Emerging Complexity: Communication between Agents in a MAS for Shape-shifting TUIs

Helen Hasenfuss[a]
Abbeyfeale, Co. Limerick, Ireland

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Abstract: Communication is an essential component for creating shape-shifting, interactive interfaces. This paper discusses the early stages in constructing a communication protocol for a specific agent (the Dod (Hasenfuss, 2019)), to be used in a multiagent system (MAS). It is part of a larger study focused on developing novel interactive interfaces. Supporting the attempt to create a viable blueprint for an agent design, communication was explored from the perspective of artificial intelligence (AI). The components necessary for communication are tied to deeper constructs that cater for qualities such as coping mechanisms, understanding, interpretation and awareness. In the process of developing aware or conscious agents, the challenges of ethical usage of such technology comes to the foreground. Raising the necessary questions around these issues even in the development of a blueprint, can ensure a more informed and wholesome adaptation of the design once these issues can be resolved (e.g. final application, construction material, working environment, etc.).

1 INTRODUCTION

As a continuation from last year's paper presented at CHIRA 2019 (Hasenfuss, 2019), this paper aims to discuss the aspect of communication necessary between agents in a multiagent systems (MAS) but also the need for machine learning or artificial intelligence (AI), in order for agents to function autonomously. A MAS consists of a quantity of individual agents operating together to create larger macro structures. A biological example is that of an ant or termite colony.

The capacity for agents to learn specifics about their environment and given task is essential in order to be able to achieve shape shifting, tangible user interfaces (TUIs). The learning process should ideally accommodate the following actions:

- learn from past experiences
- remember optimum cluster formations in the creation of specific 3D structures,
- cope with partial malfunctions,
- Cope with unexpected event (falling of an edge, being pushed by other agents, etc
- recognise actions of the user and respond to them,
- forget irrelevant or obsolete information

This list is not exhaustive but aims to illustrate the complexity of each task when it is necessary to build or code these behaviours from the beginning. Alongside the question of intelligence, is its connection to the concept of ethics. Whilst ethics is a difficult topic to define, it is useful to consider the effect, of applying certain values in the early stages of technology development. Contrary to the current trend of designing machines that behave ethically (e.g. self-driving cars), a focus of this paper will be to consider design parameters that can define or accommodate ethical restraints.

The Dod design will be used to demonstrate the process of creating rulesets necessary to initiate autonomy in artificial agents. The Dod is a design based on a dodecahedron, with a retractable arm extending from each of the 12 facets (Hasenfuss, 2019), see Figure 1.

The overall result of the study that produced the Dod design, is a blueprint of a MAS agent design that can be used as is, or adapted to future technological developments or applications.

Section two will highlight some of the works that have focused exclusively on agent communication

[a] https://orcid.org/0000-0001-5703-2685

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and have created working prototypes. It highlights how different approaches to communication can influence design choices and also have an impact on the design itself.

Figure 1: The Dod.

The Dod represents a primary focus on developing a physical agent design. As a result, the communication procedure envisioned for the Dod adapts to the physical affordances. It also draws inspiration from organic behaviours of lifeforms that have similar physical qualities, (e.g. as exhibited by octopuses, sea anemones, or starfish). This process will be discussed in section three.

In section four, the rulesets defined for the current state of the Dod will be explored. This relates to the local structures it is capable of creating (e.g. line, curve and cluster) and its effect on the overall macro structure. Elements such as textural changes, colours and movement can be useful in the design of user interactions with shape-shifting technology.

The proof that biological systems have already catered for many extraordinary designs is evident in the diverse number of research projects that are directly or peripherally influenced by elements of nature (Ridden, 2015; Petersen et al., 2014; JPL, 2012). Therefore, it is not entirely unrealistic to consider developing the Dod into the biological domain. Continuing along this avenue not only brings technological challenges but also ethical ones. Section five will discuss the relevancy of ethical parameters that can arise when designing AI agents, as is required for shape-shifting technology.

