specific facet functions such as attachability, the Dods surpass this obstacle by building a structure from the ground up. Once the Dods have passed the pit, the lower section of the course contains varying terrain is the form of
irregular spiked closely placed mounds. Similar to car suspension ideally when passing over this style of terrain rather than approach each mound individually the Dods should move over the obstacles using the arms to compensate for the irregular surface topology.

The first few times the simulation was run, both extreme states were trialled (all arms extended and retracted) and predictably they both exhibited similar difficulties. Without the ability to adjust their shape these Dods could not reliably complete the whole course as they were not able to adapt to changing circumstances. Both states tended to become stuck by exhibiting a packing behaviour and were unable to continue moving forward. This is evident as early as the shallow gaps at the beginning of the course. Once the Dods stopped moving, they lost momentum and without a form changing mechanism (in this case the extending arms) they were unable to move from their position. This packing behaviour is useful for situations in which it is necessary for Dod’s to build a mass, e.g. causing a blockade or a solid structure see Figure 6.5a and 6.5b.

![Figure 6.5 Jamming behaviour](image)

**Figure 6.5 Jamming behaviour** - (a) Dods creating a localised blockade, b) a continuous blockade.

### 6.7.1.1 Upper Terrain

Figure 6.6 shows the ability of the Dod to extend and retract specific arms to enable it to adapt to a variety of different shaped spaces as well as with other agents. With this technique, it is possible for Dods to overcome small obstacles. Eventually when the Dod is behaviourally developed further it may be possible for the last Dod that crosses the gap, to attach to the Dods in the gap and help them out of the gap. This behaviour is hinted at in supplementary material 6: *Lower Terrain* (01:43) in the lower section of the course. Due to the extension of the arms of a Dod at the bottom of the structure, the top Dod nearest the edge of the pit is enabled to get out and continue with the
6. Discussion

When the exposed arms, of the Dods in the shallow gap, extend, they act as a springboard for following Dods, see supplementary material 4: Upper Terrain (00:10 and 00:27). The advantage of having multiple arms that can extend and retract with respect to confining spaces is illustrated in the Figures below. The variety of arm configurations make the Dod a versatile and adaptable agent.

![Figure 6.6 Filling behaviour](image)

*Figure 6.6 Filling behaviour* - The Dod adapting to confined spaces whilst still creating a level platform for remaining Dods.

6.7.1.2 Middle Terrain

The ability to manoeuvre over large irregular mounds and bridging a pit is tested in the middle section. For the large pit, it becomes evident that in the extended state, fewer Dods are required to create a sufficient platform for other Dods to cross over. Even when more Dods fall into the pit, the extended configuration offers greater support and it is not necessary to resort to packing through quantities of Dods. It is possible to allocate specific Dods to fulfil supportive task, similar to the ants that comprise the bottom of the raft. As is evident, it is possible for a Dod to use the extending arm as a means to move aside or to gain forward momentum, this is the predominant difference in design when compared to existing projects. The more arms that can extend sequentially, the greater the possibility of generating momentum to move backwards or forwards.

6.7.1.3 Lower Terrain

In the lower section of the course, after the Dods traverse the pit they continue to navigate over very irregular, spiked terrain. Whilst the two previous sections of the course were completed with ease by both types of Dod (short and long arm extension)
the lower section proved to be problematic at times for the Dod with a short arm extension. As seen in Figure 6.7, the Dods with the short arm extension got caught more often as they could not use their arms to push off from the boundaries. However, from a structural perspective it is possible to use this behaviour as a means to fill in small gaps so that other Dods can cross over them and the terrain with greater ease, see supplementary material 6: Lower Terrain.

![Figure 6.7 Adaptation behaviour - The Dods adapt to the environment.](image)

The Dods with the longer arm extension exhibited a more dexterous buffering ability, similar to a car’s suspension. This behaviour is also being considered in relation to space exploration through the application and development of tensegrity structures (SunSpiral 2012, Agogino et al. 2013). In being able to distribute impact forces throughout the overall structure rather than have it localised to one point is advantageous with respect to the device’s longevity and robustness in unpredictable environments. The design of the Dod embodies this potential. The arm mechanism allows the Dod to efficiently use the propulsion gained from the potential energy contained in the spring through compression. In spreading an impact through the arms and thereby a larger surface area, the inner core of the Dod is more protected from damage. The spring can support the Dod’s own weight and that of one other Dod. It begins to compress if more Dod’s are placed on top of it unless the material from which it is constructed is appropriately chosen, i.e. if rigid structures are required it is possible to use less flexible or malleable material, (see Chapter 6, section 6.5.4 - difference between the String and Latch Dod).
6.7.2 Motion
The second simulation explores the Dod’s locomotive ability, especially halting and forward and reverse motion based on the ability to extend arms. The arms extend in a sequential and clockwise manner for forward motion and in a counter-clockwise motion for reversing\textsuperscript{32}. The complete motion of the Dod is not discernible as the two arms that extend into the z plane would introduce a slight alternating divergence from a straight-line in forward or backward motion. This is due to the offset nature of the facets of a dodecahedron, it can be visualised by the curved lined example in Chapter 5, section 5.4.1. The application of these (z-plane) arms in the forward motion can either be used for stability - similar to training wheels on a bicycle or aid the Dod in manoeuvring around irregular terrain.

The breaking mechanism occurs simply by extending an arm out of sequence, i.e. if forward motion is active then rather than following the sequence Arm1, Arm2, Arm3 - breaking or halting would entail that Arm 3 is triggered after Arm1 and that Arm2 remains static. A valuable insight from this simulation is the observation that for the Dod to move on land, it is necessary for the Dod to gain enough momentum so that its midpoint is past its centre of gravity. This results in the Dod moving forward on the edges of each facet as opposed to landing completely on a facet, see supplementary material 7: Dod Motion. The latter tends to act as a breaking mechanism due to the larger surface area and whilst this is desirable for structural stability, it is important to consider that the size of the facet cannot be larger than the ability of the Dod to move beyond its centre of gravity with respect to facilitating motion.

The insights gained from these simulations not only support the design of the Dod but are also suggestive of the behavioural patterns required for different applications. It is clear from the simulations that the Dod addresses another key element often mentioned in the literature regarding interactive, tangible interfaces and that is the ability to shape-shift or alter the form in a particular manner. In the 1st simulation all of the Dod’s arm move simultaneously instead of individually. Whilst the arms should ideally move sequentially, the simulations indicate that even at a reduced level of functionality, the practicality of the design is still maintained.

\textsuperscript{32} Ideally the Dods in the first simulation should avail of this type of forward motion as well.
Shape shifting is a very common feature in nature. In animals, shape-shifting is most commonly seen in the ability to make themselves appear larger to act as a deterrent when they are threatened. However, there are also instances where becoming smaller is more advantageous. Reducing in size can be achieved physically, in the arrangement of appendages or body parts (e.g. octopus, blowfish), through secondary physical elements like hair or spikes (e.g. cats, hedgehogs), or by a specific action / motion such as rolling together or retracting appendages and becoming a smaller target (e.g. caterpillars, armadillos, turtles). Shape-shifting has other uses, and is a desirable quality for interfaces that are envisioned to represent and manipulate digital data. This quality should also preferably occur in real-time. The main difference between naturally occurring shape-shifting and that imagined by man, is the ability to change into completely different entities that potentially have no relation to each other (e.g. tool, interface, extension of a machine, etc) - the ultimate freedom ((Bole 1993) and essentially the ability to adapt to any situation. The closest to this type of freedom and unboundedness are devices such as the smartphone, tablet and laptop. Although these devices do not physically shape-shift they do transition between tasks that were once clearly separated and intended only for each device. This highlights the concept that it may be more advantageous to develop technology that is blank until a task is imposed onto it, like object orientated programming.

The Dod design encompasses the ability to change size through the arm extension but also to change its surface topology. From a relatively smooth topology of a faceted geometric polyhedron to a coarse and gaped topology when the arms are all or partially extended makes the Dod a versatile with respect to handling irregular and / or smooth surfaces, see Figure 4.20a and 4.20b. In studying the physical design of the Dod it has become clear that there are several layers of shape-shifting that are distinguishable: the core layer which involves the agent’s ability to alter its shape, the group layer - when several agents function together and change shape as a whole and the outer layer which is also responsible for defining the boundary conditions in which the agents find themselves.

The exploration of the Dod design has highlighted the potential for further development and the variety of combinations possible regarding material and application. In creating this kind of design blueprint, it is possible to use it as a blank
canvas which can be further moulded to suit the requirements of the user. Chapter 7 will discuss ideas and functionality of various aspects of the Dod, to further conceptualise and provide insight into other avenues of the design’s development. These range from local enhancements, relating to the Dod itself, to broader topics such as its context and uptake in the overall domain of shape-shifting, programmable interfaces.
7. Future Work

7.1 Introduction

Chapter 1 presented possible scenarios and applications where tangible, shape-shifting, interactive, interfaces could be implemented. The prototype to date consists of a rigid, structure printed out of PLA containing 3mm ball magnets in each facet. Different versions of this prototype have been printed to represent the variety of arm configurations. This chapter explores possible avenues of future work and / or development with the aim to create a platform from which research can continue.

There are four main sections that explore the potential of the Dod with respect to considering further adaptations to its physical form as well as possible variations to its overall behaviour: A) developments of the Dod design (facet and arm function, methods of motion), B) energy, C) boundary conditions and D) 3D thinking.

An element that has not been explicitly detailed in the previous chapters is the functionality of the Dod’s arms and facets. Currently they are designated in assisting the motion of the Dod and are used in the creating structures through specific arm configurations (e.g. line curve, cluster). The first section of this chapter reviews further functionality of the facets of the Dod regarding sensing, assembly, and possible contributions to the energy harvesting and generation cycle. Other methods of motion are also explored as this relates to the environment in which the Dod may eventually find itself. Whilst the issue of energy and power supplies is not resolved in this study, this section appraises potential technology that might be suited for the Dod’s design. This includes triboelectric generators, piezoelectric materials and chemical reactions. Eventually possible solutions for the energy issue will most likely emerge from research completed in the medical domain, since the nanobots developed in this domain must ideally be powered independent of an external source but also be delicate enough in order not to damage the finely tuned biological system in which they will eventually operate.
Even though boundary conditions have been mentioned throughout this study, the concept will be addressed in greater detail in the third section of this chapter. Boundary conditions provide a frame through which systems are interpreted and perceived. Even though they are not always consciously considered they are necessary for defining the limits of a system, guiding a design or defining the parameters in which a system can operate. For a complex MAS, boundary conditions are critical throughout the various layers of which the system is comprised of. For the design process, they act as physical manifestations of a specific perspective.

The last section attempts to address the issue of application regarding the shape-shifting interactive interfaces discussed in this study and throughout the relevant literature. As mentioned in chapter 6, the artworks created through this study are an attempt to bring the concept of the Dod as an agent in a MAS into the public realm. One reason why it is important to make certain areas of these research ideas accessible to the public is that, in a lab setting the focus is narrowed and can at times become too exclusive. Equally to the coding process (and many others), the more knowledge a person has, the higher the potential risk of over-complicating a task or situation, as usually the simple solutions work the best. One method of overcoming this obstacle in the design process is changing the nature of the Dod. Similar to the work of Hsiao, introducing the Dod to the public as a toy or game is a worthwhile consideration (Hsiao 2015). This suggestion is not unwarranted as it links the Dod to an interaction method for which it is designed: haptic exploration through the act of play.

The scope for the Dod to develop further across the chemical, material science or engineering domains, among others, is substantial. The ideas presented in this Chapter do not only aim to provide inspiration but also illustrate the importance of a multidisciplinary approach in an academic as well as industry setting to address a project of such complexity.

7.2 Dod design

The Dod has twelve facets that can be used in a variety of combinations: sensing, communicating and attachment; sensing and attachment; sensing and communication, etc. Each facet can have different or twelve of the same function. The facet function is to an extent dependant on the task for which the Dod is used, e.g. building specific
structures (line or curve) requires a minimum of three active arms. These can be used for attachment whilst the remaining static arms can be used for sensing or communication, etc.

As mentioned earlier, facet functions can include the following\(^{33}\):

- **environment sensing** - receiving input from an external source and possibly reacting to it.
- **assembly mechanism** - receiving signals that indicate to connect to a neighbouring agent or boundary surface
- **energy harvesting** - gathering energy and either storing it for later use or using it to complete a task (arm extension, Dod motion, etc),
- **energy generation** - using organic material in the generation of energy (optoelectrical, e.g. solar power, bioelectrical, e.g. algae, chemical reactions)

### 7.3 Environment sensing

In whichever direction the Dod develops, it is likely that it will require some method of communicating with the environment in which it finds itself. The first step in this process is having some database to communicate. This data is collected through sensors. The creative exploration of human interaction and the continuous research into how the world is perceived by the wide variety of lifeforms on this planet, means that the technology used to measure and record information is being refined and enhanced. These sensors can be internally or externally integrated into the design and be made of a variety of different materials. A recent development in industry automation is the relationship between worker and machine. Rather than completely replacing the human workforce the aim is to create a more symbiotic relationship, i.e. integrated industry 4.0. This requires extremely accurate and sensitive sensors, as well as efficient programming, because the margin for error is very small (Pilz 2017, Festo 2018). In relation to the Dod there are three different setups which may be useful considerations with respect to sensor allocation.

\(^{33}\) Aside from their actual purpose, these functions also allow for information to be generated that can be communicated internally as well as externally to neighbouring Dods.
In the application where the Dod has sensors hardwired onto specific facets that can either see, hear, detect energy, etc, this configuration would lend itself to specific tasks whereby the Dod would potentially only operate with a few other Dods or even individually. This setup could be used for detailed or specific tasks possibly in the medical domain, e.g. drug delivery systems. Not all arms would require sensors therefore several arms & facets would be free to complete other tasks. This kind of configuration would be very task orientated.

An alternative configuration would be to have the same sensor on each facet. The options exist to A) have all the data be controlled from a central point within the Dod, or B) to distribute the data to several secondary points throughout the arm and spring structure (Doyle et al. 2016) like that of an octopus. The brain of an octopus is divided equally between a central part and its skin. This enables quick colour adaptations and precise camouflaging. This type of configuration is more suited towards larger quantities of Dods working together whereby each Dod requires spatial information about its environment and neighbour.

On an even larger scale each Dod may be configured to act as a sensor itself and be used in a larger network of distributed sensors (Gorbet et al. 1998, Lifton et al. 2004, Richardson et al. 2004, MIT Media Lab 2018). The main difference between the last two suggestions being that if a Dod were to be configured to act as a sensor it would only gather and transmit data rather than act upon it or affect its surrounding environment.

7.4 Assembly mechanism
Self-assembly and dis-assembly are two important qualities that are considered to have a high priority for the Dod design, as its aim is to aid in the construction of 3D structures. As discussed in Chapter 2, the observance of ant and their species specifics are a significant influence with respect to assembly mechanisms. To briefly recap, they avail of three techniques A) a fixed-shape claw (it cannot be altered or retracted) - this is reflected in the pentagonal, outer facet of the Dod, B) mandible-to-tarsus (requires conscious intervention) - this is reflected in the Dod’s extension mechanism and possibly also linked to the attachment mechanism, e.g. a sensor on a facet activates the attachment mechanism and C) a chemical excretion from each ant’s tarsus - whilst
this element is not yet embodied by the Dod, the project MicroTugs developed by Christensen provides a viable description of the potential advantages and applications of such a technique (Christensen et al. 2015).

Controllable adhesives are evident in the natural world (e.g. capillary force), particularly in amongst the insect world and like the natural equivalent, Christensen’s directable and controllable adhesion mechanism primarily functions on smooth surfaces. It provides the micro sized structure or robot that uses it, with the ability to interact with its macro sized environment, e.g. a 25x35x25mm MicroTugs structure weighing 13.7g is able to tow a 45N weight across a smooth surface. The ability to facilitate a smooth and quick detachment from the surface is incorporated into the design through wedge-like grippers that comprise the adhesive pad. Under normal load the tips of the wedges make contact but as soon as a shearing force is applied, a greater surface area of each wedge comes in contact with the surface, thereby providing directed adhesion (Christensen et al. 2015). A development of this technique, to accommodate a climbing mechanism, is achieved by inserting cuts that reach the substrate. When a shearing force is applied, in the correct direction, the pad will adhere and when this shearing force is reversed, the pad will release quicker because the deeper cuts enable the wedges to break contact with the surface at a larger area (Hawkes et al. 2015)

The prototypes described in Chapter 4 avail of magnetism to demonstrate the self-assembly behaviour. A recurring issue with magnetism is A) the necessity for external actuation and B) the zones of magnetic constructive and destructive interference. In the Dod prototype, due to the close proximity of the ball magnets it is inevitable that they experienced varying degrees of constructive and destructive interference. From the physical experimentation with several Dod prototypes, the zones of destructive interference simulate the ability to dis-assembly, however since magnets do not naturally dis-assemble, an external separating force is required.

The alternative assembly mechanism that was explored is the Velcro concept - essentially a hook and sling mechanism. This would technically require certain facets of the Dods to have facets that have the hook (key) elements and the other facets to have the receiver (lock) elements. Traditional Velcro elements proved difficult to reduce in scale and in conjunction with this, requiring certain facets to have specific
assembly elements, essentially ‘hardcoded’ onto the facets. This may limit the functionality for the Dod, i.e. one facet would only have the hook elements and could only every attach other facets that have the latch elements. This is reminiscent of the 1st modular prototype described in Chapter 3, section 3.3.1. Therefore, alternatives for Velcro were researched and Gekko tape was tested with the Dod prototypes, see Chapter 6.

7.4.1 Polymagnets
An alternative to Gekko tape, and the more traditional electro- and permanent magnets, is the development of polymagnets. This relates to printing magnetic patterns thereby altering the magnetic field lines. The company Correlated Magnetics is working on varying designs ranging from Latch, Align, Attach, Spring and even printing magnetic patterns onto non-linear surfaces. In their latest line of research are magnetic patterns that are encoded onto the required part so that it can be read by sensors (Polymagnet Correlated Magnetics 2016).

Polymagnets build upon magnetic qualities that already exist in rare-earth magnets (e.g. neodymium magnets). The novelty lies in being able to ‘print’ unique or custom magnetic patterns using voxels (magnetic pixels) (Sullivan et al. 2005, Polymagnet Correlated Magnetics 2016). To demonstrate the potential of this technology, consider a conventional magnet versus a polymagnet that has a checkerboard pattern printed on it. Both magnets have the same attractive energy however by altering the force-distance curve via the North-South (N-S) pole patterns, the feel and behaviour of the magnets differ. In the checkerboard pattern, the N-S poles do not have as far to travel before meeting the next pole, therefore the field lines are much closer together. This proximity means that the magnetic energy is more focused around the centre of the magnet and will have a much stronger hold than the conventional magnet. Whilst this is advantageous in localising or limiting magnetic field lines – in particular when working with items that are sensitive to magnetic fields, e.g. credit cards or data storage devices, etc. – there is a trade-off with respect to the force of attraction over distance. The polymagnet does not have as strong a pulling force when compared to the conventional magnet over a longer distance.
With respect to the practicality of printing these pole patterns, complex patterns require more area, simply to be able to print more poles. This aids in resolution and clarity. The smallest pole area that the company has achieved is 0.5mm and the size of a N-S pole region is approx. equal to the thickness of the magnet, e.g. if the region is 1mm then the magnet is also approx. 1mm. Of specific interest to this study is the Latch mechanism. It is a combination of an *Attract* and *Spring* mechanism. The pattern printed resembles a circular lock & key. Both magnets are restrained via a rod, which runs through the centre. When the latch is open the magnets repel each other and act like a spring, i.e. it cannot fully close and there is a specified distance between the magnets when at rest. When one magnet is rotated the magnetic pattern aligns and exhibits an attractive force essentially locking the magnets together and withstanding perpendicular outward forces (Polymagnet Correlated Magnetics 2016). There may be potential to print such patterns onto specific facets of the Dod and thereby automatically connecting a locking mechanism to the rotation-extension motion of the arm. Depending on the functionality requirements of the agents, i.e. what structure they are supposed to build, it may even be possible to design custom magnetic patterns, that work in conjunction with a weighted, core behaviour, to ensure that a predisposition for specific configurations can be reaffirmed. If specific arm configurations are established with only a certain number of arms active, the static arms can be attributed mechanisms for energy generation or processing, such as used as batteries, or power supplies.

