Reinventing the Cube: An Alternative Agent Design for Shape-shifting Technology

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Abstract: In 2002 William Butera suggested the concept of a paintable computer. It is a blend of the concept of the internet of things (IoT) and multiagent computing. He 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 (Butera, 2002). Expanding on this concept to create a liquid computer that could change its physical shape, i.e. it would be able to create unique 3D structures depending on user requirements. 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. This paper details an agent design that is orientated towards this kind of shape-shifting interface technology.

1 INTRODUCTION

The concept of shape-shifting technology that can morph into any user defined shape or form is a growing field of interest. Inspiration is often taken from nature and science fiction. Creating this kind of technology requires ingenuity, creative problem solving and a multidisciplinary approach. The aim of this paper is to present and discuss a physical agent design that is situated in the discipline of tangible, shape-shifting interfaces.

The general consensus and portrayal of shape-shifting technology is, that it is comprised of many small parts operating together to create a larger entity. This is essentially a multiagent system (MAS). These small parts are represented by the term *agents* throughout this paper. An agent is an autonomous entity that can be represented organically as well as inorganically and has a physical shape and form. It has the capacity to make decisions and learn according to its capability, based on behavioural coding. There are numerous examples of biological MAS that have received much attention in academia, e.g. bee, ant or termite hives. The primary focus of this research has been on A) communication techniques (agent-to-agent or multiagent in terms of sequencing, transmitting, receiving, deciphering, error handling, etc) and B) the self-assembly process (structural cohesion, attachment mechanisms, group and environment cuing and orientation, error and unforeseen event-handling, etc). Whilst the value of this research is evident in the dissemination of this knowledge into other disciplines, there has been little progress with respect to the physical agent design itself, i.e. the agent body. The cube is still the shape of choice for many projects exploring self-assembly (Gilpin et al., 2010, Romanishin et al., 2015, Roudaut et al., 2016). Whilst the reasons for choosing the cube are logical,

- 6 facets,
- 90degree dihedral angle,
- scalable,
- calculable
- familiarity in society (cuboid shape = building blocks, Lego®, voxels, Minecraft),

it may not be the optimal shape on which to design self-assembling or communication techniques. The agent design discussed throughout this paper is based on a PhD that was successfully completed in 2018 (Hasenfuss, 2018).

Section two will present related work in the field of shape-shifting, tangible interfaces, also referring to Tangible interface classification scheme.

The third section, whilst briefly indicating which methodology is used, primarily describes the key aspects of research on which the agent design is

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based. These aspects include the differentiation between dynamic and static self-assembly, and biological system of *Solenopsis Invicta* (fire ants).

The agent design, the Dod, is described in section four. This encompasses its physical structure and mechanisms. The characteristics that helped define the Dod's design are also presented.

The fifth section reflects on the how the Dod fulfils the current design characteristics but is also further adaptable in order to consider elements that have yet to be resolved, such as energy manipulation: its generation and utilisation within a multiagent system. Following from this discussion, a brief summation of the elements that define the Dod's uniqueness concludes the section.

2 RELATED WORK

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, of *continuous plastic tangible user interfaces (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 aims to accommodate 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., 2004)).

Within the scope of the agent design described in the original study (Hasenfuss, 2018), it is not only the overall or whole entity that is changing (i.e. the larger entity 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. 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 complex interface, like 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. 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.

Haptics is essential in forming a holistic 3D impression of the world (MacLean, 2008). Unique to haptics is the opportunity to develop morphing or shape-changing designs (Horev, 2006). Similar to bi-directionality, malleability and reversibility are characteristics that provide unique human-computer interactions as well as design challenges (Coelho and Maes, 2008).

Similar to the other senses, haptics also aims to facilitate practical as well as emotional aspects of interaction (Parkes and Ishii, 2010, Rasmussen et al., 2012). A key difference in the design of future haptic interfaces, is the concept of dynamic design. The original design would no longer be static, like a mouse or keyboard. Instead significantly more ownership is handed to the user with respect to creating malleable TUIs, suited to their specific needs. Pushpin computing, smart fluid interfaces and existing physical MAS projects are explored in the following section.