2 RELATED WORK

The concept of communication in a MAS has received a large proportion of attention in academic research because it is a) accessible, particularly in digital format, b) relatable and provides insight into a diverse range of social groups and c) there is still a great deal that is not completely understood. MAS communication is not just used in shape-shifting technology but also helps explore concepts such as swarm computing, crowd or insect behaviour and networked systems such as IoT. With respect to the behaviour traits and communication of Dod agents, since the aim was not to build a fully functioning prototype. The projects listed in this section were explored for their suitability and inspired the proposed communication behaviours, for the Dod, detailed in section four. Three of the projects are based on working prototypes and effectively illustrate the interconnected relationship between communication and physical structure. The method of communication can also influence the style of self-assembly (static or dynamic). Several different approaches for programming these methods have been developed as a result (Butera, 2002; Le Goc et al., 2016; Özgür et al., 2017; Romanishin et al., 2015; Roudaut et al., 2016;Rubenstein, 2014). These approaches will be briefly described in the following list. 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 describes information travelling from one agent to another via programming fragments: a distributed sensor network (Lifton, 2002). 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 agents 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 (Le Goc, 2016; Bojinov et al., 2002).
- ‘Ghost’ trails (Uhrmacher et al., 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 is strengthened. An initially chaotic field of trails eventually becomes ordered into optimum paths (Tero et al., 2007).
- Organisation according to stigmergy is another approach. It 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 or change 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.

2.1 Existing Platforms

Adaptability, flexibility, stability, endurance and robustness are desirable qualities of a MAS communication protocol. Kilobot, Zooids and Cellulo are three projects that embody these qualities and will be briefly discussed in order to provide valuable insights that can help define behavioural characteristics of any kind of physical agent, and in this case the Dod.

2.1.1 Kilobot

Rubenstein details the effective swarm communication of robots numbering in the hundreds (approx. 1024 Kilobots) (Rubenstein et al., 2014). The Kilobot is a circular robot with IR sensing for distance and positioning calculation, and vibration motors for locomotion (Rubenstein et al., 2014). These robots are based on defining boundaries rather than the placement of each agent, and they self-organise into shapes (quasi 2D planar shapes) as opposed to self-assembling into 3D structures (i.e. along the z-axis).

Defining boundaries indicates a great deal of system flexibility with respect to packing patterns for self-organisation. Being able to sense or recognise boundaries is also a crucial skill for an autonomous agent, especially in the process of adapting to specific, complex, prescribed boundary conditions such as a keyed interface. Such flexibility is also indicative of a natural approach to organic assembly (Rubenstein et al., 2014). It incorporates the ability to be adaptable and responsive to changing circumstances which can be beneficial in the survival of a particular design or behaviour. Each agent in this project is only aware of itself in relation to its local neighbouring agents. Localisation is achieved by averaging the distance samples between the sensing agent and its surrounding neighbours. Distance is defined by the communication between agents, i.e. the update of messages. Maintaining a list of sampled distances ensures that behavioural adjustments can be made based on the comparison of values. For example, if a robot were pushed over a ledge it would realize from the sudden change in several distance-values, that its position had changed suddenly and not as part of the self-organising process.

The following observations that emerged from the Kilobot project can be applicable and relevant for any multiagent system:

- Variation in the ability of agents due to components (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

2.1.2 Zooids

Zooids is a project based on swarm computing to create user interfaces. The main aim of this research is to close the gap between actuated tangible table-tops, whereby solid materials can be manipulated, and shape displays that use the method of physical deformation to manipulate digital data. Like a natural ant hive, this project has a centralised control system to coordinate the Zooids. Similar in physical structure to Kilobots, Zooids are battery powered, circular robots; they move according to motor driven wheels and they can self-organise. They utilise capacitive touch for sensing and communicate through a radio receiver (Le Goc, 2016). 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 each individual Zooids. Once each Zooid receives its instructions specific predefined algorithms are initiated and executed as required. Of interest is the conclusion that to be considered viable 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*' (Le Goc, 2016; Nielson, 1995). This relates to the user's expectation, focus and need for feedback regarding system states. 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 of 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.
- The ability of agents to change their roles is a quality that is also echoed in certain ant species (Gordon, 2010). The ability to decide which function is appropriate to the current task contributes to the awareness level, enabling the agent to determine the next course of action with greater independence.

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 for MAS agents. Cellulo agents communicate via Bluetooth and have a downward facing camera to read the printed microdot patterns over which they move. The agents are capable of holonomic movement due to an omnidirectional ball drive (Özgür, 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 and this system is an example of how each agent is instructed what to do individually. An important quality in this project, 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 for communication protocols of artificial agents. The following section explores 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.