### 7.5 Motion

The simulations in chapter 6 demonstrate that the Dod is capable of forward and reverse motion in its current design. This section presents two alternatives to enabling the Dod to move, the first is based on an organic method seen in plants, and the second considers the development of modular hydraulics. With respect to mechanical movement mechanisms, aside from motor movements, electromagnetism and angular momentum are alternative methods that have been used to date, to create motion in man-made agents (Gilpin *et al.* 2010, Gajamohan *et al.* 2012). The primary issue with these techniques is scalability. Whilst they work adequately on a macro scale, reducing all the components required is often problematic.
7. Future Work

7.5.1 Plant motion
Motions and behaviours exhibited by plants are a valuable source of inspiration (Guo et al. 2015) in particular because of the reactive nature of plants as opposed to a clearly defined neural network. Nastic motion, hydrotropism and capillary action are just some methods of motion that may provide alternative design solutions regarding energy and motion.

7.5.1.1 Capillary motion
Capillary action facilitates the flow of water from the roots of a plant to its leaves. It is a force that utilises surface tension and the cohesion and adhesion force of liquid and solid molecules. The interesting qualities of this force are that it is capable of going against the gravitational force and does not require energy as input. Even though it is not applicable to all liquids, it is a force that tends towards a state of equilibrium even though the condition of the state often seems precarious, e.g. water traveling upwards in a narrow tube.

7.5.1.2 Nastic motion
Nastic motion is a plants response to external stimuli such as light or temperature. They are driven by gradients and the osmotic flow created via the shrinking and expansion of specific ‘motor’ cells located throughout the plant. Unlike tropic movement, the direction of movement is independent of the direction of the stimulus (Li and Wang 2015, Rafsanjani et al. 2015). The Venus fly trap and mimosa plant are examples of how this occurs in real time. It is possible to simulate nastic motion through fluidic origami, i.e. creating the equivalent of plant cells through which a liquid could be pumped (Li and Wang 2015). This has been tested by adapting the Miura-Ori crease pattern. In creating these cellular structures, it is also possible to achieve tuneable stiffness by altering the crease pattern or by altering the volume of liquid contained in each cell. This has the added benefit of contributing to the morphing quality of the resulting structure. Translating this concept to a liquid based Dod, it may be possible to use the fluid in which the agents move to help expand the arms. For example, in the compressed state the cells would be empty, the spring remains compressed and the arm is retracted. When required to expand an arm, a valve
located on the outer face of the arm would open allowing fluid to enter the cellular spring structure. By sealing this valve once more, with the fluid contained inside, would help maintain the rigidity of the overall extended arm. Once the extension is no longer required the fluid can be expelled via compression of the arm and the cells become empty once more. This type of behaviour resembles Non-Newtonian or smart fluids, in that once the external liquid is soaked or drawn into the Dods it would effectively create a semi-solid mass through which a 3D structure could emerge.

7.5.1.3 Hydrotropism

Hydrotropism is the roots response to water, that permits them to grow in the direction of water (Eapen et al. 2005). This type of motion is dependent on the expansion and contraction of cells. In contrast to nastic motion, hydrotropism depends on the cell locations. This makes it possible to create a variety of patterns of motion. For example, the Selaginella lepidophylla is a plant that curls and unfurls its leaves depending on the water content within its cells. It can survive long periods without water and protects the young green leaves in its centre. In its dehydrated state, it forms an overall roughly spherical shape whilst the individual leaves curl into a spiral shape due to a strain gradient along the length of the stem (Rafsanjani et al. 2015). This kind of mechanism in conjunction with fluid origami or microfluidics could provide a viable alternative for constructing the spring or arm structure of the Dod. Figure 7.1a and 7.1b illustrates a design iteration of the Dod whereby it is hollow throughout and narrow tubes are envisioned to be placed alongside the vertical, diagonal fold, that comprises the extending arm. When these tubes were empty the arm would be contracted and when they were filled would have extended the arm. It may not be possible to achieve as high a compression rate as when paper is used however this extreme compression may or may not be ultimately necessary. The diagonal connection is created by offsetting one end of the connection to the next vertex on the outer facet, in a clockwise direction, Figure 7.1b. This offset between outer facet and the inner core ensures a degree of rotation.
7.5.2 Modular hydraulics

The last method of motion that could prove advantageous in further developing the Dod design is that of modular hydraulics proposed by Doyle in the project MBlocks (Doyle et al. 2016). This work is of interest if the Dod is to be applied in a liquid based environment. Doyle envisions this liquid-based propulsion system to be applicable in confined and small places, e.g. vascular systems, but also to enable a module to move in 3D space. Scalability and motion are key design parameters that influenced this research. A cube was used as the basic module shape, with a network interface, thruster and connection sensor located on each facet. The basic principle of this system is based on Newton’s 3rd law of motion - for every action there is an equal and opposite reaction. When the system is inactive fluid can flow freely throughout the module via channels that penetrate each facet through to the core of the cube. When the thrusters are activated liquid is pumped from the reservoir, at the core of the module, into the external environment creating a motion in the direction opposite the thruster. The reservoir is constantly replenished through the thrusters that are inactive (Doyle et al.}
When two or more modules are connected, the network through which liquids can flow is extended but continues to function in a similar manner. This setup could be applicable to the Dod’s design as construction around an inner space is already accounted for (i.e. the inner core dodecahedron). The arms can potentially provide a greater degree of controllability regarding direction and orientation, due to its semi spherical shape and greater number of facets. Being able to hollow out the Dod as seen in Figure 7.1, also allows channels to be modelled that can act as thrustors similar to the cube construction used in MBlocks.

Another study completed in this project is exploring the benefits of a decentralised versus a centralised motion controller (Doyle et al. 2016). The decentralised motion controller means that the sensory input is located at each facet. It also means that when two facets are connected that these would be not be used as a means of propulsion. In contrast, the centralised motion controller is similar to a brain that coordinates all data with respect to receiving, analysis and transmitting instructions to the appropriate actuators. This setup requires significantly more computational ability. These types of setups have been considered throughout this study, as they can be applied to mechanical functions as well as behavioural models (see Chapter 5).

These examples provide substantial material and research for further work in developing the Dods design. Whilst some research could be applicable directly or in the near future, other strands of research remain further on the horizon. The latter consideration, with respect to the future work directly involving the Dod, involves the advances in 3D printing and material sciences.

**7.6 3D bio-printing**

The domain of material sciences opens the potential for a rich diversity and range of materials to use, combine or create. Ranging from organic to inorganic, smart fluids polymers and gels, it is now possible to create materials with specific qualities in order to accomplish specific task. Sensors can be integrated into the material itself and new mechanisms for integrating renewable energies are under continuous investigation (Xiaotian Hu et al. 2017). The path from the discovery of these new materials to their actual application in a real-world setting is also not often precisely predictable. The suggestions of these types of materials and techniques aims to draw attention to
alternative approaches to manufacturing technology with a focus on the advancements in 3D printing regarding living interfaces and biomedical nanobot construction.

As discussed in Chapter 3, 3D printing has been and still is an important influence in the areas of construction and prototyping. The technology and techniques not only influence the presentation of the final product but it is also changing and influencing the manner in which objects and processes are being designed. A simple example of this can even occur in the most basic 3D print. Aside from the 3D model itself designers/ hobbyists/ researchers are learning to consider the negative space around the model through the design of the support structures for the actual model itself. The nature of 3D printing is influencing the thought processes of 3D modellers and engaging them to examine or explore their model from alternative perspectives. In conjunction with this, the types of materials that can be used are increasing on a regular basis. Whilst it is not yet possible to 3D print with living cells it may only be a matter of time (Cohrs et al. 2017). A recent study from the advanced materials department in MIT has seen it possible to 3D genetically programmed bacterial cells contained in a hydrogel (Liu et al. 2017). These bacteria respond to different types of chemical stimuli by triggering green fluorescent proteins (GFP) and are envisioned to further the research into living devices. Multi ink 3D printing enables logic gates and other complex structures to be created in high resolutions which can emit GFP as a means of indicating output (Liu et al. 2017). Being able to print with different materials allow each quality of the material to be used to its full potential, e.g. programmable viscoelastic material (Wang et al. 2013, MacCurdy et al. 2016). Other materials such as conductive inks and glass are also becoming more accessible and applicable in the 3D printing process (Sun et al. 2013, Kotz et al. 2017). For example, researchers have discovered another variant of carbon: glassy carbon, that is light, strong, elastic and electrically conductive and may prove to advance applications ranging from space travel to defence armour (Meng Hu et al. 2017). Similar to the 3D mesostructures that are discussed in Chapter 4, compression is used in this process of handling carbon which causes areas of buckling throughout the graphene sheets. This buckling creates the specific bonding states required to produce the varieties of metastable materials. An impressive feature of this compressed glassy carbon is its elasticity, which according to researchers has recovery rates higher than those of smart memory alloys.
(SMAs) (Meng Hu et al. 2017). An advantage of this type of material are the tuneable electric properties. Therefore, depending on the application, it is possible to customise material appropriate to the task.

As mentioned in Chapter 6, 3D printing a biological Dod, or other agent designs, has the potential to solve or progress issues such as energy (generation and consumption), networking and physical mechanisms in so much that it would be possible to 3D print a biological scaffolding around which a Dod could be grown. Growing biological computers may be a worthwhile consideration rather than continuing to construct computers with materials that cannot be completely recycled or reintegrated into the environment.

Electro-spinning is currently used to create bio-compatible scaffolding into which cells can assimilate and grow around (Leibniz Universität Hannover 2017). This technique is used to create fibres at the scale of both micro- and nanometres using synthetic as well as organic polymers (polystyrene, silk, cellulose, etc). The spinning method creates a scaffold whereby the porosity is tuneable and it has a high surface area to volume ratio. It is most often applied in the medical domain for wound dressing and tissue engineering (Bhardwaj and Kundu 2010). Since the cells cannot completely penetrate this scaffolding it limits the ability to be used in complete organ reconstruction, however it is currently being explored in the use of creating customised stents for individual patients, i.e. medicine that is adaptable, customisable and uniquely individual (Leibniz Universität Hannover 2017). The Dod structure could be created from this scaffolding which could act as the core skeleton of the Dod.

The versatility of biological matter provides rich inspiration for many areas of research. A study in 2008, had researcher Doris Taylor utilise a cleansed pig heart as a scaffolding and injected it with human stem cells. Several days later the heart began to pump as the stem cells assimilated their environment and began fulfilling their function (Maher 2013). This also opens the opportunity for qualities such as self-repair which benefits the individual agent as well as the overall system. The question that arises how do these cells know what function there are supposed to execute? There is no doubt, that the ability to grow or 3D print complex organs is still beyond current technological abilities. However, using this knowledge to begin with a smaller, simpler entity may provide further insights and information required to continue progressing.
this field of research. If it were possible to manipulate this matter, it would be possible to replace the origami spring structure with muscle tissue and thereby increase the lifespan of such a mechanism. Issues such as the acute angles, evident in the origami spring, that weaken due to stress and strain, could be replaced by biological mechanisms that can accommodate and achieve these angles and withstand repetitive stress and strain for longer periods of time (e.g. Cyclophora albipunctata, Figure 7.2).

As suggested earlier, the inner core of the Dod could contain the computational parts of the Dod and it too could eventually be programmed and designed to exhibit the required or desired behaviours. It is known that biological material can function on this scale and smaller, the question of future research lies in how this kind of growth can be directed (or controlled) along a predetermined, newly defined pattern? Research into the most fundamental level of biological life is another step in realising the potential of growing a Dod. This relates to DNA manipulation: from creating DNA glues, to the addition of another base set that can survive cellular division, to restructuring bacterial DNA or building mechanical metamaterials made from DNA hydrogel (Hao 2002, Lee et al. 2012, Qi et al. 2013, Zhou et al. 2014, Liu et al. 2017, Zhang et al. 2017), DNA contains the fundamental programming for cells and as a result for the lifeforms that are created through the combination of these cells. This is a highly summarised example of a small fraction of work in the domain of DNA manipulation and should primarily be viewed as suggestions for new avenues of thinking about the manner in which technology is manufactured. It’s implementation with respect to creating a complete lifeform from scratch is still a considerable distance away. Aside from the wide spectrum of ethical issues that would naturally arise in this line of research, it sheds light on those aspects of humanity that still remain unknown.

\[34\text{ An alternative to this is dividing the brain between a core location and spreading it amongst the appendages similar to an octopus.}\]
7.7 Energy

Energy is a difficult obstacle to overcome. Whilst this study has not addressed it directly (for obvious reasons) this section of the future work relays several ideas that may be implemented in the Dod design. Future developments of the technology detailed in the following projects may potentially influence the design of autonomous agents used in physical MAS, swarm or hive computing systems. At the basic level of existence, is the handling and conversion of energy at a given temperature. In general, without heat and energy, electrons do not have the ability to move and atomic structural integrity would not exist. The movement and flow of energy is expressed through energy gradients. A fundamental concept in thermodynamics is that energy flows from a high state to a lower more stable energy state (Atkins 2010). This is also known as a spontaneous system and holds true for organic and inorganic processes. The ideal aim is that any artificial and autonomous agent should have a mechanism that enables it to convert energy and that it can complete this process independent of external assistance (e.g. a user having to change a battery). This is not only vital for the self-sufficiency of the agent but it also affects other processes such as scaling and freedom of movement. Energy gradients are present throughout any system that moves from a state of imbalance to equilibrium. Since the flow from higher states to lower states occurs naturally or the system has a tendency towards balance, this process often requires little or no extra energy input. The energy required is to reverse this process so that it can begin again. By using the environment or another secondary function to provide this energy would be ideal, e.g. motion / friction to provide electrical energy, the users (touch: galvanic response), pressure, photosynthesis, heat, hydration, chemical exchange via an electrolyte, etc.

7.7.1 Organic Process

Taking inspiration once again from biological sources provides insight into a variety of methods in which energy is handled and processed. In this instance the osmotic process, which utilizes energy gradients, is briefly illustrated and how it could relate to the Dod design. The osmotic process is reliant on semi permeable membranes in order to enable energy gradients to be formed. An example of a semi-permeable
membrane is found in a blood vessel wall. In a healthy example, the vessel contains large (albumin & globulins – long chained proteins, white blood cells, red blood cells) & small (potassium, chloride, serum, platelets and small white blood cells) components. The larger cells inside the blood vessel exert an attractive force on the smaller components, which constitutes the osmotic force. The greater the number of cells and proteins present, the greater the osmotic force which attracts the smaller components from a less concentrated solution through the semi-permeable membrane to equalise the concentration gradient.

The sodium-potassium pump is another example of how the osmotic process functions, as it requires energy to artificially increase the concentration of ions on one side of a membrane to create an osmotic gradient. In short, the interesting feature is that this gradient enables the ions to move against the concentration gradient, i.e. move from lower to higher concentrations. This biological principle potentially links in with the concept of being able to 3D print an organic Dod expressed in section 7.6. For this scenario, the Dod’s environment is liquid based and the process of extending an arm is considered as the structure in which to setup the appropriate gradient. The origami spring is the equivalent to the vessel and is made of a semi-permeable membrane, whilst the space between the spring and the outer skin represents a filled body. If the fluid in the spring has a high osmotic value, less energy is required to create a higher concentration gradient and the fluid in the body contains small components that can cross past the semi-permeable membrane. This osmotic value will attract volume out of the body thereby by expanding and simultaneously untwisting the spring as the osmotic gradient is equalized. Expansion of the arm would occur naturally due the higher osmotic value in the spring. The arm retracts when energy is applied and the smaller components, including fluids, are transported back into the body reducing volume with in the spring thereby causing it to twist and retract.

The osmotic principle is based on a sophisticated and complex organic energy system. Even though it is currently not implementable, it is the idea of organic energy gradients that is a worthwhile goal to strive for in future research. Alternative energy handling systems exist, that depend on reaction to the change in the immediate environment. The following concepts are briefly outlined to present an overview of how a change in
the environment\textsuperscript{35} can provide a means of energy for individual agents: using solar energy, heat, pressure and chemical reactions.

Algae and lichen are interesting organisms with respect to converting solar power into energy via photosynthesis. They utilise chemical and optical gradients to generate energy which provides further ideas for potential physical design adaptations. For example, instead of each Dod having its own power supply (energy system) it may be that the Dod connects with its environment, or other Dods, and forms a symbiotic relationship like that of lichen. Lichen are robust and adaptive to their environment. They are made of two components: a fungus and algae and / or cyanobacteria (photobionts) (British Lichen Society 2018). The photobionts generate energy in the form of carbohydrates through the process of photosynthesis whereas the fungus requires an external food source which it acquires through its immediate environment. The diversity in lichen varieties stems from the fact that their basic component (the photobiont) is similar throughout all species of lichen and that variety is dependent on the environment in which they grow and the types of minerals and materials that are available to the fungal component. The primary issue with natural or organic processes is Time. These processes have taken time to develop and perfect, and in contrast, in the computing industry it is not often about achieving the most efficient system rather it is about achieving the maximum that materials can offer. It is a common perception that newer technology does not ‘last’ or is ‘not as good\textsuperscript{36}, as technology from 10 to 20 years ago. Lichen and algae can live for a long time because their process is slow and steady - being human, there is a tendency or desire for events to happen in real-time preferably immediately (in particular with respect to digital manipulation of data). Perhaps a new attitude must initially develop towards this branch of shape-shifting technology in order for these new types of interfaces to find their first foothold. Rather than propagate a throwaway culture through constant new updates, or releases, it may be possible to create a highly individualised computer interface that acts as an

\textsuperscript{35} This is closely related to the problem of external actuation. A user changing a battery is also a change in the environment on which an agent may be dependent. However, it is the act of developing a battery that has less of an environmental impact which would be the desired outcome of this exploration.

\textsuperscript{36} Good in this instance relates to longevity of the device, not its functionality. For example, computers are capable of significantly more regarding processing, storage, resolution, speed and accuracy, than when they first arrived on the market.
extension or augmentation of human abilities but that takes a few hours to assemble, as opposed to a few seconds\textsuperscript{37}.

### 7.7.2 Triboelectric Energy

Wearable technology is a domain in which finding power supplies other than batteries is very important - not only for aesthetics but also for practicality. Whilst many devices are still self-contained (bracelets, watches, etc) and can accommodate a traditional style battery, the development of smart fabrics requires an alternative power supply. The additional quality of flexibility inherent in most fabrics makes integrating technology an interesting challenge. Based on what is sense-able in the environment (e.g. heat, moisture, chemical) being able to react is more easily accomplished than being able to trigger a response, (colour change, sound, etc) because it requires more energy. In the majority of cases solar energy is still the primary focus with respect to providing alternative energy supplies. For example, fabrics are most often used to either integrate an energy system directly or the quality and behaviour of fabrics is replicated / emulated through the use of alternative materials. Elements such as copper filament or optical fibres can be woven into fabrics (Li et al. 2016, Institute of Making 2018) and materials such as perovskite can be constructed in a chainmail fashion which can be used as fabric (Xiaotian Hu et al. 2017). A branch of wearable technology in which finding less bulky power supplies is of importance is in the domain of active prosthetics.