2.1 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 can consist of,

- actual pins, which are exposed (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),
- elements that are made of smart memory alloys (SMA).

These interfaces focus on 3D relief, they are useful for small-scale projects as there are no mechanical mechanisms in the elements themselves and they are capable of repeatedly transitioning between two states (Coelho and Maes, 2008). These materials allow for a greater degree of freedom with respect to moving along the x, y and z-plane (Poupyrev et al., 2004, Minuto et al., 2012) and attempt to create a greater boundary transparency between the physical world and digital information (Nijholt 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 graphical user interfaces (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).

2.2 Smart Fluids

Non-Newtonian (NN) and smart fluids were the starting points of research in the original study, specifically those exhibiting shear thickening behaviour. These fluids are colloid suspensions and the most commonly known NN fluid is cornstarch and water (*Oobleck)*. Depending on the suspension ratio, when this fluid is agitated it becomes semi-solid around the agitation source and for the duration of the agitation (Bi et al., 2011). The particles have the ability to form structure by assembling into chains or hydroclusters. Once this external force ceases the structures dis-assemble and return to a liquid state.

Magneto- and electro-rheological smart fluids behave in a similar fashion to NN fluids, the main difference being that a shear-thickening behaviour is induced via a change in a magnetic field and electric field respectively. Research into these disciplines informed the characteristics for the core structure of an agent body: particle material and construction. These characteristics include size, shape, surface topology, quantity and dispersion (Fall et al., 2012).

Interfaces based on these materials exploit the aesthetic behaviour of fluids whereby practical application or implementation has a lower priority in the design process. Ferrofluid is most often used in these types of projects because of its unique and unusual reaction to a magnetic field. This is dependent on strength and location of the magnetic field. Ferrofluid is expensive to manufacture and is not suitable for direct interaction therefore it is necessary to enclosed it in a container (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, it primarily has a visual appeal and 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).

An interesting quality of these materials is the ability to return to the original state and to repeat the process of shaping and resetting. 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, 2010). Similar to 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 malleable behaviour into digital information.

2.3 Multiagent Systems (MAS)

A MAS is a freestanding system and they are pervasive through nearly all levels of existence, e.g. individual cells working together, a flock of birds, the stock market, solar system, etc.

With respect to artificial MAS, these interfaces consist of modular agents, i.e. they are 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) or B) in the physical handling of the overall system created by many small parts.

The unique quality of modular interfaces is the ability to add and subtract agents (Gorbet et al., 1998, 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 kinaesthetics since the interfaces are completely 3D (McElligott et al., 2002, Kim, 2010). The peripheral technology, as described for pushpin and smart fluid interfaces, is primarily intrinsic to each agent.

The emphasis of a MAS is on agent autonomy. The qualities from the research gathered in these disciplines and projects helps inform a set of agent characteristics that will be incorporated into the final agent body design.

3 METHODOLOGY

The methodology used in this project is the STEAM approach. Whilst a detailed description of it will not be given in this paper, it is sufficient to highlight that this methodology is a combination of inductive and deductive reasoning and utilises the diversity of the STEAM disciplines. Creative and scientific techniques are merged to create informed and viable sources of research that can be explored further (Hasenfuss et al., 2018).

An important characteristic of MAS agents is the ability to self-assemble particularly with respect to 3D tangible interfaces. The term self-assembly more so than self-organisation is used because creating 3D structures is not automatically implied in the latter. It conveys the aspect of packing and orientation of agents within a system (Rubenstein et al., 2014, Le Goc et al., 2016).

An important distinction in self-assembly is that it 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 other than the naturally existing magnetic field or end-goals that can change according to a dynamic environment. In contrast to the ball magnets, when examining the way ants self-organise, it becomes apparent that they work together to achieve an end-goal (creating a bridge, raft, etc). It can be argued that ants only follow a specific program of behaviour similar to magnets, but a primary difference is a degree of choice.

The latter type of self-assembly is described as intent-ful or dynamic self-assembly (Whitesides and Grzybowski, 2002). It is desirable for 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, e.g. agents being pushed, removed, breaking, etc (Rubenstein et al., 2014).