3 COMMUNICATION TYPES

As mentioned previously the term MAS has had most usage describing digitally simulated, multiagent systems. An advantage in testing communication protocols, such as the ones described in section two, via digital simulations, is the possibility to manipulate the variable of *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. Digital simulations are 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, however, 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 et al., 1998; Lifton et al., 2004; Nakayasu, 2010; Richardson et al., 2004). The Dod is primarily designed to accommodate self-assembly and the ability to create complex, 3D macro structures. In this case the element of communication has secondary priority, i.e. it must develop from the physical structure. The field of Biomimicry had a strong influence on defining design parameters for the Dod. The octopus, star fish, sea anemone and euplectella aspergillum were referenced in relation to how a design such as the Dod could move, how its internal circuitry could be accommodated and what kind of behaviours would be possible. For example, the brain of an octopus is divided between an internal component and its skin. Rather than having just one central processing unit, its skin / appendages also have a degree of processing power allowing it to execute complex camouflaging with greater ease. Examining these structures, provides insight into existing communication and awareness models and how they function in relation to their given physical form. The act of communication will be separated into two processes for this paper: intrinsic and extrinsic communication.

3.1 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 become leading agents, 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.

3.2 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 faster, it would ensure that each Dod is aware of the overall system. This is useful for determining system states or if the Dod based MAS is applied in a sensor network application.

Applying 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 the outline of 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, i.e. direct coding, falls outside the scope of this study, the application of learning algorithms is an important aspect of future work for the Dod agent.

Considering these approaches has an impact on the development of the Dod design, since a fundamental difference exists between an internally driven and an environmentally driven motivation to self-assemble or self-organise. For example, in ant hives, 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. Whilst extrinsic and intrinsic communication describes how an agent acts and learns within the entire system, another layer of programming exists that is specific to each individual agent. This layer of programming refers to a fundamental ruleset and is evident in biological and inorganic agents.

The model presented by Kristinn Thórisson was 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):

- 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 layers 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 description is an example of a purely mechanical or logical 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 can begin to emerge.

The integration of these three levels provides the capacity for varying degrees of awareness and thereby communication abilities. This includes being able to prioritize knowledge through active learning, forgetting irrelevant information, pooling knowledge between agents and passing on or receiving knowledge gained from past experiences or different parts of the system.

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.

4 Dod RULESET

The Dod's fundamental ruleset (the inner layer), emerged from the affordances of its physical design. As mentioned in section three, 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 or tentacles that can extend or retract, are flexible and are essential in completing everyday tasks such as environmental exploration, foraging, protection, defence, camouflage, etc. With the ability to extend arms, the Dod could also use it's extendable arms as 'feelers' to scope out its surrounding, or communicate with neighbouring Dods, 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 rudimentary mechanisms (e.g. creating line or cluster structures) that are possible through its design (e.g. extending arms, semi-spherical nature, etc). This means that if the Dod develops further, with respect to construction material, sensory ability, user application - this ruleset should remain unaffected; the equivalent to default factory settings. For the following description of developing a fundamental ruleset, the Dod hypothetically determines its position through IR sensors that are set into each arm / facet.

4.1 Level 1 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
- 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 states, 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 states have been established for the Dod: line, curve and cluster. They 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, see Figure 2. 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. Therein lies great flexibility, because it is possible for the Dod to reposition and orientate itself irrespective of the task, location and orientation.

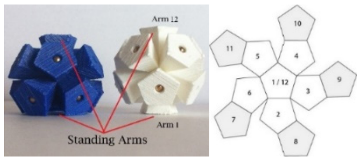

Figure 2: Root position – (a) root position with standing arms retracted & extended indicated by the red lines, (b) Facet / Arm allocation.

Figure 2b. illustrates the mapping of the remaining arms when in the root position configuration, Arm 1 (bottom hemisphere) and Arm 12 (top hemisphere) are designated as the default standing arms in root position.

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 3.

Figure 3: Line heights - Varying heights due to the configuration of arms that are retracted or extended.

4.1.2 The Curve Tag

Curve tag (CT): In the curve state, the fundamental rule is: opposite arms never engage or activate together. 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) or the ObCurve tag (ObC) for an obtuse angle (root position + arm from upper hemisphere).

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 type of 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 4a. Applying this tag to a line, creates a spiralling, curved line, Figure 4b.

Figure 4: (a) circle of Dods, (b) curvy line of Dod.

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.

Whilst it is possible to define or code the line and curve tag with greater accuracy, the challenge arose in attempting to define the Dod's 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 extendable 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. 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. These are described through the definition of four Cases.

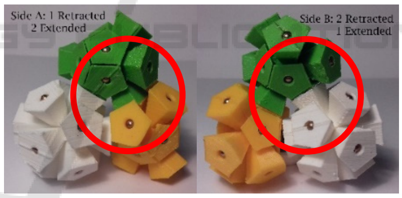

Figure 5: Craters - A crater formation of *2E1R Arms* is evident on Side A and a *R1E Arms*, crater is visible on Side B.

4.1.4 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), see Figure 6.