The development of smart skin aims to have beneficial results regarding more realistic looking prosthetics but also to use them to generate sufficient electricity to help power certain aspects of a prosthetic. This is done through research into triboelectric mechanism (Rekimoto 2002). It is based on the piezoelectric principle and generates energy from friction forces as parts of the prosthetic comes in contact with different materials. Its application as wearable skin, aims to improve motion detection and finger-point detection resolution. In this capacity, it is important to develop a material that does not have wires and battery attachments but one that is flexible, light and has a low production cost (Bauer et al. 2014, Kim et al. 2014, Nassar et al. 2016, Shi et al.\textsuperscript{37})

\textsuperscript{37} It takes MITs new living tattoos 12hrs to react to chemical stimuli, (Liu et al 2017).
The triboelectric effect is being coupled with forces such low electric fields, sound, motion, light, etc. to utilize environmental energy (Jeong et al. 2014, Cui et al. 2015, Mao et al. 2015, Dhakar et al. 2016). In the attempt to replicate the human skin structure and physiology, qualities such as flexibility, elasticity, self-repair and identity are useful concepts in the construction of micro-sized man-made agents. For example, just as a form of identity is inbuilt into fingerprints it may be possible to accomplish a similar feature for the Dod. In this way, each Dod can be individually identified through an exterior marker (unique skin pattern) and would not have to send a digital tag as a means of identifying itself. The skin and what it represents, i.e. a self-renewing boundary layer that has the potential to filter or absorb specific materials, expand and contract, and to protect from a wide variety of environments, is an interesting approach particularly referring again to developing the Dod from a biological perspective. As described in Chapter 4 the spring creates the core strand of the extending arm, whilst the skin connects the edges of the outer plate to the edges of the inner core. If the material of the skin is designed like a triboelectric generator then it has the potential to generate sufficient energy to execute secondary function such as extending and retracting the arms. Another feature of skin is its galvanic response. Several projects utilise this response as a means of interaction with an interface (Rekimoto 2002, Lavery 2011). This has the advantage that an interface may be tuned to a particular individual but also that the interface is only re-activates when the user is touching it i.e. the user provides the alternative energy source. Similar to the symbiotic nature of the lichen, an interface that uses the user as a primary source of energy could prove to be an intriguing avenue of research. The manner in which lichen take on characteristics of their surroundings, it would be interesting to observe how interfaces could develop depending on what the user does or how s/he acts. For example, if the Dod is the basic component (like the photobiont) and if the user represents the fungus, if the user’s movements are slow or fast, soft or hard, small or extravagant the structures that are created could reflect this in the speed, accuracy, size and form in which they are created. The textures may vary depending on emotional state of the user: if they are angry or anxious textures could be coarse and irregular, whereas if the user is relaxed the texture may form regular patterns or portray undulating motion, etc.
Currently the power generated by the galvanic skin response is insufficient to power an entire interface, and there are issues with the use of man-made piezoelectric devices. For example, material durability regarding packaging, (e.g. if the moveable electrode above the nanowires pushes down too hard then no electricity is generated) and the longevity of such devices\(^\text{38}\) (Wang 2012). Therefore, research into other organic materials that generate piezoelectricity (bone, tendons, DNA) indicate that it may be possible to tap into other potentially renewable sources of energy (Guerin 2015). In conjunction with scaling the Dod to the appropriate micro level may shift the size to power ratio and make this source of piezoelectricity a viable alternative.

### 7.7.3 Chemical process

Developing a biological energy system suitable for the Dod may still be a long way from implementation but an alternative more accessible method of handling energy is through chemical reactions. These reactions can be quite potent, difficult to control and are usually not bi-directional, i.e. once a reaction occurs it is often difficult to retrieve or return to the initial components (Bergbreiter 2014, Miyashita et al. 2015, Parmar et al. 2016, Vilela et al. 2017). However, these elements can be used to an advantage depending on the application and its context. Similar to the living interfaces research conducted in MIT, the most recent example of living tattoos illustrates how bacterial DNA can be manipulated so that they be triggered to emit fluorescent proteins when the encounter specific chemicals (Liu et al. 2017). If the Dod is constructed such that the arms are flexible then it may be possible to design them so that when they come in contact with a specific environment that they fulfil their function, e.g. when no water is present the arms stay retracted and when water is present the arms extend either altogether or just the arms that sense a water source, through an increase in humidity (e.g. hydrotropism).

- Similar to the OctoMag (Kummer et al. 2010) whereby the construction material of the microbot is also used as a means to direct and control it, the following projects describe experiments with respect to photo- and chemotactic motion. It illustrates how energy is absorbed from the environment and

\(^{38}\) On average piezoelectric generators last approx. 50hrs.
converted to complete a specific task. This is suitable for systems that are required to complete a single task. The first two projects illustrate motion through the generation of photo gradients with respect to light sensitive chemicals or polymers. The third project highlights the ability for particle locomotion via chemical reactions and the fourth project demonstrates the movement of appendages through the use of pneumatics.

- The microbots described by Lozano illustrate how they react and reorientate according to a light source similar to the manner in which plants orientate towards the sun (Lozano et al. 2016). The microbot is spherical in shape with a diameter of 2.7 micrometers and functions in a liquid based environment. One hemisphere is covered in transparent silicone whilst the other hemisphere is coated with a thin layer of light-absorbing carbon. This construction allows the microbot to re-orientate their polarity according to the photo gradients generated by a laser line focus. The light causes the carbon capped particle to rotate and the temperature to slightly increase. This increase induces local changes in the concentration gradient around the particles and through diffusiophoresis enables the particle to exhibit motion (Lozano et al. 2016). As with many such systems temperature plays a critical role, a high light intensity is required to generate a strong photo gradient. At temps <20deg the photo gradient is not strong enough to illicit any change in the system.

- Another example of how a high light intensity can induce a change is using smart polymers and gels. In the project using graphene-elastin composite hydrogel, a hand shape cut of this thermo-reactive polymer is actuated by the presence of a laser beam. The point at which the laser hits the polymer, the increase in temperature causes it to contract allowing the cut-out to alter its position, i.e. in this instance an appendage could bend upwards. Once the temperature was reduced the cut-out reset to its original state (Wang et al. 2013). An aim of this research was to improve response time and actuation control, elements that are difficult to implement in organic systems. The ability to create smart polymers that can exhibit the behaviours of a variety of materials, may be a viable intermediary step with respect to creating a Dod. Similar to the manner in which the physical design contributes to certain structural functions, the material make-up of the Dod can assist in carrying out
functions that will eventually be controlled by an inherent awareness of the Dod. Honouring the current trend of new technological interfaces, the appropriate behaviour would be simulated but not necessarily innately autonomous. The hydrogels exhibit a reversible behaviour which is advantageous even though it is dependent on external conditions. Many biomedical devices are design to react to a specific trigger within their environment. This is most evident in the development of targeted drug delivery systems (Leong et al. 2009, Palleau et al. 2013, Breger et al. 2015).

- A variant of these types of microbots or particles are those that have catalytic reactions with their environment. Vilela demonstrate liquid based particles that react to water in order to provide them with forward propulsion (Vilela et al. 2017). The primary objective of these particles is water sanitation. They are spherical in shape and are on average 15-20 micrometres in diameter. Each particle is comprised of four materials: their inner core is comprised of iron which is useful for removal as well as guidance properties, one hemisphere is coated in magnesium and the other hemisphere is coated in silver and gold nanoparticles. The magnesium coated hemisphere provides the particle propulsion. When magnesium and water interact hydrogen bubbles are released, the shape and iron core allow for these particles to avail of additional trajectory control. This reaction can last 15+ mins. In relation to the other hemisphere, silver has bactericidal qualities and is the primary mechanism for incapacitating the harmful pathogens in the water sample. The gold layer aids in thiol attachment, i.e. enabling the harmful pathogens to stick to the silver surface of the particle. Once this reaction has expired the particles can be removed via a magnet. An added consideration of this project is to create a robust, low-cost, effective water cleaning system, that has little environmental impact. This relates to the particle production process and the harmful by-products that often result from the use of traditional disinfectants (Vilela et al. 2017).

- Yet another variant of this concept is one that was also an initial starting point for this project: combining living matter with an inorganic fluid that could exhibit shear-thickening qualities. In the case of active fluids, in particular the project of living liquid crystal, swimming bacteria are introduced into a
lyotropic liquid crystal. Among the valuable results to emerge from this project, a key development was using the bacteria as an energy source thereby creating and internal power supply for the liquid crystal (Zhou et al. 2014). Applying such a construction to the Dod is suggestive of a symbiotic relationship that is comparable to the lichen and algae example described earlier.

- The Octobot is a project in the domain of soft robots which utilises the principle of pneumatics based on chemical reactions. The previous particle design explored the direct reaction with the environment, whereas this design is analogous to a diesel engine - the reaction is inbuilt and the resulting output is used throughout the system. The Octobot is comprised of approx. four sections: fuel tank, fuel regulator, reaction chamber and venting channels (i.e. appendages). The fuel tanks are elastic and can, by accommodating a larger volume, create a pressure gradient that forces fuel into the regulator. Through an alternating fuel injection system once the fuel has reached the reaction chamber it decomposes rapidly forming pressurised gas. This gas is directed along the venting channels until it is eventually vented to the outside (Wehner et al. 2016). The system is controlled via a microfluidic logic circuit which enables this design to be considered for soft robotic applications where shape shifting and flexibility are key requirements. The challenge in this system is maintaining the correct balance between fuel injection, actuation and venting pressure and exhaust rate. Translating this concept to the Dod could have substantial potential as the pressure generated in such a system could be used to extend and retract the arms. The current version of the Octobot is approx. the size of an SD card (11x15mm) which is another positive attribute with respect to scaling agent designs. The microfluidic circuit has demonstrated that it is possible to create soft circuitry using alternatives to electricity (Jansen 1990, Wehner et al. 2016).

These projects demonstrate some of the alternative mechanisms by which agents can function and appropriate the energy available to them in the environment. Whilst a large proportion of these processes are dependent on external actuation, it is still possible to learn and further influence the Dod’s design by considering these
possibilities. It should be noted that the projects discussed above each belong to an individual and established research domain, e.g. chemistry, material science, microfluidics, etc. Whilst there are a vast number of other projects in each of these fields the purpose of their discussion in this chapter is to highlight the potential of the Dod design. The fact that these designs can be considered avenues of future research indicate the versatility of the design and the strength and value of the multidisciplinary approach to design.

7.8 Boundary conditions
The concept of one or many boundary conditions is very important (Wu et al. 2017) as they can have a considerable effect on the system to which they are applied. The pertinence of this concept was discussed by Fuller who made the connection between the manner in which geometry is taught, to the way people treat each other or vice versa (Sieden 1989), i.e. in geometry, shapes are identified by the enclosing boundaries - what is inside is seen and identified with (e.g. a triangle); in a society, groups define their boundaries via common interests, beliefs, behaviours, etc and those that are different are viewed as outsiders. Realising how inherent this quality is, is important with respect to how research is analysed and processed. Fuller’s Dymaxion Map (Chapter 1) is an example of how influential boundary perception can be. Boundaries can be both liberating and restrictive depending on the context in which they are applied. Without boundaries, it is difficult to define structure and order, as even chaos has certain boundaries. It is possible to say that no system can exist without boundaries because then it would tend towards an extreme. In the world as it is known the ability of systems to oscillate between extremes is the necessary equilibrium for a system to perpetuate.

It is a transient concept and it is necessary to be aware that there are some boundaries which are consciously created, used, altered, etc but also some boundaries that are inherent to the object or system being explored. For example, consider the shear thickening effect analysed in Non-Newtonian fluids. One scenario illustrates the effect on the fluid in a small container and the other illustrates the effect on the fluid in a swimming pool sized container. In both scenarios, the shear-thickening effect is evident however to varying degrees, depending predominantly on the size of the
boundary condition: the container. The strength of the effect\textsuperscript{39} adapts accordingly. In contrast, the boundary of an air bubble surrounding a fire ant as it is submerged in water directly affects the object itself. These boundaries are physical and to an extent tangible. The impalpable boundaries are more difficult to work with and to predict but can potentially yield the most interesting results. In this project, the boundary conditions are relevant although not always obvious. For example, they have been present in the choice of mechanism for self-assembly: magnetism, the construction of artworks, in the design process itself, etc. For an entity to define its own boundaries is more complex because it requires knowledge of itself, and at least knowledge of its immediate neighbours and/or surroundings. This is pertinent to creating artificial awareness as opposed to artificial intelligence.

In jazz music when learning to improvise the most daunting element for beginners is the vastness of choice. It is interesting that in the possibility of going \textit{anywhere} musically, many players in reality can go \textit{nowhere}. There is too much choice, therefore, boundaries such as scales, riffs, and patterns are just some of the constructs that are used to guide the creativity of the musician in an improvised solo. In relation to this study, even though it was possible for the Dod design to specialise in any one of the numerous avenues discussed in this chapter, the challenge was to create a design that is applicable in as many different solutions as possible: openness or blankness was a defining boundary condition for this design. Self-imposed boundaries, like those implemented as design choices, can adapt according to the designer, but are subject to the current external state as well as the character of the designer. Several research projects support the requirement for restrictions within a system, especially those orientating towards building 3D structures as it is necessary for maintaining structural cohesion (Ishii and Ullmer 1997, Gorbet \textit{et al.} 1998, Overvelde \textit{et al.} 2016). It also depends on the level of control that is desired for the final outcome. More control can equate to a larger quantity of boundary conditions, that could potentially become conflictive in nature, or less yielding boundary conditions. Similar to control if boundary conditions are applied as guidance and provide beneficial limitations to a system or process, it is possible to blend function and creativity effectively.

\textsuperscript{39} Other aspects affect this quality, \textit{e.g.} ratio of water to cornstarch, temperature, force of agitation, etc.
7.9 3D thinking through games

This section of future work considers how the Dod in its concept of being an agent that is part of a larger MAS, can A) become more disseminated, B) how it can encourage haptic exploration through play and C) how it can potentially help train 3D thinking. These are important qualities for the envisioned tangible, shape-shifting interfaces proposed by Butera, Ishii, Sutherland, etc. In its current state, the Dod lends itself to the development into the game or toy domain. This development would have an immediate benefit of dissemination and as the technology becomes more refined would have the later benefits in that the public would be more familiar with the MAS, or programmable matter concept.

An interesting challenge that arose, in relation to the subject of the structures that would be possible to create with the Dod as a new building block, is the 3D visualisation. It is easy and generally widely accessible to express 2D\textsuperscript{40} and 3D ideas with pen and paper. As indicated in Chapter 3 sketching is a powerful tool to convey ideas. However, unless a person is immersed in the practice of visually representing 3D structures (e.g. product designer, artist, architect, etc) or has an aptitude for this skill, even conveying 3D ideas can be difficult. Should 3D thinking be as natural as a person’s ability to speak, do mathematics or draw a picture? Is it right that spatial reasoning is an aptitude that requires special testing or should it be viewed simply as the way children are taught to think? These questions are relevant because people are living and daily manipulating a 3D world yet when it comes to designing and conceptualizing ideas the process is reduced to a more uncomplicated yet limited method - often through sketching. Through education, which is generally issued by adults, a condensed, biased, and focused view of information is presented to children. Children have their own innate methodology and comprehension of the world, which is often much broader, open for possibilities and less prejudiced than that of adults (Sieden 1989). This can be demonstrated by an early example from Buckminster Fuller’s childhood. As a child, he was incredibly short-sighted but he didn’t receive glasses until he was 5 years old. Up to that point he modelled the world according to

\textsuperscript{40}Ironically however even though this process is defined as a 2D medium everything even sketching already occurs 3 dimensionally, i.e. even paper has depth. In a simplified summary, 2 dimensional shapes or constructs only exist conceptually / mathematically and these shapes form planes, which in turn can be used to form 3D objects (Sieden 1989).
his perspective: his reality which up to this point was a blur. In a kindergarten exercise using dried peas and toothpicks the children had to build structures, since Fuller could not see the way buildings were traditionally constructed, i.e. right angles, he developed the octet truss. He would later patent this structure in 1961 but it proved to be stronger, and a closer reflection of nature’s protocol to design for maximum performance with optimum material usage ((Fuller 1975, Sieden 1989). Fuller’s early childhood experience of having an alternative perspective (literally) to the rest of his social world, enabled him to be open to the unknown rather than fear it.

Despite many people being capable of processing and interacting with 3D information, the discrepancy continues to be propagated in the interaction with digital information. Digital representations of 3D objects & and environments are as much an illusion as they are on pen and paper. Thinking in 3D should not be an issue but because it still presents a challenge, new research and types of products are being developed to encourage, facilitate, and train this skill. For example in the digital domain 3D modelling software is available and more importantly accessible to every person with access to a computer, (SketchUp solidworks, zbrush, maya, blender, etc), 3D printing technology is changing the prototyping and fabrication process (Ultimaker, Form1, Makerbot, etc) and actual 3D pens are taking the next step into realising 3D concepts without first translating it into a 2D representation (3D magic Imagi Pen, ID03D Vertical, AtmosFlare, 3Doodler, CreoPop, etc). In other domains such as human computer interaction (HCI), the process of multi-material prototyping, including hands-on modelling, has a strong focus as it encourages the 3D exploration of the prototyping process. Gupta and Khanna are educators that have made physics principles accessible and applicable for young children through the development of toys, e.g. a race car built on a twisted rubber band (Gupta 1991, Gupta 1997, Gupta 1999, Khanna 2000, Khanna et al. 2004). The children can create these toys themselves using readily available materials. The understanding gained through this process is invaluable because they not only learn how the toy works but also how to construct it. This type of learning encompasses a wider range of modalities than the traditional classroom setting, i.e. haptic learning as opposed to a purely cognitive uptake of knowledge. Other toys such as Topobo (Raffle et al. 2004), Meccano, K’Nex, Baufix (Figure 7.3a – 7.3c) and Lego® aim to foster understanding of physics,
engineering, electronics and construction concepts, among other, but also inherently encourage 3D manipulation and an understanding of a 3D environment\textsuperscript{41}.

![Figure 7.3 3D thinking – (a) Meccano, (b) K’Nex, (c) Baufix](image)

Some of the mainstream toys (e.g. Lego®, Meccano) are a simplified representation of the world – straight lines and $90^\circ$ angles. There is however a much larger scope of shapes for achieving the same and sometimes even better results. The entrenched dogma of how the world is viewed is currently based on those who have the most power and thereby who can exert the most influence. Buckminster Fuller’s life can be regarded as evidence of this processes occurring on a frequent basis: Stockade bricks, Dymaxion map, car and house, his geodesic dome designs. These designs were like the truss construction, the dome shape could withstand significantly more wear and tear due to its more natural. Similar to the construction-based toys that already exist, to base a building block on a semi-spherical shape can open opportunities for a new range of creative solutions. As with many of the systems described throughout this study, translating the technology from a lab to a ‘real-world’ environment is a challenge. Each project is primarily exploring one strand of research however it is important to consider that solutions to certain problems may be solved when a larger community becomes involved. Whilst this idea is not new, many projects and ideas are potentially relegated to shelf duty once the study period has expired. Therefore, to maintain a presence in the social conscience, developing the Dod as a toy or a game became a consideration in order to continue its development towards functioning in an autonomous multi agent system.

\textsuperscript{41}A greater trend exists nowadays for children to play on flat computer screens more often; therefore, 3D manipulation may be done artificially through digital representation. In the long term, this may have an effect on the ability for 3D conceptualization and may be the reason why thinking & designing in 3D is still viewed as more challenging.
7.9.1 Game-piece Dod

An interesting result of using a dodecahedron as a fundamental building block is the transient nature of its shape, i.e. it has flat faces enabling stable planes to exist, whilst at the same time embodying the essence of the curved form of a sphere. It can create straight lines by the extension of opposite arms as well as create curves along 2 axes. The Latch Dod demonstrates the motion, function and degree of rigidity / robustness that is required for the Dod design to be implemented as a potential game piece. It currently uses large door springs as latches yet it is possible to reduce this is scale and weight for example by using the latching mechanism found in pens and there is a wide range and choice of colours and materials available. Combining these elements with the use of polymagnets may help define the functionality or gameplay of the Dod in how they connect to one another. Since a game or toy is orientated towards direct user interaction, the need for a power supply is reduced in priority or even superfluous. The size of the design also has greater flexibility and could potentially be presented in varying sizes (e.g. Hoberman sphere). The following games and projects provided inspiration regarding the potential of the Dod to be developed in this direction: Cellulo, Tantrix, Domino, Jenga and Kaltoh. They will be briefly discussed with the elements of relevance to the Dod design highlighted.

7.9.2 Cellulo

This project was mentioned in Chapter 5 as a means of identifying behaviour patterns and methods of their implementation, for the Dod design. To recap, Cellulo is a project that uses swarms computing to link macro-sized robots to affect motion, haptic sensation and visual perception. The aim of the project is to make “tangible what is intangible in learning” (Özgür et al. 2017). Three primary requirements have guided the development of this project to make the interaction with data more accessible: ubiquity, practicality and flexibility. By designing the robots to be ubiquitous follows in the recommendations of Mark Weiser’s description of an excellent tool. The tool itself should be intuitive and easy to learn and so natural to use that the focus and attention of the user is directed towards the task itself rather than be distracted by the implement used to carry out the task (Weiser 1991). Practicality is an essential component of these types of robots and in this instance more accurately refers to the
necessity for robustness of the materials - not only the physical outer appearance but also the interior circuit components. Cellulo is intended to be used regularly in a classroom setting, for a variety of subjects and by children of varying ages. Being able to cope with the unexpected is an advantageous design consideration. Since Cellulo is designed for the scenario of robots in education flexibility and versatility are key factors. Being applicable to a multitude of subjects encourages the integration of this type of technology but also ensures that the robot design is focused towards ease of use, i.e. it should not take up any of the teacher’s time to set up thereby potentially detracting from teaching the subject material itself.

