Emergent order through swarm fluctuations

A framework for exploring self-organizing structures using swarm robotics

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In modern architecture, construction processes are based on top down planning, yet in nature but also in vernacular architecture, the shape of shelters/nests is the result of evolutionary material processes which takes place without any global coordination or plan. This work presents a framework for exploring how self-organizing structures can be achieved in a bottom up fashion by implementing a swarm of simple robots (bristle bots). The robots are used as a hardware platform and operate in a modular 2D arena filled with differently shaped passive building blocks. The robots push around blocks and their behaviour can be programmed mechanically by changing the geometry of their body. Through physical experimentation and video analysis the relationships between the properties of the emergent patterns (size, temporal stability) and the geometry of the robot/parts are studied. This work couples a set of agent based design tools with a robust robotic system and a set of analysis tools for generating and actualising emergent 2D structures.

Keywords: Multi Agent Systems, Generative Design, Swarm Robotics, Self-organizing patterns

INTRODUCTION

Unlike the modern architects’ fascination with machines and simplicity, digital architecture has developed a fascination for complexity and has drawn inspiration by freeform shapes found in nature. The first digital age in architecture celebrated geometric complexity which was enabled by digital tools but also created a gap between the materiality of architecture and the immaterial logic of digital design. This initial gap was bridged by the application of digital fabrication techniques and industrial robotic arms (Gramazio and Kohler, 2014). Additionally, the mature use of digital tools has led architects to consider computation as an alternative for solving complex design problems rather than merely using it as representation tool (Kalay, 2004). Although the advent of information age and the digitalization of the building industry have radically changed the way we conceive and construct building structures in the recent years, in many cases digital technologies are used as means to express designers’ formal aspirations and as extensions of long established design
paradigms instead of fulfilling new ones (Bechthold, 2010). However, at a time when the complexity of building design goes beyond the cognitive capacity of a single design team and digital design systems become so intractable that designers can no longer fully understand and therefore control them, the question arises on how to develop new design paradigms and tools based upon complexity and emergence. More specifically how we can develop generative design methodologies which are coupled with evolutionary models and swarm robotics. The motivation of this work is to merge agent based design approaches with research from complex systems. Work from the latter has shown that the linking of computational models which describe social insects’ coordinating mechanisms at the particle/individual level with quantitative data can explain pattern formation at a higher collective level (Fouquet et al., 2014)

Visionaries such as B. Fuller acknowledged as early as the 1970's the necessity of looking at design from a scientific perspective and emphasized the importance of updating existing design models by embracing nature's complexity and not by reducing it (Fuller, 1975). Pask and Frazer envisioned the use of computation in design not merely as developing drafting aids that improve descriptive design methods but as a way to redefine design based on the nature's metabolic and evolutionary processes (Frazer, 1995). This approach is now more relevant than ever because of the increasing computational capacity which offers new ways for formalizing algorithmic design thinking and tooling methods. In the second digital age that we are currently going through, more than any other concept, understanding and accommodating complexity via computational means appears to be the core design issue (Oxman, 2006). Although work has been done towards managing complexity from within the fields of Architecture Engineering and Construction (AEC), there are alternative approaches and scientific tech-

Figure 1
Table with bottom up construction processes from the field of vernacular architecture, biology and swarm robotics. From left to right we illustrate in different scales a builder, the environment it operates, different building diagrams and the resulting global structures. Image sources from top to bottom: Navajo Nation, Wikipedia.org google.com/maps (top), Perna & Theraulaz / Journal of Exp. Biology / http://jeb.biologists.org (middle), Petersen K.H & Werfel J./ Wyss Institute (bottom)
techniques that can be disseminated from different fields such as experimental biology, computer science, engineering and complexity theory. The study of complex adaptive systems, has gathered a lot of attention as it offers an alternative way of designing intelligent systems, in which self-organization, emergence and distributed behaviour can replace control, programming and centralization (Bonabeau et al., 1999). By closely examining the behaviour of complex systems, scientists try to defer bottom up rules and build stochastic models to investigate how non linear systems achieve order (Heylighen, 1989).