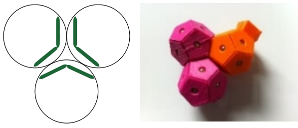

Figure 6: Case A.

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), see Figure 7.

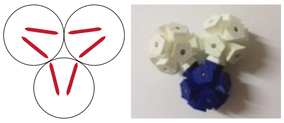

Figure 7: Case B.

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.

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), see Figure 8.

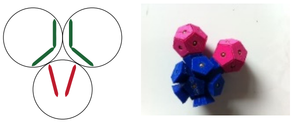

Figure 8: Case C.

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 Figure 9.

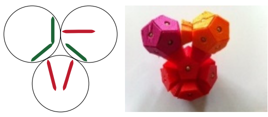

Figure 9: Case D.

The aim of this section is to illustrate the rulesets that will eventually define how the Dod behaves and communicates. It is the inner layer according to Thórisson's awareness model and represent the inherent rulesets that each Dod can avail of. Greater in-depth detail of the Dods fundamental rulesets can be read in the original study (Hasenfuss, 2018). The next section will discuss the implications of learning algorithms, important factors to consider in the communication process and the ethics involved in using AI.

5 DISCUSSION

The previous section has presented the rudimentary functions envisioned for the Dod. These are primarily influenced by its physical affordances. The kind of sensing capabilities the Dod can eventually avail of, will be in part dependant on the end application, and the environment it will be used in. In conjunction with the programming described in the Zooids and Kilobot projects, it is feasible to postulate that it would be possible to create a high-fidelity working prototype of a Dod based MAS. With the addition of each layer of awareness, as proposed by Thórisson, the degree of complexity increases. Feynman's response to complex systems had a strong influence in the process of modelling the Dod's fundamental rule-sets. He suggests that 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 of which are dependent on 6 others, 8 are interlinked with 11 (3 of which belong to the group of 6) and 5 that occur only when there is a change in 4 of the other variables (3 of the interlinked group and 1 of the dependent). It becomes clear that as the simple rules increase in complexity within themselves, it is more difficult to model the system accurately. The number of variables that affect the system grows significantly and the ability to predict its behaviour is greatly decreased (University of Groningen, 2016). Whilst this is only a fictitious example it offers perspective into the task of defining fundamental rulesets for autonomous man-made agents that will eventually be able to interact with, act on and react to their environment. Another concept, also illustrated through this example, is with the increase of complexity comes an increased probability of error and unpredictability. In the process of developing a working blueprint for a MAS agent design, rather than a working prototype, it has been possible to consider alternative influences, such as error and randomness. The two influences that will be discussed in this section is the role and interpretation of error and the ethical considerations in dealing with intelligent agents.

A 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 and 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 itself. 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. The concept of coping, also inherently holds the ability to interpret error, which in theory provides a more wholesome degree of awareness. In general, error is considered to be unacceptable predominantly because it delineates how a system or product has not functioned as intended. It is true that certain errors are fatal to systems and clearly define the space between functioning and being irreparably broken. However, before these detrimental errors occur, there is a degree of scope or tolerance, whereby errors, mistakes or failures are essential components in the process of learning and creativity. It introduces an element of unpredictability. Whereas unpredictability, randomness and chance have been primarily embraced in the arts-based disciplines, this state of existence or outcome proves more problematic in the sciences, particularly in engineering (for valid reasons). Throughout the development of the Dod, error was explored with respect to its suitability to be considered a creative or mutative force in the self-assembling and design process. Whereas the act of learning from mistakes is a relatively intuitive procedure for most organic organisms, translating this into an artificial algorithm becomes an interesting challenge. Should artificial agents be able to recognise the difference between error and creativity? If they can make that distinction, shouldn't they be able to use their interpretation for problem-solving rather than avoiding the behaviour or action, that caused an 'error', altogether? It may be that through error, alternative, possibly even better, methods for completing tasks can evolve. For example, exploring how people with a neurodiversity learn (e.g. autism or dyslexia) can provide valuable insights into alternative processing, interpretation and understanding mechanisms that are involved in learning. It has the potential to assist in creating more adaptable learning algorithms. By imbuing agents with this degree of learning ability, a natural progression for agents is to continue learning beyond the confines of their original programming. It raises questions of sentience and is being continuously explored through the diverse range of human expression: from logic to creativity.