7.9.3 Dominoes & Tantrix
Both games are based on the placement of tiles with specific values on them and can be played solo or as part of a group. A Dominoe tile is a cuboid prism on which a certain number of dots is printed on either half of the tile on one surface divided by a line. The numbers range from 1-6 like a dice. A Tantrix tile is a hexagonal prism and has three lines of different colours and orientation printed on one surface going from one edge to another. In each game, a variety of other puzzles developed from the basic game play: each player chooses a number of tiles whilst the rest remain unallocated and can be used throughout the game when the player’s own tiles cannot be played. In Dominoe tiles must be placed adjacent to each other whereby a following tile can only be placed at one of the two ends of the previously played tile, doubles act as branching points whereby tiles may be placed at one of the four sides of the tile. In Tantrix each player choses a colour and must attempt to lengthen their coloured line by the placement of other tiles. As each tile contains three colours in total it is necessary for the player to ensure that the other colours on the tile also match the previously played tiles. Whilst this can mean one player enhances another players position (by lengthening their line), the line orientations on the tiles (i.e. straight, curved, etc)

42 Dominoes are also famous for their alternative application in their use as a tool to initiate and facilitate chains of reaction (e.g. Dominoe Day). Variants of 3D Dominoe also exist, the 2012 version uses cuboid prisms (divided into 2 cubes through colour) that have one of two colours printed on every side (BoardGameGeek 2012) and a version where triangular prism tiles were used that could connect to create larger 3D structures s.
ensure that it is not a reliable method of gaining an advantage because the line may also be curtailed, e.g. if it does a U-turn.

In both of these games the simple aim of adjoining matching numbers or colours is enhanced and elaborated on by the physical shape of the tile. They are good examples of the principle that complexity can emerge through the interaction of a simple set of rules. These games start from a single origin point and build-up to generate a larger playing field - similar to the concept of having a seed agent that communicates throughout the entire network.

### 7.9.4 Jenga

Jenga is a game based on cuboid building blocks. 54 blocks are stacked in alternating orientation of 90°, in rows of three until a tower of 18 rows is standing. Players alternate in turn each taking one block from any layer (apart from the top two layers) and placing it on the topmost layer in alternate orientation to the existing layer, i.e. the layers of blocks must lie perpendicular to each other. A player may only use one hand but can bump or nudge a block to check its willingness to depart from its current location. A steady hand, as well as good spatial awareness and dexterity are skills practised in this game. The game ends when the tower can no longer retain a stable equilibrium and topples. Similar to Dominoe and Tantrix variants of Jenga also exist, however in Jenga the original playing field is determined from the beginning. As each block is moved, the original tower structure is reconstructed. It succinctly reflects the fundamental thermodynamic property that energy cannot be created or destroyed only altered in its representation.

### 7.9.5 Kal-toh

Many sources of inspiration in the sciences could not exist without the element of creativity. The last game suggestion (Kal-toh) is first mentioned in the science fiction series Star Trek. It is a geometric, shape-shifting based game, whose aim is to train patience as well as logical and rational thought of the user in their attempt to create the final shape of two nested icosidodecahedra. The inner shape is connected to the outer shape by the centre points of the edges (Memory Alpha 2018). Similar concepts such
as the 3D interlocking wooden puzzles already exist today, however the interesting
difference is that the player’s moves in Kaltoh have the potential to initiate a chain
reaction of shape-shifting that can work towards achieving the final structure or,
contrary to the players advantage, can work towards creating greater chaos (like snakes
and ladders), i.e. the game is reactive to the user’s actions. Figure 7.4 illustrates the
starting and end position of Kal-toh (Memory Alpha 2018).

![Figure 7.4 Kaltoh](image)

A key feature of the game is finding the “seeds of order even in the midst of profound
chaos” (Memory Alpha 2018). The player adds or moves the thin rods to specific
locations to set in motion a change of shape that eventually leads to the final structured
geometric shape (like the reapplication of Dominoes, regarding chain-reactions).
Whilst the actual shape-change process is conveniently blurred through special effects
the idea of the game is appealing. The reason and design of the game is explored more
so than the functioning mechanism of the rod attachment which is the strength of art
and in this case science fiction. The icosidodecahedron is an Archimedean solid based
on two primary polygons: pentagon and triangle, which meet in identical vertexes.
Each side of a pentagon is connected to a triangle which has pentagons attached at the
remaining two sides until they meet each other, i.e. the Hoberman sphere. The rods
used in the game enable the player to create the icosidodecahedron by outlining the
edges of the required polygons.

The following points highlight more accessible qualities that make the Dod more
immediately relevant but are also reflected in the academic development of the Dod as
a MAS agent. A game piece must:

- be robust,
- facilitate quick learning (i.e. clear affordances),
- be versatile, possibly have multiple puzzles in one (i.e. shape and size change),
- pattern matching,
7.9 3D thinking through games

- playing with others or individually,
- haptic engagement through 3D exploration (i.e. bi-directionality)

As mentioned throughout this study, Time is an ingredient that has unique effects and pervades every level of existence, regardless if it is artificial or organic, and must be given due respect. The scope for creativity in this domain is substantial because the objectives and boundary conditions have altered. It brings a new set of challenges, but also considers the importance for momentum in research to continue developing the Dod so that it is not relegated to shelf duty. The elements discussed in this chapter provide further sources of research and inspiration that will help refine and contribute to the larger domain of shape-shifting, interactive tangible user interfaces.
8. Conclusion

8.1 Conclusion
This chapter brings together the most important aspects that have arisen in the exploration of real-time, programmable, shape-shifting matter in the domain of tangible user interfaces. The literature discussed throughout this study highlights the areas of interest with respect to the actual physical design. It also informs the contextual question of why this type of interface should be investigated and what space it should inhabit. It is problematic to clearly define applications for interfaces, such as the one proposed in this project because it is technology that aims to redefine how people interact with (digital) information. Instead of developing technology that will alter an existing interface, the technology proposed in this study, as well as the preceding research into emulative processes proposes a novel approach to combining digital and real-world situations.

In Chapter 1 the contribution of this study is mentioned as being twofold, producing A) a tangible prototype of a new agent design and B) a blueprint for potential uses and functions of this agent design both for solid and liquid environments. As the concluding chapter of this study, the important milestones are highlighted that were encountered throughout the research. It demonstrates show these elements form a continuously evolving cycle relating to the subject matter and the researcher. The research question asks what constitutes an adaptable agent design to function in multiagent systems (MAS) for creating 3D real-time shape shifting tangible user interfaces?

The physical representation of this question is the Dod. The very nature in which the shape has been explored demonstrates its versatility and potential. In designing for haptic interfaces, it is important to engage with the subject matter in the mode that is required. Animations and simulations provide valuable insights from varying vantage
points, whilst the construction of prototypes and artworks creates a familiarity with the shape, form and 3D structure of the core design: the dodecahedron.

The philosophical representation of this question can be best portrayed in the attempt to emulate the studied system rather than replicate it. As mentioned in Chapter 1 replication, and thereby understanding, is the first step in exploration and learning. Graduating from this stage of learning to applying knowledge is entailed in the emulation process. This represents working with the essence of an existing system and translating it into an adaptation that works for the new user. Megabot from Chapter 1 is representative of the emulation of a naturally occurring ant hive. It can create structures larger than itself, in any shape or form, but the differences are that it can be directly controlled and its structure is based on geometrical polyhedrons.

In the creation of shapes or structures that are useful for human application, it is necessary to create a usable agent in an emulative rather than replicative approach. Biological systems have had a strong influence on the research procedure throughout this study. An irreplaceable ingredient that these living systems have is Time. It has allowed them to become efficient, optimised and beautiful. These attributes are important criteria that were also considered in the design process. To date, the cube has been and still is the most popular choice for agent design. This applies to large and small-scale proposals for these kind of interfaces, particularly where self-assembly into 3D structures is desired. Whilst this is a good and natural starting point, this study provides evidence that the Dod is potentially better suited for shape-shifting and self-assembling interfaces. The basis of the Dod, the dodecahedron, is in the same polyhedral family as the cube but it bridges the gap between faceted and curved geometry and compromises between both extremes. The imperfection of the Dod, regarding packing, is a characteristic that has not been considered in previous self-assembly projects. This degree of imperfection is sufficient for the overall multiagent system to cope with unexpected environmental changes but is not detrimental enough to interfere with the rudimentary functioning of each Dod. The potential of the Dod is vastly increased through the ability to extend arms that are connected to each facet of

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43 Even though Rubenstein states that the packing order does not make a difference it can be argued that the Kilobot system is based on self-organization more so than self-assembly
8. Conclusion

the inner core dodecahedron. The arms themselves can be made from rigid or soft material, depending on context and use, and the construct of a twisting spring is both scalable and offers other unique behaviours such as bouncing, suspension, structural stability. The facet function is also definable depending of final application. Since there are twelve arms it is possible to organise various setups, so that a certain number of facets could be dedicated to energy harvesting, whilst the remaining arms provide attachment and / or sensory capabilities. Alternatively, the Dod could be made from different materials allowing for one hemisphere to provide purely structural stability whilst the upper hemisphere remains flexible and attuned to the environment, like sea anemones.

The aim of this study was not to create a one size fits all type of agent but rather to extract the essence of shape-shifting interfaces which currently embodies Non-Newtonian fluid-type behaviour, i.e. shear-thickening, which is the ability to behave as a liquid and as a solid. Liquid behaviour allows for smooth and aesthetic transitions and being able to adapt to different sized spaces. Solids are self-contained and can maintain specific functional structures. They are clearly definable and offer suitable affordances with respect to human-computer interaction. In the study of Non-Newtonian and smart fluids the main challenge is to translate the external actuation required for a state change into an internal process, so that a MAS based interface can be directed to what it should transform into, rather than be told how to do so. This differentiation led to research that helped define particle qualities that enabled this kind of shear thickening behaviour. In conjunction with these parameters, analysing the existing research into programmable, self-assembling matter created a list of qualities that relate to the physical design of a particle or agent suitable for creating shape-shifting interfaces. These are as follows:

- The particles are semi-spherical in nature with an irregular, cratered surface. They varied in overall size, enabling relatively close packing when the liquid is displaced.

- The ability to change shape by either changing a smaller part of it (e.g. the surface topology) or all of it (i.e. its fundamental and overall form).

- Scalability: the ability to be able to exist on the macro, micro or even Nano level is advantageous. This means the particle or agent would potentially
8.1 Conclusion

consist of one material that is controllable and / or requires all components to scale accurately. The problem of wear and degradation through continuous use must be considered in the latter option. In scaling to these levels, it is important to consider the natural affordances of shape and form that are inherent in structures (e.g. cubes - can be built upon whereas spheres can be rolled over, etc).

- It is not possible to maintain control over every individual particle / agent as this requires a significant amount of energy and there are too many variables to account for. This requires the ability to function without a hierarchical chain of command and ensures each agent has the autonomy to function as individual agent.

- Simplicity in design is an important consideration. This applies to the tangible as well as the behavioural aspect of an independent agent. Complexity that develops over time and is build up from the interactions of simple constructs is better than a starting complexity and for complexities sake.

- Reversibility is an essentially quality in shape-shifting interfaces and in this instance, is expressed through self-assembly and dis-assembly.

These qualities provide guidelines that inform the design process for the tangible aspects of the agent. The Dod described in this study is envisioned to change its form by becoming larger and smaller, a quality inherent in the Hoberman sphere. This feature is comparable to creating a mass of agents of varying sizes, as seen with cornstarch particles. Aside from becoming larger or smaller, a change in surface topology is inherent in this design. The varied arm configurations enable craters to be formed and thereby contributes to the size change also evident in the cornstarch particles that constitute rheopectic, Non-Newtonian fluids. The issue of scalability is of great importance for the domain of shape-shifting interfaces or programmable matter. The smaller the agent, the higher the resolution of macro structure it can create. Static prototypes were constructed in this study and reduced to a scale of approx. 2mm in diameter which indicates the suitability of the dodecahedron as a basic structure. Microfluidics and micro origami are promising domains that can potentially aid in creating functioning Dod models at this reduced scale.
This study has outlined and discussed features of the Dods physical design and rudimentary behaviour. If agent autonomy has lower priority, i.e. that external control or actuation is acceptable, then the possibility to develop the more immediate potential of the Dod is in the material sciences. The ability to create custom polymers with inherent characteristics such as elasticity, conductivity or thermal reactivity, etc, will stimulate the design process. In creating the Dod as a template, rather than focusing solely on one application, environment, or function, the design process has to retain an element of versatility. Even though scenarios are proposed for this kind of shape-shifting technology, the reality is presently still undefined. The are many examples of technology or tools that are used in ways for which they were not initially intended and some examples of how technology has been adapted and amalgamated, e.g. TV, computers, smart phones, spork. This is both the beauty and curse of human nature: its unpredictability, adaptability and the ingenuity to find uses in both qualities.

Since the aim of these interfaces is not only to react to the user but to interact with them it is necessary for the design to accommodate the quality of bi-directionality. This is evident and unique to the haptic sensory modality. It enables a person to receive input through the act of sensing via touch and to affect the output by reacting to it. For example, vision allows a person to see but not to change or effect what is being seen. Touching a button relates information about texture, shape and material but it is then possible to press the button and thereby affect a direct change in the environment.

Whilst the simulations illustrated that motion is possible in a land or air-based environment, it may be better suited to a liquid environment. The larger outer facets require a greater momentum to overcome the surface area. As described in Chapter 6 the Dod in the simulation moved forward on the edge of the facet and when the flat facet came in full contact with the ground, acted as a brake. The project MBlock which describes a method of modular hydraulics provides a plausible alternative for motion in a liquid. Rather than being a hindrance, the conclusions from the motion simulations support the perspective of the Dod being able to move in a liquid (as a liquid) and building structures (as a solid). Table 8 briefly summarises all the exploratory studies carried out as the research developed.
<table>
<thead>
<tr>
<th>Studies</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Chapter</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct replication</td>
<td>Ant claw</td>
<td>Dodecahedron (HCM 157)</td>
<td>3 and 4</td>
<td>Limited in their compliance with the remaining design parameters. In directly replicating these structures they primarily fulfil their original function but were not easily adapted to alternative applications.</td>
</tr>
<tr>
<td>MR agent</td>
<td>Structural definition</td>
<td>Magnetophoretic display (MD)</td>
<td>4</td>
<td>Whilst being scalable to 2mm, this design lost the structural definition of a dodecahedron and became more spherical. Not ideal, i.e. as restricted as the cube. This design did not work in a MD because the relationships between suspending liquid and magnetic particles do not scale linearly.</td>
</tr>
<tr>
<td>ER agent</td>
<td>Magnet exposure</td>
<td>Container</td>
<td>4</td>
<td>It was possible to maintain the structure of the dodecahedron which is an improvement on the MR based agents. Would require a suitably scaled and controllable attachment mechanism.</td>
</tr>
<tr>
<td>Magnet size</td>
<td>Tetrahedron and dodecahedron</td>
<td></td>
<td>4</td>
<td>5mm ball magnet proved to be superfluous in relation to size and strength. The 3mm ball magnet adequately simulates an assembly behaviour.</td>
</tr>
<tr>
<td>Origami springs</td>
<td>Pentagonal vs octagonal</td>
<td>Scaling</td>
<td>4</td>
<td>Two types of origami towers were studied and their suitability was analysed. Pentagonal spring could be reduced successful in scale, used less material whilst still maintain required strength for the conceptual prototype, demonstrated interesting behaviours (pre-buckling strength). It was also possible to adapt the spring design to create an inverted pentagonal frustum with the same functionality and qualities.</td>
</tr>
<tr>
<td>Structural capability</td>
<td>surfaces</td>
<td></td>
<td>4</td>
<td>The PLA printed prototypes were used to explore the structural capability on a variety of surfaces. As well as this the rudimentary structural elements were deduced: line, curve and cluster.</td>
</tr>
<tr>
<td>Line and curve command</td>
<td></td>
<td></td>
<td>5</td>
<td>Code was generated to test the basic application of static and relative IDs.</td>
</tr>
<tr>
<td>Cluster validity check</td>
<td></td>
<td></td>
<td>5</td>
<td>Code was generated to determine which kind of cluster is formed and whether it is viable, in relation to the anchoring cases that were devised. From this code it could be possible to determine the arm configuration of the next adjoining Dod.</td>
</tr>
</tbody>
</table>
Scalability | Extreme configurations | 6 | The Dod design was tested by scaling the on the Ultimaker and Form 1 printer. The first reduction is such that a ball magnet can fit inside each prototype and the Form 1 prints decrease in scale until the final design (Dod with extended arms) is no longer structurally viable.

Attachment mechanism | Gekko tape vs ball magnets | 6 | Even though ball magnets are free to rotate in the Dod prototype, there are still areas of constructive and destructive magnetic interference that distort the assembling behaviour. Gekko tape reliably connects and disconnects to other agents but is not as strong as the magnet force.

Platonic solids comparison | 6 | The remaining polyhedrons were tested with the arm mechanism. Criteria were determined, the most important of which is being able to generate viable arm configurations, and the 5 polyhedrons were compared.

Artworks | 6 | Steampunk and Origami Dod were primarily tactile and haptic explorations of the dodecahedron shape, informing basic criteria such as packing efficiency, ease of motion and structural advantages (e.g. withstanding greater shearing forces). The String and Latch Dod focus of specific question that emerged later in the research (e.g. soft or ridged material makeup, pre-defined arm configurations).

Comparative analysis | metamaterials | 6 | Elements of a particular study (e.g. origami, use of extension mechanism and regular polygons) were analysed and compared to the Dod design in order to test the validity of hypothesis emerging from an art-based approach.

Simulations | Varied terrain, drops, adaptations to gaps | Motion | 6 | The simulations provide a proof of concept for the Dod design, demonstrating the various behaviours defined as a result of the design parameters.

Table 8 Exploratory studies summary

From a personal perspective the design process in its entirety has been tied together by Don Norman’s concept of emotional design. The influence of emotional affect on the design characteristics, the perception of a specific design itself and the actual design process has been taken into consideration. This converges with the method of handling
control in the decision-making process and defining how much intervention is required. Control attempts to alleviate or compensate for the feeling of fear, with respect to research, generally there is a significant portion of the unknown. The ratio of fear to the unknown is defined by time and is relative to the value of the result. Each component of this equation has a myriad of variables associated with it. All the variables are interpreted from the perspective of the individual, even if the individual is not able to directly influence them. It is a highly individualised equation, combining both the emotional and rational aspects of human nature. In the case of this study, tempering the emotional reaction by increasing positive affect contributed in bringing the agent design to the next level.

Future developments on both immediate as well as future time frames are explored in Chapter 7. Depending on how and in what manner the Dod is required to adapt to, (environmentally orientated, user-centred or application focused), the potential of the Dod design has the scope to be developed further in a variety of fields and functions.

Creating a refined prototype that demonstrates functionality of one isolated research avenue, is an investment of time energy, resources, and funds, e.g. creating a motorised Dod that can move on land. This acute focus of research is the standard procedure, i.e. defining an ideal condition set and studying each individual variable within. In creating a design of a template (the Dod), this study demonstrates that until a specific application or use is defined for shape-shifting interfaces, focusing research at this point in the development of MAS, may overlook opportunities that enable substantial progress to be made. A core approach that has supported the design process is the STEAM approach. The segregation between art and the traditional STEM disciplines was not always as distinct as it is today. This study is an example of how it is possible to bridge the gap between a variety of scientific and artistic fields. Whilst it is necessary to train and develop specific skillsets in order to establish areas of singular expertise, it is as important to develop an expertise in traversing field boundaries whilst still maintaining the integrity of the methodologies unique to each discipline. These are the skills developed by a multidisciplinary expert. As the design space, the advancement of technology and the requirements for creative solutions grows, it is advantageous to refine the ability to evenly combine creative with logical aspects of a diverse range of subjects. Multidisciplinary experts have a select knowledge and
understanding of the fields they specialise in. For example, for this study a good knowledge of handcrafts (crochet and origami), art (aesthetics and haptic exploration), 3D modelling (ceramics and SolidWorks, biology (insects and internal systems) and technology (coding and hacking) provided the fields into which the idea of the Dod could develop. The diverse knowledge base acquired through the combination of these skills, developed an efficiency in finding which areas of specific disciplines have the highest potential relevance.