In digital design, Coates and Miranda, Snooks and Leach have focused on investigating swarm intelligence as an alternative to established design paradigms and have applied it to problems which range from urban to architectural design (Miranda and Coates, 2000, Leach, 2009, Snooks, 2011). Menges has explored how agent based design models can be used for generative design purposes and how they can be implemented materially (Baharlou and Menges, 2013), while Scheurer has investigated how self-organization can be applied for the design and optimization of real design applications (Scheurer, 2005). Big part of these research efforts have been based on algorithms that have been developed in fields of computer science and engineering (i.e. Reynolds' swarm behaviour algorithm, Reynolds, 1987) and have been appropriated for architectural design research purposes. However, in their early manifestations such agent based models were decoupled from physical constraints until the later stages of design and in many cases the design outcomes have proven to be challenging to materialize even in small scales (i.e. size of a pavilion). Trying to address this issue, Tibbits among others has been focusing on how to program matter directly in a bottom up fashion by controlling geometric properties of materials which can allow them to self-assemble into emergent forms (Tibbits, 2011).

Additionally, research in the field of robotics, inspired by the concepts of biomimicry, focuses on how autonomous robotic systems can be used for reducing engineering and construction complexity of large scale structures (Werfel et al., 2014). The application of robots in real construction sites during the 90’s in Japan has shown that there are issues of communication, control, maintenance cost and reliability which significantly increase the complexity and makes their actual application in the building industry harder (Warszawski and Navon, 1998). Understanding the behaviour and mechanisms which characterize nest building of termites and transcribing the flexibility, robustness and self-organisation of such processes is considered crucial for developing distributed robotic systems which can achieve tasks that may be too complex for one robot to accomplish (Beni, 2004). Werfel has shown the potential benefits of using multi agent systems for reducing computational complexity by combining software and hardware platforms and by using distributed swarm robotics for achieving complex global behaviours and structures (Werfel et al., 2014). By using local information and basic sensing mechanisms such systems can remain simple even when they scale up. Current work suggests that designing and fabricating several task specific robots which can operate autonomously for performing building tasks can be more reliable and less complex than programming and controlling multiple industrial robotic arms (Petersen, 2014). For instance, explicit robot-to-robot communication rapidly becomes a big issue when the number of robots increase: such an issue can be eliminated by controlling robot-to-robot communication implicitly via the geometric conditioning of their interactions and the interaction with their environment (embodied behaviour). Moreover, when dealing with multiple robots, the reliability and robustness of the system as a whole increases because the failure of one or several robots won’t prevent task completion, while when using a single robot an error can be preventive for the task completion. (Figure 1)

Despite the fact that research in the field of engineering suggests that distributed robotic systems can be more flexible and fault tolerant and therefore more suitable for the unpredictable and dynamic
environment of the construction site, academic research in the field of architectural robotic construction so far has been mainly focusing on the use of industrial robotic arms (Gramazio and Kohler, 2014). Another gap is that although generative design techniques are becoming more popular for design exploration using local rules in a bottom up fashion (i.e. agent based models, genetic algorithms), material constraints and design optimization are applied at the later design stages and their construction is done using strictly top down techniques. Consequently, the generated geometries in many cases are the outcome of the arbitrary manipulation of a number of parameters which condition a specific digital model and not the result of an evolutionary material process (Jencks, 1997).

On the contrary, if we refer to nature, in the case of termite colonies for instance, each construction act from an individual termite changes the stimulus of the whole swarm which is operating collectively and therefore affects the outcome of the global structure (Perna and Theraulaz, 2017). Similarly, vernacular architecture offers a large variety of examples where the generation of design alternatives is the direct result of evolutionary material processes which are influenced by environmental conditions, social parsimony and iterative construction processes (Rudofsky, 1964). Unfortunately, vernacular architecture has been largely overlooked and only in few cases there has been interest in computationally implementing vernacular building techniques as in the case of reciprocal frames (Larsen, 2008). Although biologists have been able to study termite colonies in depth, by conducting physical experiments in laboratories and by building computational models using the gathered data, evolutionary design patterns of vernacular structures have yet to be rigorously studied under the light of computation and digital design models are often not coupled with vernacular building wisdom. While the complex geometry of termite mounds has fascinated architects formally for biologists it is considered as the result of several evolutionary parameters which include: physiology of the termites’ body, environmental conditions, speciation, available resources, the longevity of the colony (Bonabeau et al., 1999) (Figure 1).

**METHODOLOGY**

This study builds upon the hypothesis that we can reconsider agent based modelling methods in architectural design by combining them with robust hardware platforms which are based upon autonomous
robotic systems. The coupling of generative design approaches with the close observation of natural systems and the constraints of distributed robotic construction methods can lead to formally complex results with built in efficiencies previously unattainable. Via the mechanical encoding of design intentions and realistic constraints into the behaviour of swarm robotic systems, the objective of the study is to: a) effectively bridge the gap between agent based design generation and design materialization using low level autonomous robots, b) to use a rigorous physical testing and analytical process for developing design behaviours and c) make use of design data visualizations to detect emerging patterns in order to inform decision making of future design iterations (Figures 2 and 3).