The ability to dis-assemble represents bi-directionality, which is a core component to haptics and tangible interaction. It indicates that a system is flexible, reusable and programmable in real time. The final design (the Dod) attempts to fulfil this mechanism but it also aims to address issues that can be problematic by the inherent qualities of current computing technology. For example, if specific components of a laptop are broken beyond repair, the entire laptop is usually scrapped by the average user as repairs are often too expensive. This approach is wasteful and detrimental to the environment, something society can no longer afford. Therefore, designing technology that can be reusable, even if several components or mechanisms fail, aims to help change the attitude to technology whilst simultaneously creating a more robust and efficient system. For example, in a MAS based interface, even if complete mechanical failure occurred in a few agents, it should still be usable because of the agents' structural shape, (more on this in section 4.1). 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 design considerations even though they may seem at this point removed from the design process.

Examining biological systems can provide insights into developing a model by which it is possible to program the behaviour to achieve this intent-ful or dynamic self-assembly.

3.1 Biomimicry

Biomimetics had a strong influence in the research for developing an agent body that would be able to function as part of a larger system of agents. 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 this task (Dumpert, 1978, Gordon, 2010). The manner in which these insects communicate and interact and the scale at which they exist provides valuable design insights. 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 inorganic systems.

Advancing from NN fluids, a biological equivalent was sourced and studied: Solenopsis Invicta (fire ants). This species of ant 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. They also demonstrate behaviour similar to NN 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) (Kasade, 2014).

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. An ant tarsus ends with a claw. The shape of this claw is of interest because it is a bistable interlocking mechanism. The claw cannot be retracted. Therefore, 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 aspects described above provided material for initial agent design and prototypes. The process is similar to the *User Centered Design* approach except that the 'user' is replaced by the interplay between scientific and artistic methodologies, i.e. the dialogue between inductive and deductive reasoning. For example, haptic exploration was an integral part to the agent design process. It was accomplished through the modelling and construction of prototypes. Accuracy, functionality and practicality were primary concerns, i.e. researching about various problems (scaling, disassembly, reversibility, etc) that previously existed in artificial MAS and trying to improve or solve them.

With the addition of artistic exploration, a shift in focus allowed for aesthetics, imagination and creativity to take higher priority thereby increasing the scope of the design. Whilst some of the conclusions could have been attained through a purely scientific approach, applying an artistic methodology suited the projects progression because on the opposite end of TUI development is how these interfaces should be used or interacted with. This is where human creativity and adaptability do not necessarily fit into moulds predetermined by scientific or logical approaches. More information on this topic can be found in the original study (Hasenfuss, 2018).

4 FINAL DESIGN: THE DOD

In this section the physical aspects of the final design are discussed. Whilst the behavioural aspects were also considered in the original study, they will not be discussed in this paper. The word *final* may indicate that it is the completed or finished article. Instead it should be interpreted as being the final stage at this point in the study's development.

4.1 Agent Qualities

The following characteristics define the Dod's design. They are not listed in any order of importance because each feature is interdependent on the other and they will be discussed further in section 5.

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

An important distinction when using biomimicry to help create artificial systems is how biological elements that are adapted to suit the new application. The difference between replication and emulation is subtle, except that emulation also entails moving beyond the original design, i.e. incorporating core elements but having alternative or new functionality. This difference is important because rather than focusing on replicating already naturally existing systems (ant, bee or termite hives, etc) it is necessary to consider what a man-made MAS must be able to do, e.g. building a makeshift raft versus interfaces with specific functions and forms.

In the original study, the design process began with a phase of replication. For the Dod design, a museum artefact, a Roman dodecahedron, was chosen as an alternative starting point to the cube see Figure 1.

Replication allows for exploration of the original artefact, its parameters and the variables that effect it. As the characteristics mentioned above emerged, the design was continuously adapted. This iterative process, as well as allowing for the influence of art and creativity, helped to gradually transition the design from the replicative to the emulative phase.