The inclusion of art in the above mentioned multidisciplinary range, provided a counter balance to the systematic and structured methodology usually applied for a project of this nature (i.e. MAS or programmable matter technology). Artistic methodologies or approaches provide an acceptance for creativity and unforeseen outcomes. Whilst scientists and engineers can be creative, the stricter rules of their field related methodologies usually constrain the expression of creativity. The success of creativity lies in the openness and tolerance of ideas and a lack of fear with respect to failure. The concept of the Silk Road is an example of the possible outcome of such creativity. The network thrived on the accessibility and sharing of knowledge. The lack of definitive boundaries, both physical and mental, ensured that ideas in art, humanities, maths and science, etc. could be actively discussed and disseminated (Salopek 2017). It is evidence for the fact that the STEM disciplines as well as the arts and social sciences are all different facets that encapsulate belief structures, that are inherent to the workings of the human mind. These facets of belief are required for the formulation and conceptualisation of abstract ideas and should not exist in isolation. Art, science, maths, physics, biology, music, etc are equivalent to different looking glasses each providing the viewer with an alternative perspective, understanding and also creating a more complete picture of the world and their place in it.

The observations made as a result of the explorations described in Chapter 6, demonstrate the viability of art as a means to hypothesise aspects that are usually considered to be the territory of the STEM fields. For example, the String Dod artwork provided insights into behaviours that are evident in smart polymers or SMA or highlights structural coherence issues considered in mechanical engineering. The ability of these hypothesise to be translated from an artistic into a scientific domain, to undergo further exploration and experimentation in the respective fields (e.g. material
sciences, maths, engineering), indicates the close relationship between subjects that are currently considered as separate entities. The interplay between the reasoning methods mentioned in Chapter 3, section 3.1.3, is an indicator that these methods are applicable to a person as opposed to any specific subject (e.g. art, maths, etc). Deduction is a narrowing of focus, whilst induction diffuses focus and over time subjects have developed different levels of tolerance or preference for either method, e.g. the association of deductive inference with science. In being able to implement both reasoning methods to varying degrees was also another advantage of being a multidisciplinary study.

An objective of this study was to create a blueprint for an agent template design. A challenge of creating such a template is the necessity for it to be applicable, flexible and initially adapt to any generalised application until a specific application can be determined, i.e. a physical manifestation reflective of the predominant reasoning approach fostered.
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Ubicomp


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Appendix A

The particles in the following images are based on the ER and MR effect from section 4.2.2 and 4.2.3. They were printed with varying wall thicknesses: 3.4mm, 3.6, and 3.8mm in order to test the overall structural integrity. The fillet indicates that the edges of the hole in the ER particle were rounded. It was determined that, at this scale, it made little different to the structure.

These particles were photographed using a Digital USB Microscope Video Camera. 1.3 Megapixels and 200x magnification factor allows for a 1280 x 1024 pixel capture resolution. It has 24bit colour with a manual focus from 10mm to infinity. It is also capable of AVI video format with internal lighting.
<table>
<thead>
<tr>
<th>Thick</th>
<th>Solid</th>
<th>Hole with Fillet (0.05mm)</th>
<th>Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>A01</td>
<td>B01</td>
<td>C01</td>
<td></td>
</tr>
<tr>
<td>A02</td>
<td>B02</td>
<td>C02</td>
<td></td>
</tr>
<tr>
<td>A02b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A02c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium</th>
<th>Solid</th>
<th>Hole with Fillet (0.05mm)</th>
<th>Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>D01</td>
<td>E01</td>
<td>F01</td>
<td></td>
</tr>
<tr>
<td>D02</td>
<td>E02</td>
<td>F02</td>
<td></td>
</tr>
<tr>
<td>D02b</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thin</th>
<th>Solid</th>
<th>Hole with Fillet (0.05mm)</th>
<th>Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>G01</td>
<td>H01</td>
<td>I01</td>
<td></td>
</tr>
<tr>
<td>G02</td>
<td>H02</td>
<td>I02</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

The following images depict the parameters of the prototypes based on Hsaio’s bisymmetric hendecahedrons. On the left side, the drawings are scaled 1:1 indicating their actual size when printed. The inscribed circle determines the size of the resulting polyhedron as it is the parameter around which the basic polygon is modelled (triangle / pentagon).

On the right side are profile images that illustrate the distance between the magnets in the various models. The apex between spheres is used as a reliable point from which to measure the position of the magnets in relation to each other. This does not represent the minimum material between the magnets.
Scaled 1:1

$\Phi 16.17$

Scaled 2:1

5 mm ball magnet
Close Together

$\Phi 11.37$

3 mm ball magnet
Close Together

$\Phi 24.83$

5 mm ball magnet
Wide Apart

$\Phi 20.21$

3 mm ball magnet
Wide Apart
Appendix C

The Line tag and Curve tag code is described in the following section and is referenced in Chapter 5, section 5.4.1.

This is original code using the Eclipse IDE and Java 8 language. The hardware used is as follows:

- Windows 10 Pro
- Processor: Intel(R) Core(TM) i7-7500U CPU@2.70GHz 2.90Ghz
- Installed Memory (RAM): 16.0GB
- System Type: 64-bit Operating System, x64-based processor

The IDE used was Eclipse Neon version 4.0.
Line Tag

/*In this piece of code the aim is to establish the root or standing position of a D6D and how it behaves when another D6D connects to it. The principle of IR Sensors is used, i.e. the lowest value is the least distance from a solid surface. In this trial sensors values are randomly generated. Once the lowest value is detected, that arm's sensor ID is adjusted relative to the static arm ID.*/

import java.util.Random;

public class LineTagCommented {
    public static void main(String[] args) {
        int sensorValue, sensorValue2, sensorNum = 0, a;
        // an array for the 12 arms
        int[] sensor = new int[13];

        // variables to store minimum value
        int minValue = Integer.MAX_VALUE;

        // these variables represent the tags that are emitted according to the situation
        boolean arm1Connected = false, arm12Connected = false,
                        arm1RC = false, arm12RC = false;

        // a random value between 1 and 255 is generated and attributed to the sensorValue this simulates the sensors
        for (int x = 1; x <= 12; x++)
        {
            Random rand = new Random();
            sensorValue = rand.nextInt(256) + 1;
            sensor[x] = sensorValue;
            if (sensor[x] < minValue)
            {
                minValue = sensor[x];
                sensorNum = x;
            }
        }

        System.out.println("Minimum sensor value is: "+ minValue + " and " + "correlates to sensor " + sensorNum);

        // setting up the array for 12 relative arm ID the key rule for the Line Tag is that only opposite arms activate because of the ability to re assign the arm ID, regardless of the sensor ID, it will always be Arm 1 and Arm 12 to create a line */
        int[] arm = new int[13];
        for (a = 1; a < 13; aa++)
        {
            // this is to reset the sensor ID and loop from 1 to 12
arm[a] = sensorNum++;  
if(sensorNum==13)
{
    sensorNum=1;
}
System.out.println(" Arm["a+1"] corresponds to "
                + "Sensor " + arm[a]);
if(a==1)
{
    //emit signal Arm 1 is connected
    arm1Connected = true;
    System.out.println("Arm 1 is activated");
}
if(a == 12)
{
    /*Arm 12 is always the opposite to Arm 1 so
     * until its sensor value decreases by a
     * certain value, Arm 12 will activate its
     * attachment mechanism. Once the value is
     * below a specified value it will indicate
     * that it is connected either to another
     * Dod or surface.
     * 
     * technically need a new sensor value here
     * this would be replaced by actual sensor
     * input */
    Random rand2 = new Random();
    sensorValue2 = rand2.nextInt(41);
    System.out.println(" ");
    System.out.println("Arm 12 is Ready to 
            + "Connect");
    System.out.println(" ");
    System.out.println("If sensor value is 
            + "less " + "than " + "20 the 
            + "Arm can attach");
    System.out.println("Sensor Value: 
            + sensorValue2);
    arm12RC = true; //turn on attaching
            //mechanism

    if(sensorValue2 < 20)
    {
        //emit signal Arm 12 is connected
        arm12Connected = true;
        System.out.println(" ");
        System.out.println("Arm 12 is now 
                + "connected and 
                + "corresponds to 
                + "Sensor " + arm[a]);
                System.out.println(" ");
    }
    
    
}
/* In this piece of code the aim is to establish the root or standing position of a Dod and how it behaves when another Dod connects to it. The principle of IR Sensors is used, i.e. the lowest value is the least distance from a solid surface. In this trial sensors values are randomly generated. Once the lowest value is detected, that arm's sensor ID is adjusted relative to the static arm ID. */

```java
import java.util.Random;

public class CurveTagCommented3 {

    public static void main(String[] args) {
        int sensorValue, sensorValue2 = 0, sensorValue3 = 0,
            angle = 0, sensorNum = 0, sensorNum2 = 0,
            sensorNum3 = 0, a, x, y, z;

        // an array for the 12 arms
        int[] sensor = new int[13];
        int[] sensor2 = new int[7];
        int[] sensor3 = new int[13];

        // variables to store minimum value
        int minValue = Integer.MAX_VALUE;
        int minValue2 = Integer.MAX_VALUE;
        int minValue3 = Integer.MAX_VALUE;

        // simulates the other arm that is either acute or obtuse
        // angle in a curve the command must include that arm 12
        // is not valid

        boolean arm1Connected = false, ObConnected = false,
            AcConnected = false;

        Random tag = new Random();
        angle = tag.nextInt(2);
        // a random value between 1 and 255 is generated and
        // attributed to the sensorValue this simulates the
        // sensors

        for (x = 1; x <= 12; x++)
        {
            Random rand = new Random();
            sensorValue = rand.nextInt(256) + 1;

            // System.out.println(sensorValue);
            sensor[x] = sensorValue;
            if (sensor[x] < minValue)
            {
                minValue = sensor[x];
                sensorNum = x;
            }
        }

        System.out.println("Minimum sensor value is: "
            + minValue + " and correlates to sensor "
            + sensorNum);

        // setting up the array for 12 relative arm ID
        // the key rule for the Curve Tag is that opposite arms
        // do not activate*/
        int[] arm = new int[13];
    }
}
```
for(a = 1; a < 13; a++)
{
    arm[a] = sensorNum++;
    //this is to reset the sensor ID and loop from 1 to 12
    if(sensorNum==13)
    {
        sensorNum=1;
    }
    System.out.println("Arm["+a+" ] corresponds to "+"Sensor "+arm[a]);
    if(a==1)
    {
        //emit signal Arm 1 is connected
        arm1Connected = true;
        System.out.println("Arm 1 is activated");
    }
    System.out.println("Arm ["+a+" ] is now connected");
} //emit signal Arm 1 is connected

if(angle == 0)
{
    System.out.println("Create an Acute angle");
    for( y = 2; y<7; y++)
    {
        Random rand3 = new Random();
        sensorValue2 = rand3.nextInt(256)+1;
        sensor2[y] = sensorValue2;
        if (sensor2[y] < minValue2)
        {
            minValue2 = sensor2[y];
            sensorNum2 = y;
        }
    }
    System.out.println("Minimum value in the lower "+"hemisphere is: "+minValue2+", this corresponds to Arm "+sensorNum2);
    //System.out.println("Arm " + sensorNum2 + " is Ready to Connect");
    System.out.println("Arm " + sensorNum2 + " is "+"now connected");
    System.out.println(" ");
    /* A distinction is made between ready to connect 
    * and connected. Once a sensor goes below a 
    * certain value, it would emit a connected 
    * signal, up until then it is waiting and 
    * simply signaling that it is ready*/
    
    // System.out.println("If sensor value is less than 
    // 20 the Arm can connect");
    // System.out.println("Sensor Value: "+sensorValue2);
    // if(sensorValue2 < 20)
    // {
    //    //emit signal Arm 12 is connected
    //    AcConnected = true;
    //    System.out.println("Arm " + a + " is now 
    //    connected");
    // }
else
{
    System.out.println("Create an Obtuse angle");
    for( z = 7; z<12; z++)
    {
        Random rand4 = new Random();
        sensorValue3 = rand4.nextInt(256)+1;
        // System.out.println(sensorValue2);
        sensor3[z] = sensorValue3;
        if (sensor3[z] < minValue3)
        {
            minValue3 = sensor3[z];
            sensorNum3 = z;
        }
    }
    System.out.println("Minimum value in the upper "+"hemisphere is: "+minValue3+", this corresponds to Arm "+sensorNum3);
    // System.out.println("Arm " + sensorNum2 + " is Ready to Connect");
    System.out.println("Arm " + sensorNum3 + " is " + "now connected");
    System.out.println(" ");
    /* A distinction is made between ready to connect
    * and connected. Once a sensor goes below a
    * certain value, it would emit a connected
    * signal, up until then it is waiting and
    * simply signaling that it is ready*/

    // System.out.println("If sensor value is less than
    // 20 the Arm can connect");
    // System.out.println("Sensor Value: " + sensorValue2);
    // if(sensorValue2 < 20)
    // {
    //     //emit signal Arm 12 is connected
    //     ObConnected = true;
    //     // System.out.println("Arm " + a + " is now
    //     connected");
    // }
}
}
Appendix D

The following code demonstrates a possible mechanism that can identify the variety of crater formations that can occur depending on the anchor cluster being formed. Case A to D describe the various arm configurations of the 3 Dods require to initiate an anchor cluster: all arms retracted (Case A), extended (Case B), 2 Dods with arms retracted and 1 Dod with arms extended, and 1 Dod with arms extended (Case C), 1 Dod with arms retracted and 1 Dod with 1 arm retract and 1 extended (Case D).

The user enters an 8-digit binary value, 2 digits indicate the Case select and the remaining 6 determine the crater formation depending on the Case and arm configuration.
import java.util.*;

public class Dod1 {
    public static void main(String[] args) {
        Scanner scan = new Scanner(System.in);
        char letter = '0';
        int digits[] = new int[8];
        System.out.println("3E = 3 arms extended + \"n\" + "3R = "+ "3 arms retracted");
        System.out.println("2E1R = 2 arms extended & 1 arm retracted" + "\n\n" + "2R1E = 2 arms retracted & 1 arm \"+ \"extended\")
        System.out.println("Case A = all anchoring arms are \"+ "retracted\" + \"n\" + "Case B = all anchoring \" + \"arms are extended\")
        System.out.println("Case C = when Agent 1 = 2 arms extended, Agent 2 = 2 arms retracted, Agent 3 = 2 arms retracted\" + "\n\n" + "Case D = when Agent 1 = 2 arms extended, Agent 2 = 2 arms retracted, Agent 3 = 1 arm + extended & 1 arm retracted\" + "\n\n" + "retracted\" + \"n\")
        while (true) {
        //Takes in user input
        System.out.print("Enter 8 digit binary value, \"+ \"e.g 10101010: \");
        int DodCluster = Integer.parseInt(scan.nextLine());
        //First two digits define the Case, remaining digits
determine the type of crater formation possible
        for (int i = 0; i < 8; i++) {
            int digitBreakdown = DodCluster % 10;
            DodCluster = DodCluster / 10;
            digits[i] = digitBreakdown;
        }
        //case A - when all arms are retracted
        if (digits[0] == 0 && digits[1] == 0) {
            letter = 'A';
            System.out.println("Case A: ");
        }
        //case B - when all arms are expanded
        if (digits[0] == 1 && digits[1] == 1) {
            letter = 'B';
            System.out.println("Case B: ");
        }
        //case C - when Agent 1 = 2 arms extended, Agent 2 =
        //2 arms retracted, Agent 3 = 2 arms retracted
        if (digits[0] == 1 && digits[1] == 0) {
            letter = 'C';
            System.out.println("Case C: ");
        }
// case D - when Agent 1 = 2 arms extended, Agent 2 = 2 arms retracted, Agent 3 = 1 arm extended & 1 arm retracted
if(digits[0] == 0 && digits[1] == 1)
{
    letter = 'D';
    System.out.println("Case D: ");
}

// the remaining values define the sides and the craters that are formed
switch(letter){
    case 'A':
        {
            System.out.println("3R A ");
            System.out.println("3R B" + "t");
        }
        else{
            System.out.println("This configuration " + "is not valid.");
        }
        break;
    case 'B':
            System.out.println("3E A ");
            System.out.println("3E B" + "t");
        }
        else{
            System.out.println("This configuration " + "is not valid.");
        }
        break;
    case 'C':
           digits[6] == 0) {
            System.out.println("3R A ");
            } 
           digits[7] == 0){
            System.out.println("3R B" + "t");
        } 
           digits[6] == 1) {
            System.out.println("2E1R A ");
            } 
           digits[7] == 1){
            System.out.println("2E1R B" + "t");
        } 
}
Appendix D

```java
    digits[6] == 0) {
    System.out.println("2E1R A ");
}
    digits[7] == 0) {
    System.out.println("2E1R B + "t");
}
    digits[6] == 1) {
    System.out.println("2R1E A ");
}
    digits[7] == 1) {
    System.out.println("2R1E B + "t");
}  
/**************************
    digits[6] == 0) {
    System.out.println("2E1R A ");
}
    digits[7] == 0) {
    System.out.println("2E1R B + "t");
}
    digits[6] == 1) {
    System.out.println("2R1E A ");
}
    digits[7] == 1) {
    System.out.println("2R1E B + "t");
}
    digits[6] == 0) {
    System.out.println("2R1E A ");
}
    digits[7] == 0) {
    System.out.println("2R1E B + "t");
}
    digits[6] == 1) {
    System.out.println("3E A ");
}
    digits[7] == 1) {
    System.out.println("3E B + "t");
}
break;

case 'D':
        digits[6] == 0) {
        System.out.println("3E A ");
    }
        digits[7] == 0) {
        System.out.println("3E B + "t");
    }
```
```java
    digits[6] == 1) {
    System.out.println("2E1R A ");
}
    digits[7] == 1) {
    System.out.println("2E1R B" + "t");
}
    digits[6] == 0) {
    System.out.println("2R1E A ");
}
    digits[7] == 0) {
    System.out.println("2R1E B" + "t");
}
    digits[6] == 1) {
    System.out.println("2R1E A ");
}
    digits[7] == 1) {
    System.out.println("2R1E B" + "t");
}
    digits[6] == 0) {
    System.out.println("2E1R A ");
}
    digits[7] == 0) {
    System.out.println("2E1R B" + "t");
}
    digits[6] == 1) {
    System.out.println("2R1E A ");
}
    digits[7] == 1) {
    System.out.println("2R1E B" + "t");
}
    digits[6] == 0) {
    System.out.println("2R1E A ");
}
    digits[7] == 0) {
    System.out.println("2R1E B" + "t");
}
    digits[6] == 1) {
    System.out.println("3R A ");
}
    digits[7] == 1) {
    System.out.println("3R B" + "t");
}
break;
```
Appendix D

```java
//switch
if(digits[0] == 9){
    break;
}
//whileloop
System.out.println("Finished");
//public main
}
//class
```
Appendix E

The physics engine Box2D, developed by Erin Catto, was used to give the Dod simulation a semblance of reality. This engine allows structures to exhibit specific behaviours when experiencing different physics. For example, in the simulation the Dod required prismatic joints to simulate the arm extension mechanism, it experienced momentum, spring, friction and gravitational forces and it interacted with the environment and other agents.

RUBE (really useful box2d editor) version 1.7.4, developed by Chris Campbell, is an IDE that made the application of the physics engine more accessible. The agent (the profile of the Dod) was constructed in RUBE and the various joints and physics forces were defined, i.e. how dense the material should behave, how strong the motors were in the prismatic joints, how far they would extend, etc. The terrain within which the Dods move, was also constructed in RUBE, but defined as a static structure as opposed to a dynamic one.

RUBE outputs JSON files which was manipulated further in CodeBlocks. The version used in this project is release 16.01, rev 10702 (2016-01-25 19:50:14) gcc 4.9.2 Windows/unicode - 32 bit. In this phase certain functionalities of the agent / Dod was linked to keyboard controls and programmed through C++ language. The functionality relates primarily to the extension and retraction of arms as well as the sequential extension for the forward motion simulation (supplementary material 7).
The code is written such that both simulations are contained in the same file and one or the other is commented out. Each Dod requires a block of code that addresses the motor and joint state (speed, direction, strength, etc).