Experimental Setup
To explore our hypothesis, we have developed a design methodology and designed an experimental case study which enables us to study the emergent self-organizing behaviour of simple robots and the appropriation of such system for architectural design purposes. In this case for reasons of simplicity, the design methodology includes the exploration of emergent 2d patterns based on the mechanical programming (embodied behaviour) of a swarm of simple robots (bristle bots). The experimental setup is based upon a workflow which was initially implemented at Smart Geometry conference 2016 (Andreen et al., 2016). It includes a reconfigurable two-dimensional environment (Arena) in which simple robots (Agents) move around passive building blocks (Parts) for specific time intervals (5-45min) or until they reach a state of an equilibrium. The shapes of the arena in which the robots operate can be considered as the boundary of an architectural panel to be designed. The design parameters which determine the geometry of the generated patterns, include the shape of the boundary, the geometry and number of the robots, the shape and number of blocks, the ratio of area to number of blocks (i.e. degree of transparency) and the runtime. The motion of both agents and blocks is tracked using a high definition camera (GoPro) and analyzed using a kit of custom developed computer vision tools (Python, OpenCV, Matplotlib) which allows for the performative evaluation of the emerging structures and behaviours. The robots are cheap and commercially available (www.hexbug.com/nano) and can move at an approximate speed of 11mm/s by combining a simple vibrating motor and 6-14 angled soft legs. The way the robots move is affected by the friction of the surface and obstacles they encounter (Figure 3f). Based on the variability of the ground surface and obstacles they encounter they can move relatively straight or follow random trajectories. In this case, we “program” the robots by altering their body geometry and the environment they operate. The body geometry of the robots is altered by adding covers with variable geometry (Figure 3b). Initial experiments showed that big and/or front heavy covers severely alter the locomotion of the robots and consequently the patterns they generate. We develop different covers to test how robots can grab and move blocks around the arena and how we can achieve specific swarm behaviors. In conjunction with the robot cover geometry we develop design alternative geometric configurations for the passive blocks (Figure 5). For simplicity purposes we start by selecting two primitive shapes such as circle and hexagon and develop different types of blocks by topologically altering the shapes. The robots operate in a modular arena, which can be reconfigured in different shapes (Figure 4).
Design Simulation Tool
An agent based generative tool was developed in order to explore different design alternatives based on the physical setup described above. Unlike existing agent based tools that implement swarm behaviours and are not connected to the physical world, the developed tool is modelled after our experimental setup and is used as a platform to see how different boundary conditions and geometries of the agents can lead to different self-organizing configurations. The tool was implemented in Processing (Reas, 2007) using Box2D as a physics engine and allows fast design iterations, which can then be tested physically. Additionally, the tool enables the designer to test the scalability of different configurations and to observe what the global impact of local rules is when a large number of agents interact in the environment. The aim is to be able to easily adjust the parameters of the tool to match the behaviour of the robots and their interactions in the physical world and explore how we can design control different swarm behaviours. The tool consists of a 2d environment which is populated with active agents and passive building blocks. The designer can parametrically alter the design of both the boundary geometry as well as the robot/part geometry using Dynamo visual scripting editor (DynamoBIM.org) and import them directly into Processing as a .json file. To achieve more realistic simulation of the locomotion, apart from their geometry, the designer can control the: a) ground friction, b) object-object friction, c) object density and the d) coefficient of restitution. The vibrating motor which propels the robots to move forward is modelled as an applied vector force on active agent with some noise to account for the variable ground friction that affects the trajectory of the robots. The robots are placed randomly in the arena and their position (x,y coordinates) at specific time interval is exported as a .csv file for visualization purposes.

Design Analysis
In order to be able to detect clusters and characterize emergent patterns that form over time from the interaction between robots and blocks, a tool has been developed which analyzes the videos of the experimental runs. The video data is processed using blob detection algorithms, which have been implemented using a computer vision library in Python language (Open CV). The aim of the analysis is to see how the geometry of passive blocks, robots and shape of boundary affects: a) the trajectory of the robots in the arena b) the formation of larger clusters of blocks through physical interlocking c) the collective transport of blocks by the robots. By fine tuning geometric parameters of the blocks we test how can we affect the behaviour and size of the emergent clusters. By changing the geometry of the robots, we can affect how they interact with the passive blocks (i.e. grab and push one block at a time) but also with other robots (i.e. form chains).