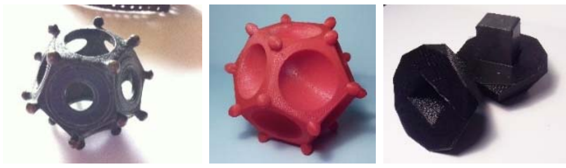

Figure 1: Early ideas and prototypes demonstrate a replicative phase.

4.2 Physical Description

The final design, the Dod, is based on a geometric, Platonic solid: the regular dodecahedron. 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. A dodecahedron 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 facets 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 (Sieden 1989).

The dodecahedron is used as the core structure but is designed with the ability to extend arms via a spiralling twist i.e. an outward rotation. This ensures that the outer plates do not interfere with each other. Rotation may 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, e.g. polymagnets (Polymagnet Correlated Magnetics 2016). 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. 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, see Figure 2a.

Magnetism is used to represent the mechanism of self-assembly. 3mm ball magnets are inserted into each of the 12 facets. Therefore, the current size of the Dod is reliant on the minimum printable material around the magnet when the arm is retracted, see Figure 2b.

It is currently proposed that each arm would be able to extend individually. However, depending on material and degree of structural cohesion required it may be necessary to have pre-configured Dods, either physically or through a Dod's behavioural coding (e.g. assignment of relative and static arm IDs).

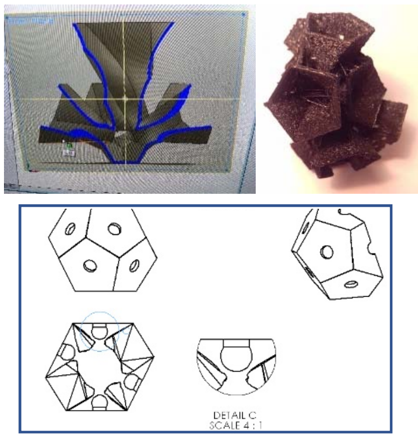

Figure 2: a) Hollow Dod and b) working Dod prototype.

Configuration in this instance refers to the number and manner of arms extended. The arms can be either arbitrarily chosen or predetermined, e.g. like an octopus whose eight legs may have fixed neural connection but are not locked to always preforming the same task, see Figure 3.

Figure 3: (a) finding equilibrium on irregular, soft surface topology (b) a top-heavy cluster held at the base by tweezers.

5 DISCUSSION

The Dod will be analysed in relation to the previously mentioned characteristics, indicating its viability as a blueprint for an artificial agent design. Following this are several scenarios that consider design adaptations to accommodate one of the most challenging obstacles in shape-shifting technology: the generation and manipulation of energy.

5.1 Characteristic 1, 3 and 5

Through the addition of an extending arm mechanism, it is possible for the Dod to transition from semi-spherical to irregular shapes. It changes the surface topology of the agent as well as affecting the over MAS structure. It makes it possible for the agent to be adaptable to a variety of environments (controlled, natural, liquid, solid, etc).

An origami pentagon spring was used in order to convey the rotational extension of the arm. Either ends of the spring connect to the facets of the inner dodecahedron and the outer plate respectively. For convenience, in the majority of prototypes generated throughout the original study, the spring formed a vertical column. However, the spring was also tested in the form folded as an inverted pentagonal frustrum. 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.

Origami is a relevant technique that is gaining a growing 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.

It can inform individual aspects of projects as well as the being the primary focus of a systems design (Lv et al., 2014, Silverberg et al., 2014, Hawkes et al., 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 (e.g. polypyrrole PPy and gold (Liu et al., 2003), temperature & light actuated materials (Corina 2014), electromagnetic waves (Liu et al., 2003, Miyashita et al., 2015), bond or foil paper to even dissolving completely when a task is completed (Christensen et al., 2015). Its application is also evident in Nano-technology in the form of micro-origami. 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.

5.2 Characteristic 2 and 6

Rather than having a central agent that controls the entire system, it is sufficient to give agents local knowledge of their own position and that relative to their immediate neighbours (Le Goc et al., 2016). With respect to information-transmitting techniques, wireless and touch based connections have been suggested in the research relating to MAS or swarm computing communication. Planting seed agents throughout a MAS is also a considered alternative communication method. Seed agents do not need to look or act different, but they may potentially have a greater capacity to store information about localised clusters that form and can communicate this information to other seed agents creating a more holistic interpretation of the macrostructure.