**Dod Simulation**

/*
 * Author: Chris Campbell - www.iforce2d.net
 *
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 * warranty. In no event will the authors be held liable for any damages
 * arising from the use of this software.
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 * appreciated but is not required.
 * 2. Altered source versions must be plainly marked as such, and must not be
 * misrepresented as being the original software.
 * 3. This notice may not be removed or altered from any source distribution.
 */

#ifndef HelTest_H
#define HelTest_H

//todo: cleanup textures in destructor

#include "rubestuff/b2dJson.h"
#include "rubestuff/b2dJsonImage_OpenGL.h"
class HelTest : public Test
{
  public:
    HelTest()
    {
      int i = 0;
      b2dJson json;
      string errorMsg;
      b2World* world = json.readFile( "C:\Users\Helen Hasenfuss\Documents\Box2d_v2.1.2\box2d-testbed-(C++) - Copy\data-files\version5.json", errorMsg );
      if ( world ) {
        // replace testbed world
        delete m_world;
        m_world = world;

        // re-set standard testbed stuff
        m_world->SetDestructionListener(&m_destructionListener);
        m_world->SetContactListener(this);
        m_world->SetDebugDraw(&m_debugDraw);

        // re-create body needed for testbed mousejoint
        b2BodyDef bodyDef;
        m_groundBody = m_world->CreateBody(&bodyDef);

        // load images
        vector<b2dJsonImage*> images;
        json.getAllImages(images);
        for (int i = 0; i < (int)images.size(); i++) {
          b2dJsonImage* img = new b2dJsonImage_OpenGL(images[i]);
m_images.push_back(img);
}

std::sort(m_images.begin(), m_images.end(),
b2dJsonImage_renderOrder_ascending);

// calling the data from JSON file
terrainBody = json.getBodyByName("Terrain");
terrain2Body = json.getBodyByName("TerrainB");

//SHORT ARM EXTENSION

// Each structure created in RUBE must be assigned a body in the world so that it can
// exist
arm1Body = json.getBodyByName("Arm1");
arm2Body = json.getBodyByName("Arm2");
arm3Body = json.getBodyByName("Arm3");
arm4Body = json.getBodyByName("Arm4");
arm5Body = json.getBodyByName("Arm5");
arm6Body = json.getBodyByName("Arm6");
coreBody = json.getBodyByName("Core");

/* // The following is necessary for the multi agent simulation
arm1EBody = json.getBodyByName("Arm1E");
arm2EBody = json.getBodyByName("Arm2E");
arm3EBody = json.getBodyByName("Arm3E");
arm4EBody = json.getBodyByName("Arm4E");
arm5EBody = json.getBodyByName("Arm5E");
arm6EBody = json.getBodyByName("Arm6E");
coreEBody = json.getBodyByName("CoreE");

arm1GBody = json.getBodyByName("Arm1G");
arm2GBody = json.getBodyByName("Arm2G");
*/
arm3GBody = json.getBodyByName("Arm3G");
arm4GBody = json.getBodyByName("Arm4G");
arm5GBody = json.getBodyByName("Arm5G");
arm6GBody = json.getBodyByName("Arm6G");
coreGBody = json.getBodyByName("CoreG");

arm1LBody = json.getBodyByName("Arm1L");
arm2LBody = json.getBodyByName("Arm2L");
arm3LBody = json.getBodyByName("Arm3L");
arm4LBody = json.getBodyByName("Arm4L");
arm5LBody = json.getBodyByName("Arm5L");
arm6LBody = json.getBodyByName("Arm6L");
coreLBody = json.getBodyByName("CoreL");

arm1XBody = json.getBodyByName("Arm1X");
arm2XBody = json.getBodyByName("Arm2X");
arm3XBody = json.getBodyByName("Arm3X");
arm4XBody = json.getBodyByName("Arm4X");
arm5XBody = json.getBodyByName("Arm5X");
arm6XBody = json.getBodyByName("Arm6X");
coreXBody = json.getBodyByName("CoreX");

arm1WBody = json.getBodyByName("Arm1W");
arm2WBody = json.getBodyByName("Arm2W");
arm3WBody = json.getBodyByName("Arm3W");
arm4WBody = json.getBodyByName("Arm4W");
arm5WBody = json.getBodyByName("Arm5W");
arm6WBody = json.getBodyByName("Arm6W");
coreWBody = json.getBodyByName("CoreW");
arm1UBody = json.getBodyByName("Arm1U");
arm2UBody = json.getBodyByName("Arm2U");
arm3UBody = json.getBodyByName("Arm3U");
arm4UBody = json.getBodyByName("Arm4U");
arm5UBody = json.getBodyByName("Arm5U");
arm6UBody = json.getBodyByName("Arm6U");
coreUBody = json.getBodyByName("CoreU");

arm1NBody = json.getBodyByName("Arm1N");
arm2NBody = json.getBodyByName("Arm2N");
arm3NBody = json.getBodyByName("Arm3N");
arm4NBody = json.getBodyByName("Arm4N");
arm5NBody = json.getBodyByName("Arm5N");
arm6NBody = json.getBodyByName("Arm6N");
coreNBody = json.getBodyByName("CoreN");

arm1IBody = json.getBodyByName("Arm1I");
arm2IBody = json.getBodyByName("Arm2I");
arm3IBody = json.getBodyByName("Arm3I");
arm4IBody = json.getBodyByName("Arm4I");
arm5IBody = json.getBodyByName("Arm5I");
arm6IBody = json.getBodyByName("Arm6I");
coreIBody = json.getBodyByName("CoreI");

*/

//LONG ARM EXTENSION

//Each structure created in RUBE must be assigned a body in the world so that it can
//exist

arm1DBody = json.getBodyByName("Drm1");
arm2DBody = json.getBodyByName("Drm2");
arm3DBody = json.getBodyByName("Drm3");
arm4DBody = json.getBodyByName("Drm4");
arm5DBody = json.getBodyByName("Drm5");
arm6DBody = json.getBodyByName("Drm6");
coreDBody = json.getBodyByName("Dore");

/* The following is necessary for a multi agent simulation */
arm1FBody = json.getBodyByName("Frm1");
arm2FBody = json.getBodyByName("Frm2");
arm3FBody = json.getBodyByName("Frm3");
arm4FBody = json.getBodyByName("Frm4");
arm5FBody = json.getBodyByName("Frm5");
arm6FBody = json.getBodyByName("Frm6");
coreFBody = json.getBodyByName("Fore");

arm1JBody = json.getBodyByName("Jrm1");
arm2JBody = json.getBodyByName("Jrm2");
arm3JBody = json.getBodyByName("Jrm3");
arm4JBody = json.getBodyByName("Jrm4");
arm5JBody = json.getBodyByName("Jrm5");
arm6JBody = json.getBodyByName("Jrm6");
coreJBody = json.getBodyByName("Jore");

arm1MBody = json.getBodyByName("Mrm1");
arm2MBody = json.getBodyByName("Mrm2");
arm3MBody = json.getBodyByName("Mrm3");
arm4MBody = json.getBodyByName("Mrm4");
arm5MBody = json.getBodyByName("Mrm5");
arm6MBody = json.getBodyByName("Mrm6");
coreMBody = json.getBodyByName("More");

arm1YBody = json.getBodyByName("Yrm1");
arm2YBody = json.getBodyByName("Yrm2");
arm3YBody = json.getBodyByName("Yrm3");
arm4YBody = json.getBodyByName("Yrm4");
arm5YBody = json.getBodyByName("Yrm5");
arm6YBody = json.getBodyByName("Yrm6");
coreYBody = json.getBodyByName("Yore");

arm1VBody = json.getBodyByName("Vrm1");
arm2VBody = json.getBodyByName("Vrm2");
arm3VBody = json.getBodyByName("Vrm3");
arm4VBody = json.getBodyByName("Vrm4");
arm5VBody = json.getBodyByName("Vrm5");
arm6VBody = json.getBodyByName("Vrm6");
coreVBody = json.getBodyByName("Vore");

arm1ZBody = json.getBodyByName("Zrm1");
arm2ZBody = json.getBodyByName("Zrm2");
arm3ZBody = json.getBodyByName("Zrm3");
arm4ZBody = json.getBodyByName("Zrm4");
arm5ZBody = json.getBodyByName("Zrm5");
arm6ZBody = json.getBodyByName("Zrm6");
coreZBody = json.getBodyByName("Zore");

arm1HBody = json.getBodyByName("Hrm1");
arm2HBody = json.getBodyByName("Hrm2");
arm3HBody = json.getBodyByName("Hrm3");
arm4HBody = json.getBodyByName("Hrm4");
arm5HBody = json.getBodyByName("Hrm5");
arm6HBody = json.getBodyByName("Hrm6");
coreHBody = json.getBodyByName("Hore");
arm1KBody = json.getBodyByName("Krm1");
arm2KBody = json.getBodyByName("Krm2");
arm3KBody = json.getBodyByName("Krm3");
arm4KBody = json.getBodyByName("Krm4");
arm5KBody = json.getBodyByName("Krm5");
arm6KBody = json.getBodyByName("Krm6");
coreKBody = json.getBodyByName("Kore");

/*/  
//SHORT ARM EXTENSION  
//to access and affect the joints of the agent, they must be called and stored in a
//variable.

m_jointT = (b2PrismaticJoint*)json.getJointByName("top");
m_jointTR = (b2PrismaticJoint*)json.getJointByName("topRight");
m_jointBR = (b2PrismaticJoint*)json.getJointByName("bottomRight");
m_jointB = (b2PrismaticJoint*)json.getJointByName("bottom");
m_jointBL = (b2PrismaticJoint*)json.getJointByName("bottomLeft");
m_jointTL = (b2PrismaticJoint*)json.getJointByName("topLeft");

//The following code is necessary for a multi agent simulation
m_jointTe = (b2PrismaticJoint*)json.getJointByName("eop");
m_jointTRe = (b2PrismaticJoint*)json.getJointByName("eopRight");
m_jointBRe = (b2PrismaticJoint*)json.getJointByName("eottomRight");
m_jointBe = (b2PrismaticJoint*)json.getJointByName("eottom");
m_jointBLE = (b2PrismaticJoint*)json.getJointByName("eottomLeft");
m_jointTLe = (b2PrismaticJoint*)json.getJointByName("eopLeft");

m_jointTg = (b2PrismaticJoint*)json.getJointByName("gop");
m_jointTRg = (b2PrismaticJoint*)json.getJointByName("gopRight");
m_jointBRg = (b2PrismaticJoint*)json.getJointByName("gottomRight");
m_jointBg = (b2PrismaticJoint*)json.getJointByName("gottom");
m_jointBLg = (b2PrismaticJoint*)json.getJointByName("gottomLeft");
m_jointTLg = (b2PrismaticJoint*)json.getJointByName("gopLeft");
m_jointTl = (b2PrismaticJoint*)json.getJointByName("lop");
m_jointTRl = (b2PrismaticJoint*)json.getJointByName("lopRight");
m_jointBRl = (b2PrismaticJoint*)json.getJointByName("lottomRight");
m_jointBLl = (b2PrismaticJoint*)json.getJointByName("lottomLeft");
m_jointTLl = (b2PrismaticJoint*)json.getJointByName("lopLeft");
m_jointTx = (b2PrismaticJoint*)json.getJointByName("xop");
m_jointTRx = (b2PrismaticJoint*)json.getJointByName("xopRight");
m_jointBRx = (b2PrismaticJoint*)json.getJointByName("xottomRight");
m_jointBx = (b2PrismaticJoint*)json.getJointByName("xottom");
m_jointBLx = (b2PrismaticJoint*)json.getJointByName("xottomLeft");
m_jointTLx = (b2PrismaticJoint*)json.getJointByName("xopLeft");
m_jointTw = (b2PrismaticJoint*)json.getJointByName("wop");
m_jointTRw = (b2PrismaticJoint*)json.getJointByName("wopRight");
m_jointBRw = (b2PrismaticJoint*)json.getJointByName("wottomRight");
m_jointBw = (b2PrismaticJoint*)json.getJointByName("wottom");
m_jointBLw = (b2PrismaticJoint*)json.getJointByName("wottomLeft");
m_jointTLw = (b2PrismaticJoint*)json.getJointByName("wopLeft");
m_jointTu = (b2PrismaticJoint*)json.getJointByName("uop");
m_jointTRu = (b2PrismaticJoint*)json.getJointByName("uopRight");
m_jointBRu = (b2PrismaticJoint*)json.getJointByName("uottomRight");
m_jointBu = (b2PrismaticJoint*)json.getJointByName("uottom");
m_jointBLu = (b2PrismaticJoint*)json.getJointByName("uottomLeft");
m_jointTLu = (b2PrismaticJoint*)json.getJointByName("uopLeft");
m_jointTn = (b2PrismaticJoint*)json.getJointByName("nop");
m_jointTRn = (b2PrismaticJoint*)json.getJointByName("nopRight");
m_jointBRn = (b2PrismaticJoint*)json.getJointByName("nottomRight");
m_jointBn = (b2PrismaticJoint*)json.getJointByName("nottom");
m_jointBLn = (b2PrismaticJoint*)json.getJointByName("nottomLeft");
m_jointTLn = (b2PrismaticJoint*)json.getJointByName("nopLeft");

m_jointTi = (b2PrismaticJoint*)json.getJointByName("iop");
m_jointTRi = (b2PrismaticJoint*)json.getJointByName("iopRight");
m_jointBRi = (b2PrismaticJoint*)json.getJointByName("iottomRight");
m_jointBi = (b2PrismaticJoint*)json.getJointByName("iottom");
m_jointBLi = (b2PrismaticJoint*)json.getJointByName("iottomLeft");
m_jointTLi = (b2PrismaticJoint*)json.getJointByName("iopLeft");

*/

//LONG ARM EXTENSION

//to access and affect the joints of the agent, they must be called and stored in a
//variable.

m_jointTd = (b2PrismaticJoint*)json.getJointByName("dop");
m_jointTRd = (b2PrismaticJoint*)json.getJointByName("dopRight");
m_jointBRd = (b2PrismaticJoint*)json.getJointByName("dottomRight");
m_jointBd = (b2PrismaticJoint*)json.getJointByName("dottom");
m_jointBLd = (b2PrismaticJoint*)json.getJointByName("dottomLeft");
m_jointTLa = (b2PrismaticJoint*)json.getJointByName("dopLeft");

/*//The following is necessary for a multi agent simulation

m_jointTf = (b2PrismaticJoint*)json.getJointByName("fop");
m_jointTRf = (b2PrismaticJoint*)json.getJointByName("fopRight");
m_jointBRf = (b2PrismaticJoint*)json.getJointByName("fottomRight");
m_jointBf = (b2PrismaticJoint*)json.getJointByName("fottom");
m_jointBLf = (b2PrismaticJoint*)json.getJointByName("fottomLeft");
m_jointTLf = (b2PrismaticJoint*)json.getJointByName("fopLeft");
m_jointTj = (b2PrismaticJoint*)json.getJointByName("jop");
m_jointTRj = (b2PrismaticJoint*)json.getJointByName("jopRight");
m_jointBRj = (b2PrismaticJoint*)json.getJointByName("jottomRight");
m_jointBj = (b2PrismaticJoint*)json.getJointByName("jottom");
m_jointBLj = (b2PrismaticJoint*)json.getJointByName("jottomLeft");
m_jointTLj = (b2PrismaticJoint*)json.getJointByName("jopLeft");
m_jointTm = (b2PrismaticJoint*)json.getJointByName("mop");
m_jointTRm = (b2PrismaticJoint*)json.getJointByName("mopRight");
m_jointBRm = (b2PrismaticJoint*)json.getJointByName("mottomRight");
m_jointBm = (b2PrismaticJoint*)json.getJointByName("mottom");
m_jointBLm = (b2PrismaticJoint*)json.getJointByName("mottomLeft");
m_jointTLm = (b2PrismaticJoint*)json.getJointByName("mopLeft");
m_jointTy = (b2PrismaticJoint*)json.getJointByName("yop");
m_jointTRy = (b2PrismaticJoint*)json.getJointByName("yopRight");
m_jointBRy = (b2PrismaticJoint*)json.getJointByName("yottomRight");
m_jointBy = (b2PrismaticJoint*)json.getJointByName("yottom");
m_jointBLy = (b2PrismaticJoint*)json.getJointByName("yottomLeft");
m_jointTLy = (b2PrismaticJoint*)json.getJointByName("yopLeft");
m_jointTv = (b2PrismaticJoint*)json.getJointByName("vop");
m_jointTRv = (b2PrismaticJoint*)json.getJointByName("vopRight");
m_jointBRv = (b2PrismaticJoint*)json.getJointByName("vottomRight");
m_jointBv = (b2PrismaticJoint*)json.getJointByName("vottom");
m_jointBLv = (b2PrismaticJoint*)json.getJointByName("vottomLeft");
m_jointTLv = (b2PrismaticJoint*)json.getJointByName("vopLeft");
m_jointTz = (b2PrismaticJoint*)json.getJointByName("zop");
m_jointTRz = (b2PrismaticJoint*)json.getJointByName("zopRight");
m_jointBRz = (b2PrismaticJoint*)json.getJointByName("zottomRight");
m_jointBz = (b2PrismaticJoint*)json.getJointByName("zottom");
m_jointBLz = (b2PrismaticJoint*)json.getJointByName("zottomLeft");
m_jointTLz = (b2PrismaticJoint*)json.getJointByName("zopLeft");

m_jointTh = (b2PrismaticJoint*)json.getJointByName("hop");
m_jointTRh = (b2PrismaticJoint*)json.getJointByName("hopRight");
m_jointBRh = (b2PrismaticJoint*)json.getJointByName("hottomRight");
m_jointBh = (b2PrismaticJoint*)json.getJointByName("hottom");
m_jointBLh = (b2PrismaticJoint*)json.getJointByName("hottomLeft");
m_jointTLh = (b2PrismaticJoint*)json.getJointByName("hopLeft");

m_jointTk = (b2PrismaticJoint*)json.getJointByName("kop");
m_jointTRk = (b2PrismaticJoint*)json.getJointByName("kopRight");
m_jointBRk = (b2PrismaticJoint*)json.getJointByName("kottomRight");
m_jointBk = (b2PrismaticJoint*)json.getJointByName("kottom");
m_jointBLk = (b2PrismaticJoint*)json.getJointByName("kottomLeft");
m_jointTLk = (b2PrismaticJoint*)json.getJointByName("kopLeft");

*/

*/

} else {

printf("Could not load JSON file.\n");
fflush(stdout);
}

}


void Keyboard(unsigned char key)
Appendix E

{
    //use keys to change motor direction
    switch (key)
    {
    //circular motion
        case 'a':
            m_jointT->SetMotorSpeed(-2);
            m_jointT->SetMaxMotorForce(80);
            m_jointTR->SetMotorSpeed(-2);
            m_jointTR->SetMaxMotorForce(80);
            m_jointBR->SetMotorSpeed(-2);
            m_jointBR->SetMaxMotorForce(80);
            m_jointB->SetMotorSpeed(-2);
            m_jointB->SetMaxMotorForce(80);
            m_jointBL->SetMotorSpeed(-2);
            m_jointBL->SetMaxMotorForce(80);
            m_jointTL->SetMotorSpeed(-2);
            m_jointTL->SetMaxMotorForce(80);
            m_jointTd->SetMotorSpeed(-2);
            m_jointTd->SetMaxMotorForce(80);
            m_jointTRd->SetMotorSpeed(-2);
            m_jointTRd->SetMaxMotorForce(80);
            m_jointBRd->SetMotorSpeed(-2);
            m_jointBRd->SetMaxMotorForce(80);
            m_jointBd->SetMotorSpeed(-2);
            m_jointBd->SetMaxMotorForce(80);
            m_jointBLd->SetMotorSpeed(-2);
            m_jointBLd->SetMaxMotorForce(80);
            m_jointTLd->SetMotorSpeed(-2);
            m_jointTLd->SetMaxMotorForce(80);
        