Figure 4
Isometric drawings and top view photos of the three experimental environments (arenas) where the robots interact with the parts.

CASE STUDY
A case study has been developed to test our workflow and experimental setup. We investigate how the emergent clusters can be translated into openings of a panel and therefore alter its level of transparency. By controlling the ratio of blocks (i.e.number of blocks * area of each block) in relation to the area of the arena (i.e. panel area) we can define the level of transparency of the generated panel, while the interaction of the robots with the blocks can define the position of such openings. Our case study consists of the following steps (Figures 2 and 3): a) we consider a design surface (i.e. planar or curved façade surface) b) discretize the surface in panels using 3 different methods (circular, triangular, rectangular panels) c)
one typical panel is selected from the surface for each panelisation method and its boundary is used to form an arena for the robots d) perform experimental runs with 20-100 robots and 2 different types of block geometries.

The design parameters which affect the behaviour of the robotic system are: a) shape global boundary b) block geometry c) robot geometry d) introduction of obstacles within the arena e) initial configuration of blocks f) the time the systems is interacting (runtime). The experimental setup presented by Andreen, Napps, Jenning and Petersen (Andreen et al., 2016) is extended by introducing different types of part and boundary geometries and study how those affect the formation of the patterns. As a first step we study a small swarm of 20 robots and investigate the level of clustering that different part geometries can achieve and how the robot geometry can affect the manipulation of the parts and the locomotion of the robot. Although the research is at a very initial stage we hereby provide a set of both qualitative and quantitative observations:

**Design of robot’s body & motion**

The robots’ motion is influenced by the weight and shape of its body and total number of parts (blocks) in the arena. Different speeds and level of agility can be achieved by changing the inclination of the body relative to the hexbug. Depending on whether the robots have grabbers or not it can engage with a block (grab it) and push it in a straight line until an obstacle is met, move along with it or simply hit it and change its trajectory. Cardboard robot bodies slow down the robots but provide more stability when they move. Robots with grabbers can align with each one is pushing one block or multiple robots are pushing a cluster of parts. Robot Designs that had no grabbers and had the same geometry like the parts, became one with the part cluster and move together along with it (Figure 8c). Robots with “grabbers” proved to be good in enabling the robots to consistently engage with one part at the time and push it forward in relative straight line (Figure 5). However, in many runs the robots clustered with only other robots and the lack of directionality of their shape resulted into one counteracting the motion of the other and therefore not moving. From the different robot body designs that were developed and tested the best ones proved to be the lighter ones with grabbers (Figure 6). A main design parameter for directing the robot is altering the friction level of the ground floor. By adding a more textured material we were able to direct the robot through a specific path until it reaches an endpoint (Figure 5). Another important parameter which affects the locomotion of the robots is the frequency of the motors rotation per minute (rpm). When the robots’ batteries wear out, the motor’s rotation slow down (rpm) and makes the robots run in circles thus changing its behaviour. Lastly, the robots cannot move if the inclination of the ground is more than 15% and they cannot push a single part if the inclination is more than 8%.

**Design of part**

As far as the part is concerned two different types of geometries were tested along with their topological variations: a) one set of designs is based on the hexagon and four different types of block designs are created, b) the second set of geometries is based on the circle and fours different types of blocks based on the topological variation of 2,3 and 4 circles are cre-
ated (Figure 6). The geometrical and topological variation is driven by how the parts can form bigger and more stable clusters by creating connecting points with higher friction. The main design parameters are the weight and the contact surface of the part to the ground which affects its friction. Moreover, the number and length of edges of the part affect the way it can connect with other parts. Hexagonal parts form more stable structures due to the friction of the sharp edges while circular parts are transported easier by the robots as they can allow for multiple grabbing points. The pushing of parts makes the robots move in more straight trajectories also. Lastly, the topological transformations of the shapes help the creation of bigger clusters but constrain the flexibility of the robots to move around the arena. We calculate how the parts occupy the arena over time as well as the size and number of parts in clusters to see how the boundary of the arena and the robot-part geometry affect the formation of clusters (self-organizing patterns).