In relation to the Dod design, the possibility for the agents to communicate via touch exists primarily because of the manner in which the agents assemble, i.e. facet-to-facet. Being able to extend arms also allows the Dod to spread its sensory processing from its inner core through its arms. This mechanism could have the advantage of transmitting a variety of data, e.g. the arms could convey tactile and thermal or light data whereas the inner core could be used to sense orientation and acceleration.

5.3 Characteristic 4

The current aim in research is to achieve an agent that is 2-6mm in overall size (Gilpin et al., 2010). At this scale, material from which the Dod may eventually be made not only has an impact on its physical and behavioural constitution, but also on how an interface will be texturally perceived in its entirety. Texture is an integral component of haptics. It is influenced by material and its behaviour in the specific environment as well as the physical shape of a structure. It can be used to guide and engage users in establishing interaction experiences.

Since the Dod is based on the dodecahedron which has clearly defined facets, it is not the facet surface that is designed to change, rather through the extending arms, it is possible to alter the surface topology of the overall dodecahedron shape. This is achieved by defining specific arm configurations or behaviours (e.g. form clusters, dense and smooth or semi-permeable mass, etc). It greatly effects the textural quality of each individual Dod and as a result the overall MAS.

Early 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, see Figure 4a. It was possible to print the reduced Dods, with sufficient accuracy, with an Ultimaker 3D printer. Removing the magnet 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 4b, as they represent either extremes with respect to available configurations. A Form1 3D printer was used for these prints because of the higher degree of accuracy possible. See Table 1 for measurements.

Figure 4: a) scaled PLA Dods (b) scaled resin Dods.

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. Considering these aspects, the Dod has the potential to embody this design concept. The rotation and twist of the arms is designed to be a smooth motion that incurs minimal levels of friction and resistance.

Table 1: Scaled Dods - The size of each agent is noted in mm, according to its diameter.

	Retracted Configuration	**Extended Configuration**
Large	8.5mm	14mm
Medium	6mm	10mm
Small	5mm	8mm

5.4 Context of the Dod

As mentioned in the introduction, the primary shape used in the development of agent communication and self-assembly is the cube. Other shapes such as the rhombic dodecahedron have been used (Bojinov *et al.* 2002), however achieving a balance between complexity and controllability has been elusive to date. Rather than place and direct each individual agent within the system, it is more advantageous to allow scope for unpredictability. The Dod design encompasses the capacity for both of these elements. Dodecahedrons do not fit together as completely as cubes however therein lies the advantage. In conjunction with the extending arm mechanism, the formations (craters) that are created ensure that other Dods can fit or lock into them. This closely resembles the shear thickening behaviour of NN fluids but also the type of physical inter-connectivity that biological systems, such as ants, can achieve.

The concept of the extending arm mechanism as a specific design feature is validated to a degree through the work of Overvelde. In the field of metamaterials, he developed an algorithm that can calculate new complex structures based on the concept of combining geometric polyhedra with a prismatic extension from all or a number of specific facets. These structures also utilise origami as a form of manufacture (Overvelde et al., 2016, Overvelde et al., 2017). The following table highlights the similarities and potential for the Dod in the field of metamaterials and in turn shape shifting technology.

Table 2: Comparison between Dod and metamaterials.

	Overvelde's metamaterials	**Dod design**
Polyhedra	cube, hexagon, tetrahedron, octahedron	dodecahedron
Extrusion	prismatic	conical
Rigidity	fixture of specific facets to maintain the reconfigure-ability of the macrostructure	fixture of specific facets to maintain stability of the agent
Structure	Macro-Units 'grow' from replications of the microstructure	Through self-assembly of multiple agents, macrostructures are created

5.5 Energy

The ability of an artificial agent to manipulate and convert energy is a challenging design problem. 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 important 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. Taking these considerations into account also guided the design process.