    }
m_jointTLd->SetMaxMotorForce(80);
break;

case 's':
    /******long extension******/
    m_jointTRd->SetMotorSpeed(3);
    m_jointTRd->SetMaxMotorForce(220);
    m_jointTd->SetMotorSpeed(-2);
    m_jointTd->SetMaxMotorForce(80);
    m_jointBRd->SetMotorSpeed(-2);
    m_jointBRd->SetMaxMotorForce(80);
    m_jointBd->SetMotorSpeed(-2);
    m_jointBd->SetMaxMotorForce(80);
    m_jointBLd->SetMotorSpeed(-2);
    m_jointBLd->SetMaxMotorForce(80);
    m_jointTLd->SetMotorSpeed(-2);
    m_jointTLd->SetMaxMotorForce(80);
    /******small extension******/
    m_jointTR->SetMotorSpeed(6);
    m_jointTR->SetMaxMotorForce(120);
    m_jointT->SetMotorSpeed(-2);
    m_jointT->SetMaxMotorForce(80);
    m_jointBR->SetMotorSpeed(-2);
    m_jointBR->SetMaxMotorForce(80);
    m_jointB->SetMotorSpeed(-2);
    m_jointB->SetMaxMotorForce(80);
    m_jointBL->SetMotorSpeed(-2);
m_jointBL->SetMaxMotorForce(80);
m_jointTL->SetMotorSpeed(-2);
m_jointTL->SetMaxMotorForce(80);

break;

case 'd':
/******long arm extension******/
m_jointTd->SetMotorSpeed(3);
m_jointTd->SetMaxMotorForce(220);

m_jointTRd->SetMotorSpeed(-2);
m_jointTRd->SetMaxMotorForce(80);
m_jointBRd->SetMotorSpeed(-2);
m_jointBRd->SetMaxMotorForce(80);
m_jointBd->SetMotorSpeed(-2);
m_jointBd->SetMaxMotorForce(80);
m_jointBLd->SetMotorSpeed(-2);
m_jointBLd->SetMaxMotorForce(80);
m_jointTld->SetMotorSpeed(-2);
m_jointTld->SetMaxMotorForce(80);

/******small extension******/
m_jointT->SetMotorSpeed(6);
m_jointT->SetMaxMotorForce(120);

m_jointTR->SetMotorSpeed(-2);
m_jointTR->SetMaxMotorForce(80);
m_jointBR->SetMotorSpeed(-2);
m_jointBR->SetMaxMotorForce(80);
m_jointB->SetMotorSpeed(-2);
m_jointB->SetMaxMotorForce(80);
m_jointBL->SetMotorSpeed(-2);
m_jointBL->SetMaxMotorForce(80);
m_jointTL->SetMotorSpeed(-2);
m_jointTL->SetMaxMotorForce(80);
break;
case 'P:
    /******long arm extension******/
    m_jointTLd->SetMotorSpeed(3);
    m_jointTLd->SetMaxMotorForce(220);

    m_jointTd->SetMotorSpeed(-2);
    m_jointTd->SetMaxMotorForce(80);
    m_jointBRd->SetMotorSpeed(-2);
    m_jointBRd->SetMaxMotorForce(80);
    m_jointBd->SetMotorSpeed(-2);
    m_jointBd->SetMaxMotorForce(80);
    m_jointBLd->SetMotorSpeed(-2);
    m_jointBLd->SetMaxMotorForce(80);
    m_jointTRd->SetMotorSpeed(-2);
    m_jointTRd->SetMaxMotorForce(80);

    /******small extension******/
    m_jointTL->SetMotorSpeed(6);
    m_jointTL->SetMaxMotorForce(120);

    m_jointT->SetMotorSpeed(-2);
    m_jointT->SetMaxMotorForce(80);
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m_jointTR->SetMotorSpeed(-2);
m_jointTR->SetMaxMotorForce(80);
m_jointBR->SetMotorSpeed(-2);
m_jointBR->SetMaxMotorForce(80);
m_jointB->SetMotorSpeed(-2);
m_jointB->SetMaxMotorForce(80);
m_jointBL->SetMotorSpeed(-2);
m_jointBL->SetMaxMotorForce(80);
break;

case 'g':
    /*****long arm extension******/
    m_jointBLd->SetMotorSpeed(3);
m_jointBLd->SetMaxMotorForce(220);

m_jointTd->SetMotorSpeed(-2);
m_jointTd->SetMaxMotorForce(80);
m_jointBRd->SetMotorSpeed(-2);
m_jointBRd->SetMaxMotorForce(80);
m_jointBd->SetMotorSpeed(-2);
m_jointBd->SetMaxMotorForce(80);
m_jointTRd->SetMotorSpeed(-2);
m_jointTRd->SetMaxMotorForce(80);
m_jointTld->SetMotorSpeed(-2);
m_jointTld->SetMaxMotorForce(80);

/*****small arm extension******/
    m_jointBL->SetMotorSpeed(6);
m_jointBL->SetMaxMotorForce(120);

m_jointT->SetMotorSpeed(-2);
    m_jointT->SetMaxMotorForce(80);
    m_jointTR->SetMotorSpeed(-2);
    m_jointTR->SetMaxMotorForce(80);
    m_jointBR->SetMotorSpeed(-2);
    m_jointBR->SetMaxMotorForce(80);
    m_jointB->SetMotorSpeed(-2);
    m_jointB->SetMaxMotorForce(80);
    m_jointTL->SetMotorSpeed(-2);
    mJointTL->SetMaxMotorForce(80);
    break;

case 'h':
    /*****long arm extension*****/
    m_jointBd->SetMotorSpeed(3);
    m_jointBd->SetMaxMotorForce(220);

    m_jointTd->SetMotorSpeed(-2);
    m_jointTd->SetMaxMotorForce(80);
    m_jointBRd->SetMotorSpeed(-2);
    m_jointBRd->SetMaxMotorForce(80);
    m_jointTRd->SetMotorSpeed(-2);
    m_jointTRd->SetMaxMotorForce(80);
    m_jointBLd->SetMotorSpeed(-2);
    m_jointBLd->SetMaxMotorForce(80);
    m_jointTLd->SetMotorSpeed(-2);
    m_jointTLd->SetMaxMotorForce(80);
/******small arm extension*******/
    m_jointB->SetMotorSpeed(6);
    m_jointB->SetMaxMotorForce(120);

    m_jointT->SetMotorSpeed(-2);
    m_jointT->SetMaxMotorForce(80);
    m_jointTR->SetMotorSpeed(-2);
    m_jointTR->SetMaxMotorForce(80);
    m_jointBR->SetMotorSpeed(-2);
    m_jointBR->SetMaxMotorForce(80);
    m_jointTR->SetMotorSpeed(-2);
    m_jointTR->SetMaxMotorForce(80);
    m_jointBR->SetMotorSpeed(-2);
    m_jointBR->SetMaxMotorForce(80);
    m_jointBL->SetMotorSpeed(-2);
    m_jointBL->SetMaxMotorForce(80);
    m_jointTL->SetMotorSpeed(-2);
    m_jointTL->SetMaxMotorForce(80);

    break;

case 'j':
/******long arm extension*******/
    m_jointBRd->SetMotorSpeed(3);
    m_jointBRd->SetMaxMotorForce(220);

    m_jointTd->SetMotorSpeed(-2);
    m_jointTd->SetMaxMotorForce(80);
    m_jointTRd->SetMotorSpeed(-2);
    m_jointTRd->SetMaxMotorForce(80);
    m_jointBd->SetMotorSpeed(-2);
    m_jointBd->SetMaxMotorForce(80);
    m_jointBLd->SetMotorSpeed(-2);
    m_jointBLd->SetMaxMotorForce(80);
m_jointTLd->SetMotorSpeed(-2);
m_jointTLd->SetMaxMotorForce(80);

/******** small arm extension ********/
m_jointBR->SetMotorSpeed(6);
m_jointBR->SetMaxMotorForce(120);

m_jointT->SetMotorSpeed(-2);
m_jointT->SetMaxMotorForce(80);
m_jointTR->SetMotorSpeed(-2);
m_jointTR->SetMaxMotorForce(80);
m_jointB->SetMotorSpeed(-2);
m_jointB->SetMaxMotorForce(80);
m_jointBL->SetMotorSpeed(-2);
m_jointBL->SetMaxMotorForce(80);
m_jointTL->SetMotorSpeed(-2);
m_jointTL->SetMaxMotorForce(80);

break;

case 'w':
//density at 1
//extension 0.5
m_jointT->SetMotorSpeed(6);
m_jointT->SetMaxMotorForce(120);
m_jointTR->SetMotorSpeed(6);
m_jointTR->SetMaxMotorForce(120);
m_jointBR->SetMotorSpeed(6);
m_jointBR->SetMaxMotorForce(120);
m_jointB->SetMotorSpeed(6);
m_jointB->SetMaxMotorForce(120);
m_jointB->SetMaxMotorForce(120);
m_jointBL->SetMotorSpeed(6);
m_jointBL->SetMaxMotorForce(120);
m_jointTL->SetMotorSpeed(6);
m_jointTL->SetMaxMotorForce(120);

/*// The following code is necessary for a multi agent simulation
m_jointTe->SetMotorSpeed(2);
m_jointTe->SetMaxMotorForce(120);
m_jointTRe->SetMotorSpeed(2);
m_jointTRe->SetMaxMotorForce(120);
m_jointBRe->SetMotorSpeed(2);
m_jointBRe->SetMaxMotorForce(120);
m_jointBe->SetMotorSpeed(2);
m_jointBe->SetMaxMotorForce(120);
m_jointBLe->SetMotorSpeed(2);
m_jointBLe->SetMaxMotorForce(120);
m_jointTLe->SetMotorSpeed(2);
m_jointTLe->SetMaxMotorForce(120);

m_jointTg->SetMotorSpeed(2);
m_jointTg->SetMaxMotorForce(120);
m_jointTRg->SetMotorSpeed(2);
m_jointTRg->SetMaxMotorForce(120);
m_jointBReq->SetMotorSpeed(2);
m_jointBReq->SetMaxMotorForce(120);
m_jointBrg->SetMotorSpeed(2);
m_jointBrg->SetMaxMotorForce(120);
m_jointBrg->SetMotorSpeed(2);
m_jointBrg->SetMaxMotorForce(120);
m_jointBLg->SetMotorSpeed(2);
m_jointBLg->SetMaxMotorForce(120);

m_jointBLg->SetMotorSpeed(2);
m_jointBLg->SetMaxMotorForce(120);
m_jointTLg->SetMotorSpeed(2);
m_jointTLg->SetMaxMotorForce(120);

m_jointTl->SetMotorSpeed(2);
m_jointTl->SetMaxMotorForce(120);
m_jointTRl->SetMotorSpeed(2);
m_jointTRl->SetMaxMotorForce(120);
m_jointBRL->SetMotorSpeed(2);
m_jointBRL->SetMaxMotorForce(120);
m_jointBLl->SetMotorSpeed(2);
m_jointBLl->SetMaxMotorForce(120);
m_jointTLl->SetMotorSpeed(2);
m_jointTLl->SetMaxMotorForce(120);

m_jointTx->SetMotorSpeed(2);
m_jointTx->SetMaxMotorForce(120);
m_jointTRx->SetMotorSpeed(2);
m_jointTRx->SetMaxMotorForce(120);
m_jointBRx->SetMotorSpeed(2);
m_jointBRx->SetMaxMotorForce(120);
m_jointBx->SetMotorSpeed(2);
m_jointBx->SetMaxMotorForce(120);
m_jointBLx->SetMotorSpeed(2);
m_jointBLx->SetMaxMotorForce(120);
m_jointTLx->SetMotorSpeed(2);
m_jointTLx->SetMaxMotorForce(120);

m_jointTw->SetMotorSpeed(2);
m_jointTw->SetMaxMotorForce(120);
m_jointTRw->SetMotorSpeed(2);
m_jointTRw->SetMaxMotorForce(120);
m_jointBRw->SetMotorSpeed(2);
m_jointBRw->SetMaxMotorForce(120);
m_jointBw->SetMotorSpeed(2);
m_jointBw->SetMaxMotorForce(120);
m_jointBLw->SetMotorSpeed(2);
m_jointBLw->SetMaxMotorForce(120);
m_jointTLw->SetMotorSpeed(2);
m_jointTLw->SetMaxMotorForce(120);

m_jointTu->SetMotorSpeed(2);
m_jointTu->SetMaxMotorForce(120);
m_jointTRu->SetMotorSpeed(2);
m_jointTRu->SetMaxMotorForce(120);
m_jointBRu->SetMotorSpeed(2);
m_jointBRu->SetMaxMotorForce(120);
m_jointBu->SetMotorSpeed(2);
m_jointBu->SetMaxMotorForce(120);
m_jointBLu->SetMotorSpeed(2);
m_jointBLu->SetMaxMotorForce(120);
m_jointTLu->SetMotorSpeed(2);
m_jointTLu->SetMaxMotorForce(120);

m_jointTn->SetMotorSpeed(2);
m_jointTn->SetMaxMotorForce(120);
m_jointTRn->SetMotorSpeed(2);
m_jointTRn->SetMaxMotorForce(120);
m_jointBRn->SetMotorSpeed(2);
m_jointBRn->setMaxMotorForce(120);
m_jointBn->setMotorSpeed(2);
m_jointBn->setMaxMotorForce(120);
m_jointBLn->setMotorSpeed(2);
m_jointBLn->setMaxMotorForce(120);
m_jointTLn->setMotorSpeed(2);
m_jointTLn->setMaxMotorForce(120);

m_jointTi->setMotorSpeed(2);
m_jointTi->setMaxMotorForce(120);
m_jointTRi->setMotorSpeed(2);
m_jointTRi->setMaxMotorForce(120);
m_jointBRi->setMotorSpeed(2);
m_jointBRi->setMaxMotorForce(120);
m_jointBi->setMotorSpeed(2);
m_jointBi->setMaxMotorForce(120);
m_jointBLi->setMotorSpeed(2);
m_jointBLi->setMaxMotorForce(120);
m_jointTLi->setMotorSpeed(2);
m_jointTLi->setMaxMotorForce(120);

/*
  //density at 0.5
  //extension 1
  m_jointTd->setMotorSpeed(3);
m_jointTd->setMaxMotorForce(120);
m_jointTRd->setMotorSpeed(3);
m_jointTRd->setMaxMotorForce(120);
m_jointBRd->setMotorSpeed(3);
m_jointBRd->setMaxMotorForce(120);
m_jointBd->setMotorSpeed(3);
*/
m_jointBd->SetMaxMotorForce(120);
m_jointBLd->SetMotorSpeed(3);
m_jointBLd->SetMaxMotorForce(120);
m_jointTLd->SetMotorSpeed(3);
m_jointTLd->SetMaxMotorForce(120);

/*// The following code is necessary for a multi agent simulation
m_jointTf->SetMotorSpeed(3);
m_jointTf->SetMaxMotorForce(120);
m_jointTRf->SetMotorSpeed(3);
m_jointTRf->SetMaxMotorForce(120);
m_jointBRf->SetMotorSpeed(3);
m_jointBRf->SetMaxMotorForce(120);
m_jointBf->SetMotorSpeed(3);
m_jointBf->SetMaxMotorForce(120);
m_jointBLf->SetMotorSpeed(3);
m_jointBLf->SetMaxMotorForce(120);
m_jointTLf->SetMotorSpeed(3);
m_jointTLf->SetMaxMotorForce(120);

m_jointTj->SetMotorSpeed(3);
m_jointTj->SetMaxMotorForce(120);
m_jointTRj->SetMotorSpeed(3);
m_jointTRj->SetMaxMotorForce(120);
m_jointBRj->SetMotorSpeed(3);
m_jointBRj->SetMaxMotorForce(120);
m_jointBj->SetMotorSpeed(3);
m_jointBj->SetMaxMotorForce(120);
m_jointBLj->SetMotorSpeed(3);
m_jointBLj->SetMaxMotorForce(120);
m_jointTLj->SetMotorSpeed(3);
m_jointTLj->SetMaxMotorForce(120);

m_jointTm->SetMotorSpeed(3);
m_jointTm->SetMaxMotorForce(120);
m_jointTRm->SetMotorSpeed(3);
m_jointTRm->SetMaxMotorForce(120);
m_jointBRm->SetMotorSpeed(3);
m_jointBRm->SetMaxMotorForce(120);
m_jointBm->SetMotorSpeed(3);
m_jointBm->SetMaxMotorForce(120);
m_jointBLm->SetMotorSpeed(3);
m_jointBLm->SetMaxMotorForce(120);
m_jointTLm->SetMotorSpeed(3);
m_jointTLm->SetMaxMotorForce(120);

m_jointTy->SetMotorSpeed(3);
m_jointTy->SetMaxMotorForce(120);
m_jointTRy->SetMotorSpeed(3);
m_jointTRy->SetMaxMotorForce(120);
m_jointBRy->SetMotorSpeed(3);
m_jointBRy->SetMaxMotorForce(120);
m_jointBy->SetMotorSpeed(3);
m_jointBy->SetMaxMotorForce(120);
m_jointBLy->SetMotorSpeed(3);
m_jointBLy->SetMaxMotorForce(120);
m_jointTLy->SetMotorSpeed(3);
m_jointTLy->SetMaxMotorForce(120);

m_jointTv->SetMotorSpeed(3);
m_jointTv->SetMaxMotorForce(120);
m_jointTRv->SetMotorSpeed(3);
m_jointTRv->SetMaxMotorForce(120);
m_jointBRv->SetMotorSpeed(3);
m_jointBRv->SetMaxMotorForce(120);
m_jointBv->SetMotorSpeed(3);
m_jointBv->SetMaxMotorForce(120);
m_jointBLv->SetMotorSpeed(3);
m_jointBLv->SetMaxMotorForce(120);
m_jointTLv->SetMotorSpeed(3);
m_jointTLv->SetMaxMotorForce(120);

m_jointTz->SetMotorSpeed(3);
m_jointTz->SetMaxMotorForce(120);
m_jointTRz->SetMotorSpeed(3);
m_jointTRz->SetMaxMotorForce(120);
m_jointBRz->SetMotorSpeed(3);
m_jointBRz->SetMaxMotorForce(120);
m_jointBz->SetMotorSpeed(3);
m_jointBz->SetMaxMotorForce(120);
m_jointBLz->SetMotorSpeed(3);
m_jointBLz->SetMaxMotorForce(120);
m_jointTLz->SetMotorSpeed(3);
m_jointTLz->SetMaxMotorForce(120);

m_jointTh->SetMotorSpeed(3);
m_jointTh->SetMaxMotorForce(120);
m_jointTRh->SetMotorSpeed(3);
m_jointTRh->SetMaxMotorForce(120);
m_jointBRh->SetMotorSpeed(3);
m_jointBRh->SetMaxMotorForce(120);
m_jointBh->SetMotorSpeed(3);
m_jointBh->SetMaxMotorForce(120);
m_jointBLh->SetMotorSpeed(3);
m_jointBLh->SetMaxMotorForce(120);
m_jointTLh->SetMotorSpeed(3);
m_jointTLh->SetMaxMotorForce(120);

m_jointTk->SetMotorSpeed(3);
m_jointTk->SetMaxMotorForce(120);
m_jointTRk->SetMotorSpeed(3);
m_jointTRk->SetMaxMotorForce(120);
m_jointBRk->SetMotorSpeed(3);
m_jointBRk->SetMaxMotorForce(120);
m_jointBk->SetMotorSpeed(3);
m_jointBk->SetMaxMotorForce(120);
m_jointBLk->SetMotorSpeed(3);
m_jointBLk->SetMaxMotorForce(120);
m_jointTLk->SetMotorSpeed(3);
m_jointTLk->SetMaxMotorForce(120);

*/
break;
case 'e':
    m_jointT->SetMotorSpeed(-2);
m_jointT->SetMaxMotorForce(80);
m_jointTR->SetMotorSpeed(-2);
m_jointTR->SetMaxMotorForce(80);
m_jointBR->SetMotorSpeed(-2);
m_jointBR->SetMaxMotorForce(80);
m_jointB->SetMotorSpeed(-2);
m_jointB->SetMaxMotorForce(80);
m_jointBL->SetMotorSpeed(-2);
m_jointBL->SetMaxMotorForce(80);
m_jointTL->SetMotorSpeed(-2);
m_jointTL->SetMaxMotorForce(80);