**Arena Occupancy and Clustering**

For each experimental case there is an entry point for all the robots and different initial configurations for the parts were tested namely: random placing in the whole arena, placing as one cluster in the middle of the arena and at the edge of the arena. Independent from their geometry, robots tend to gather towards the boundaries and can draw constant trajectories following the boundary of the arena, unless it has sharp angles (90 or smaller) which tend to trap the robots. The introduction of fixed parts (obstacles) in the arena reduced the variability of the clusters and depending on the number of obstacles (1-3) constrain the motion of the swarm. This led to the convergence towards of clusters that the robots could not alter within the experimental run and the swarm was stuck. In Figure 7 we plot the level of clustering of experimental runs of 30 robots and 60 parts, in different arenas. By analyzing the graphs we can observe that in all cases we start with a high number of small clusters (1-2 parts) that evolves into a lower number of clusters with bigger size (20-25). In the rectangular arena we can observe that at different timestamps medium (Figure 7a) and large size (Figure 7d) clusters are created for a small duration. Additionally, the hexagonal components form medium and large clusters for longer duration (1-2 min) unlike the circular components (<1min). In the triangular arena we can observe the formation of bigger clusters with the hexagonal parts (ca 20 blocks) which persist for the whole duration (Figures 7b and 7e).

**CONCLUSIONS AND NEXT STEPS**

In this study we have investigated the generation of 2D self-organizing structures using a swarm robotic system. By changing the geometry of the robots, the parts and the environment (arena) where they interact we can achieve different swarming behaviours. We extend an existing approach proposed by An-dreen D. and present a series of experimental results in which we explore how changes on the shape of robots and parts as well as on the boundary and ground friction of the environment affect the behaviour of the swarm. By working with a simple and cheap robot, we can physically test the interaction of a large number of entities and implement different swarm behaviours. By keeping our robotic system robust and by controlling a set of input parameters namely: population size, geometric shape of part and robot, shape of boundary and ground friction we can test which parameters have a greater impact on the emergent structures. The behaviour of each individual robot is simple and its motion appears random, but the modulation of friction (Figure 8a) and the geometric interaction with passive blocks affect the motion of the robots and can lead to complex global structures and synchronous behaviours (Figure 8b). The initial results show that we can obtain control over the motion of the robots by creat-
Figure 8
Plots of the number and size of clusters (between robots and parts) over time in 6 experimental runs. The top row shows results of the experimental runs with circular parts in the 3 different arenas while the bottom row shows results of the runs with the hexagonal parts.

Figure 9
Generation of robot’s toolpath using the developed tool in Processing(a), tracking of the motion of 5 robots interacting with parts equipped with UV lights in a rectangular arena(b) and diagram of the additive manufacturing platform currently under development(c).

The developed robot-bodies can transport circular parts for longer distances in almost straight lines. The creation of clusters is closely related to the design of the parts: curvilinear geometries (circular parts) are less likely to create stable clusters while the hexagonal parts can form bigger and more stable structures (Figure 8c). If the arena entry point remains open after the robots enter, then the robots navigate and/or push material outside of the arena by themselves.

The limitations of the experiment include that we operate in a 2d environment and that we have not yet tested a very large number robots (>100). Additionally, no feedback mechanism is yet implemented into the robots in terms of identifying where they are positioned in relation to other robots or the arena boundary. Our future steps include to improve the simulation of the robots using the data collected from the videos, and provide a User Interface so that the designer can easily change robot and boundary designs and easier explore alternative designs. We also aim to test feedback mechanisms on the robot (electromagnet, proximity sensors) so that we can obtain more control over their behaviour. More importantly, we need to run multiple experiments with different number of robots and parts to test if the patterns and clusters persist independently of the size of the swarm. Our objective in studying whether these behaviours and robots’ motion path persist in various scales is to use them for the development a distributed additive manufacturing platform where the trajectory of the agents over time is used as a printing tool-path for the curing of UV sensitive resin. The design of this platform is illustrated in Figure 9 and its design is based on the adaptation of open source 3d printer for curing UV sensitive resin (Calderon et al., 2014). The overarching target of the work is to connect digital agent based simulation techniques with the physical world by investigating distributed fabrication platforms based on swarm robotics and to explore how such strategies can be utilized in generative architectural design.
ACKNOWLEDGEMENTS
The research was initiated at a workshop during the Smart Geometry conference 2016 in Gothenburg and further implementation done at the University of Southern California. Further prototyping and physical experiments were conducted at Autodesk’s BUILD Space facility in Boston supported by the joint program “Builders In Residence” between Autodesk Inc. and the Institute of Advanced Architecture in Catalonia (IAAC). The authors would like to give special thanks to the programs coordinators A. Markopoulou and R. Rundell as well as to the facility supervisors A. Moore and A. Allard.

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