The following section describes several energy processes. Some are linked to possible mechanisms of motion, that were useful in developing scenarios as to how the Dod design could be adapted in future research.

5.5.1 Organic Process

Organic energy processes are of interest in relation to agents that could eventually be 3D printed or grown from biological material. The osmotic process, which utilizes energy gradients is of interest in conjunction with a Dod that is constructed of semipermeable materials. The osmotic process is reliant on semi permeable membranes in order to enable energy gradients to be formed, e.g. sodium potassium pump.

The interesting feature is that this kind of gradient enables the ions to move against the concentration gradient, i.e. move from lower to higher concentrations. 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.

Algae and lichen are interesting organisms not only because of their ability to photosynthesise but also because of their symbiotic relationship. 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 are capable of photosynthesis whereas the fungus component acquires food through its immediate environment. This latter component is responsible for the vast diversity of lichen, i.e. the variety of minerals and materials on which the fungus feeds.

Yet another variant of the concept of symbiotic relationships 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*, 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)

The primary issue with natural or organic processes is Time. These processes have taken time to develop and perfect. In contrast, in the computing industry, it is not often about achieving the most efficient system, instead it is about achieving the maximum that materials can offer. Rather than propagate a throwaway culture through constant new updates, or releases, MAS based interfaces may make it possible to create a highly individualised computer that acts as an extension or augmentation of human abilities but that takes a few hours to assemble, as opposed to a few seconds. For example, it takes MITs new living tattoos 12hrs to react to chemical stimuli, (Liu et al., 2017).

5.5.2 Triboelectric Energy

Wearable technology is a domain in which finding power supplies other than traditional batteries is very important - not only for aesthetics but also for practicality. Whilst many devices are still self-contained (bracelets, watches, etc) the development of smart fabrics requires an alternative power supply, e.g. solar energy - copper filament or optical fibres can be woven into fabrics and materials such as perovskite can be constructed in a chainmail fashion which can be used as fabric (Hu et al., 2017). A branch of wearable technology in which finding less bulky power supplies is of great importance is *active prosthetics*.

The development of smart skin aims to have more realistic looking prosthetics but also to aid in the generation of sufficient electricity to help power certain aspects of a prosthetic. This is done through research into the *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. 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). In the attempt to replicate the human skin structure and physiology, qualities such as flexibility, elasticity, self-repair and identity are useful concepts to potentially incorporate into MAS 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 identification. 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.

In this scenario 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). 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.

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, e.g. packaging material durability and device lifespan. Research into other organic materials that generate piezoelectricity (bone, tendons, DNA) indicates 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.

5.5.3 Chemical Process and Motion

Alternatives to a biological reaction are systems that process energy 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, Vilela et al., 2017). However, there are advantages depending on the application and its context. Similar to the living interfaces research conducted in MIT, MAS agents could be programmed to react when they 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).
Using the environment to trigger a chemical reaction that produces energy, has been primarily implemented in conjunction with agent motion. Photo- and chemo-tactic motion is achieved by manipulating photo or concentration gradients of light sensitive chemicals or polymers. When these gradients are localised around each agent, diffusiophoresis enables the agents to exhibit motion (Lozano et al., 2016, Vilela et al., 2017).

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 completely biological Dod. Hydrogels exhibit a reversible behaviour which is advantageous even though it is dependent on external conditions. Many biomedical devices are designed 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).

Lastly, developments in the discipline of soft robotics and microfluidics is of value with respect to pneumatic motion. The Octobot is a project 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 (chemical reaction), and the resulting output (gas/pressure) is used throughout the system (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.

6 CONCLUSION

The Dod is only one part of a larger study into MAS agent design. Rather than create another prototype in the domain of shape-shifting technology that cannot be applied beyond the lab environment, the aim of the study was to produce a viable blueprint. This blueprint can act as the basis for developments in the present but also provide a canvas for future adaptations once applications and materials are better defined. This paper has focused on the practical description, of an agent, more so than the STEAM methodology that was used to achieve and support the final design. However, one aspect of the methodology that is evident in this paper, is the diversity of disciplines that informed the design and the process itself.

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