/*// The following code is necessary for a multi agent simulation
m_jointTe->SetMotorSpeed(-2);
m_jointTe->SetMaxMotorForce(80);
m_jointTRe->SetMotorSpeed(-2);
m_jointTRe->SetMaxMotorForce(80);
m_jointBRe->SetMotorSpeed(-2);
m_jointBRe->SetMaxMotorForce(80);
m_jointBe->SetMotorSpeed(-2);
m_jointBe->SetMaxMotorForce(80);
m_jointBLE->SetMotorSpeed(-2);
m_jointBLE->SetMaxMotorForce(80);
m_jointTLE->SetMotorSpeed(-2);
m_jointTLE->SetMaxMotorForce(80);

m_jointTg->SetMotorSpeed(-2);
m_jointTg->SetMaxMotorForce(80);
m_jointTRg->SetMotorSpeed(-2);
m_jointTRg->SetMaxMotorForce(80);
m_jointBRg->SetMotorSpeed(-2);
m_jointBRg->SetMaxMotorForce(80);
m_jointBg->SetMotorSpeed(-2);
m_jointBg->SetMaxMotorForce(80);
m_jointBLg->SetMotorSpeed(-2);
m_jointBLg->SetMaxMotorForce(80);
m_jointTLg->SetMotorSpeed(-2);
m_jointTLg->SetMaxMotorForce(80);

m_jointTL->SetMotorSpeed(-2);
m_jointTL->SetMaxMotorForce(80);
m_jointTRl->SetMotorSpeed(-2);
m_jointTRl->SetMaxMotorForce(80);
m_jointBRI->SetMotorSpeed(-2);
m_jointBRI->SetMaxMotorForce(80);
m_jointBl->SetMotorSpeed(-2);
m_jointBl->SetMaxMotorForce(80);
m_jointBLl->SetMotorSpeed(-2);
m_jointBLl->SetMaxMotorForce(80);
m_jointTLl->SetMotorSpeed(-2);
m_jointTLl->SetMaxMotorForce(80);

m_jointTx->SetMotorSpeed(-2);
m_jointTx->SetMaxMotorForce(80);
m_jointTRx->SetMotorSpeed(-2);
m_jointTRx->SetMaxMotorForce(80);
m_jointBRx->SetMotorSpeed(-2);
m_jointBRx->SetMaxMotorForce(80);
m_jointBx->SetMotorSpeed(-2);
m_jointBx->SetMaxMotorForce(80);
m_jointBLx->SetMotorSpeed(-2);
m_jointBLx->SetMaxMotorForce(80);
m_jointTLx->SetMotorSpeed(-2);
m_jointTLx->SetMaxMotorForce(80);

m_jointTw->SetMotorSpeed(-2);
m_jointTw->setMaxMotorForce(80);
m_jointTRw->setMotorSpeed(-2);
m_jointTRw->setMaxMotorForce(80);
m_jointBRw->setMotorSpeed(-2);
m_jointBRw->setMaxMotorForce(80);
m_jointBw->setMotorSpeed(-2);
m_jointBw->setMaxMotorForce(80);
m_jointBLw->setMotorSpeed(-2);
m_jointBLw->setMaxMotorForce(80);
m_jointTLw->setMotorSpeed(-2);
m_jointTLw->setMaxMotorForce(80);

m_jointTu->setMotorSpeed(-2);
m_jointTu->setMaxMotorForce(80);
m_jointTRu->setMotorSpeed(-2);
m_jointTRu->setMaxMotorForce(80);
m_jointBRu->setMotorSpeed(-2);
m_jointBRu->setMaxMotorForce(80);
m_jointBu->setMotorSpeed(-2);
m_jointBu->setMaxMotorForce(80);
m_jointBLu->setMotorSpeed(-2);
m_jointBLu->setMaxMotorForce(80);
m_jointTLu->setMotorSpeed(-2);
m_jointTLu->setMaxMotorForce(80);

m_jointTn->setMotorSpeed(-2);
m_jointTn->setMaxMotorForce(80);
m_jointTRn->setMotorSpeed(-2);
m_jointTRn->setMaxMotorForce(80);
m_jointBRn->setMotorSpeed(-2);
m_jointBRn->SetMaxMotorForce(80);
m_jointBn->SetMotorSpeed(-2);
m_jointBn->SetMaxMotorForce(80);
m_jointBLn->SetMotorSpeed(-2);
m_jointBLn->SetMaxMotorForce(80);
m_jointTLn->SetMotorSpeed(-2);
m_jointTLn->SetMaxMotorForce(80);

m_jointTi->SetMotorSpeed(-2);
m_jointTi->SetMaxMotorForce(80);
m_jointTRi->SetMotorSpeed(-2);
m_jointTRi->SetMaxMotorForce(80);
m_jointBRi->SetMotorSpeed(-2);
m_jointBRi->SetMaxMotorForce(80);
m_jointBi->SetMotorSpeed(-2);
m_jointBi->SetMaxMotorForce(80);
m_jointBLi->SetMotorSpeed(-2);
m_jointBLi->SetMaxMotorForce(80);
m_jointTLi->SetMotorSpeed(-2);
m_jointTLi->SetMaxMotorForce(80);

/*/ 
//***********long***********/

m_jointTd->SetMotorSpeed(-2);
m_jointTd->SetMaxMotorForce(80);
m_jointTRd->SetMotorSpeed(-2);
m_jointTRd->SetMaxMotorForce(80);
m_jointBRd->SetMotorSpeed(-2);
m_jointBRd->SetMaxMotorForce(80);
m_jointBd->SetMotorSpeed(-2);
m_jointBd->SetMaxMotorForce(80);
m_jointBLd->SetMotorSpeed(-2);
m_jointBLd->SetMaxMotorForce(80);
m_jointTLd->SetMotorSpeed(-2);
m_jointTLd->SetMaxMotorForce(80);

/*// The following code is necessary for a multi agent simulation
m_jointTf->SetMotorSpeed(-2);
m_jointTf->SetMaxMotorForce(80);
m_jointTRf->SetMotorSpeed(-2);
m_jointTRf->SetMaxMotorForce(80);
m_jointBRf->SetMotorSpeed(-2);
m_jointBRf->SetMaxMotorForce(80);
m_jointBf->SetMotorSpeed(-2);
m_jointBf->SetMaxMotorForce(80);
m_jointBLf->SetMotorSpeed(-2);
m_jointBLf->SetMaxMotorForce(80);
m_jointTLf->SetMotorSpeed(-2);
m_jointTLf->SetMaxMotorForce(80);

m_jointTj->SetMotorSpeed(-2);
m_jointTj->SetMaxMotorForce(80);
m_jointTRj->SetMotorSpeed(-2);
m_jointTRj->SetMaxMotorForce(80);
m_jointBRj->SetMotorSpeed(-2);
m_jointBRj->SetMaxMotorForce(80);
m_jointBj->SetMotorSpeed(-2);
m_jointBj->SetMaxMotorForce(80);
m_jointBLj->SetMotorSpeed(-2);
m_jointBLj->SetMaxMotorForce(80);
m_jointTLj->SetMotorSpeed(-2);
m_jointTLj->SetMaxMotorForce(80);

m_jointTm->SetMotorSpeed(-2);

m_jointTm->SetMaxMotorForce(80);

m_jointTRm->SetMotorSpeed(-2);

m_jointTRm->SetMaxMotorForce(80);

m_jointBRm->SetMotorSpeed(-2);

m_jointBRm->SetMaxMotorForce(80);

m_jointBm->SetMotorSpeed(-2);

m_jointBm->SetMaxMotorForce(80);

m_jointBLm->SetMotorSpeed(-2);

m_jointBLm->SetMaxMotorForce(80);

m_jointTLm->SetMotorSpeed(-2);

m_jointTLm->SetMaxMotorForce(80);

m_jointTy->SetMotorSpeed(-2);

m_jointTy->SetMaxMotorForce(80);

m_jointTRy->SetMotorSpeed(-2);

m_jointTRy->SetMaxMotorForce(80);

m_jointBRy->SetMotorSpeed(-2);

m_jointBRy->SetMaxMotorForce(80);

m_jointBy->SetMotorSpeed(-2);

m_jointBy->SetMaxMotorForce(80);

m_jointBLy->SetMotorSpeed(-2);

m_jointBLy->SetMaxMotorForce(80);

m_jointTLy->SetMotorSpeed(-2);

m_jointTLy->SetMaxMotorForce(80);

m_jointTv->SetMotorSpeed(-2);

m_jointTv->SetMaxMotorForce(80);
m_jointTRv->SetMotorSpeed(-2);
m_jointTRv->SetMaxMotorForce(80);
m_jointBRv->SetMotorSpeed(-2);
m_jointBRv->SetMaxMotorForce(80);
m_jointBv->SetMotorSpeed(-2);
m_jointBv->SetMaxMotorForce(80);
m_jointBLv->SetMotorSpeed(-2);
m_jointBLv->SetMaxMotorForce(80);
m_jointTLv->SetMotorSpeed(-2);
m_jointTLv->SetMaxMotorForce(80);

m_jointTz->SetMotorSpeed(-2);
m_jointTz->SetMaxMotorForce(80);
m_jointTRz->SetMotorSpeed(-2);
m_jointTRz->SetMaxMotorForce(80);
m_jointBRz->SetMotorSpeed(-2);
m_jointBRz->SetMaxMotorForce(80);
m_jointBz->SetMotorSpeed(-2);
m_jointBz->SetMaxMotorForce(80);
m_jointBLz->SetMotorSpeed(-2);
m_jointBLz->SetMaxMotorForce(80);
m_jointTLz->SetMotorSpeed(-2);
m_jointTLz->SetMaxMotorForce(80);

m_jointTh->SetMotorSpeed(-2);
m_jointTh->SetMaxMotorForce(80);
m_jointTRh->SetMotorSpeed(-2);
m_jointTRh->SetMaxMotorForce(80);
m_jointBRh->SetMotorSpeed(-2);
m_jointBRh->SetMaxMotorForce(80);
m_jointBh->SetMotorSpeed(-2);
m_jointBh->SetMaxMotorForce(80);
m_jointBLh->SetMotorSpeed(-2);
m_jointBLh->SetMaxMotorForce(80);
m_jointTLh->SetMotorSpeed(-2);
m_jointTLh->SetMaxMotorForce(80);

m_jointTk->SetMotorSpeed(-2);
m_jointTk->SetMaxMotorForce(80);
m_jointTRk->SetMotorSpeed(-2);
m_jointTRk->SetMaxMotorForce(80);
m_jointBRk->SetMotorSpeed(-2);
m_jointBRk->SetMaxMotorForce(80);
m_jointBk->SetMotorSpeed(-2);
m_jointBk->SetMaxMotorForce(80);
m_jointBLk->SetMotorSpeed(-2);
m_jointBLk->SetMaxMotorForce(80);
m_jointTLk->SetMotorSpeed(-2);
m_jointTLk->SetMaxMotorForce(80);
*/
break;

default:
    Test::Keyboard(key);
//end of switch
}//end of void Keyboard

void Step(Settings* settings)
{
    Test::Step(settings);
    m_debugDraw.DrawString(5, m_textLine, "Top joint is: ", m_jointT);
m_textLine += 15; /*
// draw images
for (int i = 0; i < (int)m_images.size(); i++){
    m_images[i]->render();
}

static Test* Create()
{
    return new HelTest;
}

vector<b2dJsonImage*> m_images;
b2Body* terrainBody;
b2Body* terrain2Body;
// short extension
b2Body* arm1Body;
b2Body* arm2Body;
b2Body* arm3Body;
b2Body* arm4Body;
b2Body* arm5Body;
b2Body* arm6Body;
b2Body* coreBody;
/*// The following code is necessary for a multi agent simulation
b2Body* arm1EBody;
b2Body* arm2EBody;
b2Body* arm3EBody;
b2Body* arm4EBody;
b2Body* arm5EBody;
b2Body* arm6EBody;
b2Body* coreEBody;*/
b2Body* arm1GBody;
b2Body* arm2GBody;
b2Body* arm3GBody;
b2Body* arm4GBody;
b2Body* arm5GBody;
b2Body* arm6GBody;
b2Body* coreGBody;

b2Body* arm1LBody;
b2Body* arm2LBody;
b2Body* arm3LBody;
b2Body* arm4LBody;
b2Body* arm5LBody;
b2Body* arm6LBody;
b2Body* coreLBody;

b2Body* arm1XBody;
b2Body* arm2XBody;
b2Body* arm3XBody;
b2Body* arm4XBody;
b2Body* arm5XBody;
b2Body* arm6XBody;
b2Body* coreXBody;

b2Body* arm1WBody;
b2Body* arm2WBody;
b2Body* arm3WBody;
b2Body* arm4WBody;
b2Body* arm5WBody;
Appendix E

b2Body* arm6WBody;
b2Body* coreWBody;

b2Body* arm1UBody;
b2Body* arm2UBody;
b2Body* arm3UBody;
b2Body* arm4UBody;
b2Body* arm5UBody;
b2Body* arm6UBody;
b2Body* coreUBody;

b2Body* arm1NBody;
b2Body* arm2NBody;
b2Body* arm3NBody;
b2Body* arm4NBody;
b2Body* arm5NBody;
b2Body* arm6NBody;
b2Body* coreNBody;

b2Body* arm1IBody;
b2Body* arm2IBody;
b2Body* arm3IBody;
b2Body* arm4IBody;
b2Body* arm5IBody;
b2Body* arm6IBody;
b2Body* coreIBody;

*/

//long extension
b2Body* arm1DBody;
b2Body* arm2DBody;
b2Body* arm3DBody;
b2Body* arm4DBody;
b2Body* arm5DBody;
b2Body* arm6DBody;
b2Body* coreDBody;

/*/ The following code is necessary for a multi agent simulation

b2Body* arm1FBody;
b2Body* arm2FBody;
b2Body* arm3FBody;
b2Body* arm4FBody;
b2Body* arm5FBody;
b2Body* arm6FBody;
b2Body* coreFBody;

b2Body* arm1JBody;
b2Body* arm2JBody;
b2Body* arm3JBody;
b2Body* arm4JBody;
b2Body* arm5JBody;
b2Body* arm6JBody;
b2Body* coreJBody;

b2Body* arm1MBody;
b2Body* arm2MBody;
b2Body* arm3MBody;
b2Body* arm4MBody;
b2Body* arm5MBody;
b2Body* arm6MBody;
b2Body* coreMBody;
b2Body* arm1YBody;
b2Body* arm2YBody;
b2Body* arm3YBody;
b2Body* arm4YBody;
b2Body* arm5YBody;
b2Body* arm6YBody;
b2Body* coreYBody;

b2Body* arm1VBody;
b2Body* arm2VBody;
b2Body* arm3VBody;
b2Body* arm4VBody;
b2Body* arm5VBody;
b2Body* arm6VBody;
b2Body* coreVBody;

b2Body* arm1ZBody;
b2Body* arm2ZBody;
b2Body* arm3ZBody;
b2Body* arm4ZBody;
b2Body* arm5ZBody;
b2Body* arm6ZBody;
b2Body* coreZBody;

b2Body* arm1HBody;
b2Body* arm2HBody;
b2Body* arm3HBody;
b2Body* arm4HBody;
b2Body* arm5HBody;
b2Body* arm6HBody;
b2Body* coreHBody;

b2Body* arm1KBody;
b2Body* arm2KBody;
b2Body* arm3KBody;
b2Body* arm4KBody;
b2Body* arm5KBody;
b2Body* arm6KBody;
b2Body* coreKBody;

*/

// SHORT EXTENSION

b2PrismaticJoint* m_jointT;
b2PrismaticJoint* m_jointTR;
b2PrismaticJoint* m_jointBR;
b2PrismaticJoint* m_jointB;
b2PrismaticJoint* m_jointBL;

b2PrismaticJoint* m_jointTg;
b2PrismaticJoint* m_jointTRg;
b2PrismaticJoint* m_jointBRg;
b2PrismaticJoint* m_jointBg;
b2PrismaticJoint* m_jointBLg;

}
b2PrismaticJoint* m_jointTLg;
b2PrismaticJoint* m_jointTl;
b2PrismaticJoint* m_jointTRl;
b2PrismaticJoint* m_jointBRl;
b2PrismaticJoint* m_jointBl;
b2PrismaticJoint* m_jointBLl;
b2PrismaticJoint* m_jointTLl;
b2PrismaticJoint* m_jointTx;
b2PrismaticJoint* m_jointTRx;
b2PrismaticJoint* m_jointBRx;
b2PrismaticJoint* m_jointBx;
b2PrismaticJoint* m_jointBLx;
b2PrismaticJoint* m_jointTLx;
b2PrismaticJoint* m_jointTw;
b2PrismaticJoint* m_jointTRw;
b2PrismaticJoint* m_jointBRw;
b2PrismaticJoint* m_jointBw;
b2PrismaticJoint* m_jointBLw;
b2PrismaticJoint* m_jointTLw;
b2PrismaticJoint* m_jointTu;
b2PrismaticJoint* m_jointTRu;
b2PrismaticJoint* m_jointBRu;
b2PrismaticJoint* m_jointBu;
b2PrismaticJoint* m_jointBLu;
b2PrismaticJoint* m_jointTLu;
b2PrismaticJoint* m_jointTn;
b2PrismaticJoint* m_jointTRn;
b2PrismaticJoint* m_jointBRn;
b2PrismaticJoint* m_jointBn;
b2PrismaticJoint* m_jointBLn;
b2PrismaticJoint* m_jointTLn;

b2PrismaticJoint* m_jointTi;
b2PrismaticJoint* m_jointTRi;
b2PrismaticJoint* m_jointBRi;
b2PrismaticJoint* m_jointBi;
b2PrismaticJoint* m_jointBLi;
b2PrismaticJoint* m_jointTLi;
*/

//LONG EXTENSION
b2PrismaticJoint* m_jointTd;
b2PrismaticJoint* m_jointTRd;
b2PrismaticJoint* m_jointBRd;
b2PrismaticJoint* m_jointBd;
b2PrismaticJoint* m_jointBLd;
b2PrismaticJoint* m_jointTLd;

/*/// The following code is necessary for a multi agent simulation
b2PrismaticJoint* m_jointTf;
b2PrismaticJoint* m_jointTRf;
b2PrismaticJoint* m_jointBRf;
b2PrismaticJoint* m_jointBf;
b2PrismaticJoint* m_jointBLf;
b2PrismaticJoint* m_jointTLf;
b2PrismaticJoint* m_jointTj;
b2PrismaticJoint* m_jointTRj;
b2PrismaticJoint* m_jointBRj;
b2PrismaticJoint* m_jointBj;
b2PrismaticJoint* m_jointBLj;
b2PrismaticJoint* m_jointTLj;

b2PrismaticJoint* m_jointTm;
b2PrismaticJoint* m_jointTRm;
b2PrismaticJoint* m_jointBRm;
b2PrismaticJoint* m_jointBm;
b2PrismaticJoint* m_jointBLm;
b2PrismaticJoint* m_jointTLm;

b2PrismaticJoint* m_jointTy;
b2PrismaticJoint* m_jointTRY;
b2PrismaticJoint* m_jointBRy;
b2PrismaticJoint* m_jointBy;
b2PrismaticJoint* m_jointBLy;
b2PrismaticJoint* m_jointTLy;

b2PrismaticJoint* m_jointTv;
b2PrismaticJoint* m_jointTRv;
b2PrismaticJoint* m_jointBRv;
b2PrismaticJoint* m_jointBv;
b2PrismaticJoint* m_jointBLv;
b2PrismaticJoint* m_jointTLv;

b2PrismaticJoint* m_jointTz;
b2PrismaticJoint* m_jointTRz;
b2PrismaticJoint* m_jointBRz;
b2PrismaticJoint* m_jointBz;
b2PrismaticJoint* m_jointBLz;
b2PrismaticJoint* m_jointTLz;

b2PrismaticJoint* m_jointTh;
b2PrismaticJoint* m_jointTRh;
b2PrismaticJoint* m_jointBRh;
b2PrismaticJoint* m_jointBh;
b2PrismaticJoint* m_jointBLh;
b2PrismaticJoint* m_jointTLh;

b2PrismaticJoint* m_jointTk;
b2PrismaticJoint* m_jointTRk;
b2PrismaticJoint* m_jointBRk;
b2PrismaticJoint* m_jointBk;
b2PrismaticJoint* m_jointBLk;
b2PrismaticJoint* m_jointTLk;

*/

int ydirection = 1;
float yspeed = 0.8;
float ypos = 250, y2pos = 270;
int nLoopCount = 50;

};

#endif