AI is a field in its own right and is still receiving a large amount of academic and industry attention: self-driving cars, human-robot collaborations. As with any design project, the Dod fulfilled certain design characteristics that influenced its physical shape:

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 projects listed in section two, demonstrate working communication protocols that could be transferred to the Dod design. Adaptations would have to be made in order to accommodate the 3D assembly aspect, however, elements regarding agent-to-agent interactions and overall environmental awareness are developed and tested. The concept of prioritising design parameters that favour physical shape over communication is also applicable with respect to an agent's autonomy and awareness. A distinction must be made relating to an agent's functional and intelligent communication. Functional communication is similar to the 1st two levels of awareness described by Thórisson; it enables the agent to function physically, to sense and form operations using that sensory information. Intelligent communication begins to integrate the environment into the awareness of the agent. It must now assess its situation relative to others and contextualise itself within the environment. In conjunction with this, the agents are also required to work together in order to create complex structures; this requires continuous learning and adaptation. The learning process itself encompasses remembering and adapting to past experiences, forgetting irrelevant information, and incorporating and interpreting new information. A variety of these aspects have been incorporated into AI learning algorithms. The degree of complexity and awareness that is beginning to emerge, is tending toward the spectrum whereby a system should ideally begin to operate on its own accord as opposed to being instructed at each step by a researcher or user.

In relation to the Dod, a question of ethics arose towards the end of the original study, when exploring the future developments of the research highlighted a natural progression for the construction of such agents to be achieved through biological 3D printing. Through the study of biomimicry, it is clear that the biological constructs are still superior to their artificial counterparts (Kriegman et al., 2020). Even though powerful advances in material science are being made with respect to emulating biological material, the multifaceted nature of biological material is difficult to reproduce. For example, the ability of cells to self-repair, to adapt, to decay without a detrimental effect on the environment, to metamorphize, the diverse types, etc. Placing this postulation into context with current research, a recent study has successfully utilised frog stem cells to create squishy robots (Kriegman et al., 2020). Essential cells (early-stage skin and heart cells) have been removed from one organism and have been used to create another. Whilst the scientific and technological developments from this research are valuable and progressive, does the fact that biological material is being used, alter moral or ethical implications? Is there a difference between reconstituting agents from another existing organism and growing a new agent from a blank canvas? Combining the technological advances in AI algorithms (both logic and emotion), with the advances in creating artificial agents from biological material, requires a conscious engagement with the idea of sentience. For example, instead of developing an artificial agent with this degree of intelligence, it may be necessary to consider sacrificing a degree of autonomy or awareness, in order to avoid ethical conflicts regarding subjugating sentient agents to a user's will.

It is not the aim of this paper to attempt a definition of sentience but primarily to highlight that design parameters of technological endeavours should also consider the consequences of specific choices, as well as fulfilling the actual goal. For example, if a new laptop only lasts seven years (after which its parts may become obsolete) can the components be reused, or properly recycled? What impact does it have on people, and the environment? The gap between what is envisioned for shape-shifting technology and reality is still very large and will take more time to reduce. The reason these ethical or moral questions become relevant is because they will inevitably influence future designs and interactions with AI technology. The art of keeping a machine as a machine, as opposed to emulating a human brings subjects such as philosophy side by side science and design. In the attempts to replicate, physical or mental, aspects of humanity, there is a striving to understand the intangible elements such as emotions, the soul, the mind, and phenomenology. In pure replication there is a risk of not only reproducing aspects of humanity that function but also the inherent flaws. As was a guiding principle in the physical design of the Dod, when developing artificial or new agents it is necessary to emulate not directly replicate existing systems (Hasenfuss, 2019).

6 CONCLUSION

The scope of developing new interactive, interfaces is beginning to extend beyond the traditional hardware, digital and material science research, and is beginning to incorporate elements that distinguish organic from artificial, inorganic agents. This paper has presented an exploration of communication possible for the Dod design, based on the physical affordances of the shape itself. Undertaking the process of creating fundamental rulesets for a novel agent, brought concepts of AI, its effects and resulting outcomes into the foreground of the design process. As designers it is not only important to fulfil the design brief but it is the responsibility of designers to consider their design from as many perspectives as possible: the advantages, disadvantages and its consequences.

In relation to the existing frameworks used to create 3D relief or complete 3D shape-shifting interfaces (Hasenfuss, 2019), a multiagent system framework appears to be most suitable. A large proportion of knowledge pertaining to these systems can and is being obtained from existing biological MAS. With time and further technological advancements, it will be a question of moving from replicating these biological systems, to emulating them. In the emulation process, elements with are currently receiving individual attention in interface research (e.g. physical form, functionality, energy manipulation, communication, etc.), will be amalgamated in order to create shape-shifting technology that can fulfil human user requirements.

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