Reflection Paper

(Final)

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INTRODUCTION

From the second half of the 20th century, many Avant Guard architects and research groups started exploring the participative and performative notions of space using new soft materials, letting go of rigid plans in favour of more flexible and adaptable solutions. These showcase the notion of softness in architecture both through the use of new, soft materials (fabrics, inflatables) in architecture, as well as with new technologies enabling for spaces to move, change, reconfigure and adapt to various conditions.

This has opened up new fields for research in architecture, notably around generative/algorithmic design and swarm robotics. New research and projects such as Gramazio+Kohler's work on swarm robotics in construction or Roland Snooks's approach to the generative design in architecture, have developed a new understanding the world and the built environment as an "adaptive ecology" composed of swarms of robots collaborating autonomously towards an architectural goal. This architecture has no blueprint but is self-organizing; it is processual, indeterminate and continuously in *formation*, as opposed to the dominance of static, predetermined forms and functions in the organization of the environment today.

Starting this project, my intention was to explore the use of swarm robotics in architectural design by using a swarm of autonomous UAVs (referred to as *creatures*) that can fly in a synchronized fashion and, together, form interactive and responsive temporary shelters in public spaces. Such shelters would be able to morph to adapt to users' changing positions and movements through time. They should also be able to modulate environmental conditions such as wind and rain shelters, daylight penetration and the acoustic resonance of the space.

The first aspect considered in the research was forming a better understanding of the integration of these UAVs in the urban context. What infrastructure is required for this multi-agent system to work? How do they act responsibly? How do they take decisions and what drives them?

The second one revolves around the individual creature's morphology: what should it be able to capture about its surrounding environment? how can it sense and interact with its environment? How are its digital moods and desires translated into a physical reactions and behaviours? How does it communicate and share information with other agents in the swarm?

The third part covers the development of a generative design algorithm that establishes a set of rules and constraints for the creatures to enact an architectural performance by forming temporary shelters over large groups of people in urban public spaces. How to design an architectural algorithm that is played out autonomously? Where does the architectural input lie in this new design paradigm? What becomes the role of the architect?

Together, these parts all frame the overarching goal of this project which is to explore new relationships between humans and the built environment through the use of multi-agent robotic systems.

SWARM ROBOTICS AND AUTONOMY: CREATING A SYMBIOTIC RELATIONSHIP BETWEEN THE CREATURES AND THE BUILT ENVIRONMENT

To better tackle the notions of emergence and autonomy in architectural design while ensuring the creatures act responsibly, it is important to find out how these autonomous algorithms work, how they drive the swarm of robots to take decisions and make choices in our environment individually, or the way they distribute information to ensure a coherent collective response to a given set of conditions.

At the recommendation of my tutor, I contacted Chris Verhoeven, associate professor in the department of microelectronics at TUDelft. His expertise in the field of autonomous robots and swarm robotics and sensor-actuator systems were of great insight in to better understanding the theoretical and practical aspects implementing decision-making algorithms. Discussions over notions such as privacy, the ability to learn and be taught as well as how these robots could express emotions and give different reactions based on moods.

This softened the approach to the design of the robotic creatures and humanized them. It was clear that to build a successful robotic creature required not only the hardware and the software but also needed to be driven by desires and emotions, respond to stimuli and stimulate in return in order to constantly provoke change like we do as humans. In response to these comments I developed two spectrums of emotions: one from sad to happy, and one from fearful to confident. These emotional states would serve as evolving drives for the creatures' interactions with humans by altering their physical state (see "Inflatable Skin" section below) and their flight paths for example.

Similarly to how the design of the creature's moods and senses would allow it to interact more deeply richly with humans, this project tends to apply the same approach to the relationship between these creatures and the surrounding built environment. Both need to understand each others' presence and augment each others' abilities. This understanding concretized the overarching role of the creature: to be a companion for the urban environment.

To illustrate how such a symbiotic relationship could take place I designed a few urban interventions that embody this desire for one to complement the other. For example, I explored the design of charging stations for the creatures that could give an added value to the built environment. One of the resulting designs is a street light composed of a hoop attached at the top of a vertical metal pole. The hoop serves as a receptacle or "landing pad" for the drone to land in. It also supplies energy for the drone to charge. In return, the drone provides light to the street/area.

MORPHOLOGY AND SENSING APPARATUS

Inflatable Skin

Inspired by the parasitical, shape-shifting and temporary nature of inflatable architecture, I was interested to express the notion of softness in architecture as a way to emphasize the constantly-shifting creature-formed structures. As such an inflatable skin was designed for the creature to enhance its morphology and be able to react differently to in different scenarios.

Using soft materials and inflatables have the benefits of considerably reducing the weight of the creature, and allows it to change its shape by varying its inflation level. It also benefits public safety while giving the creature a more playful and approachable appearance, which is key in this attempt to make these creatures a part of the built environment.

In order to get a better understanding of these materials, I met with Rob Schraff, who leads a soft robotics course at the faculty of Industrial Design at TUDelft. This provided great insight into the different material types, properties and applications for inflatables such as different samples of silicone rubber, thermoplastic eurethane (TPU). One material seemed to offer a higher potential in terms of flexibility and architectural qualities: silicone rubber. I was also presented with the possibility to combine materials such as fabric with silicone rubber in order to vary the materials elasticity. Some prototypical projects from the IAAC have been experimenting with such silicone-fabric compound for an inflatable facade prototype. Similarly, using this silicone-fabric compound material as the skin surrounding each creature, this composite material would act as a "facade" for the assembly from by a swarm of creatures.

The final design of the skin is composed of a staggered grid of silicone cells all around the spherical drone body and kept together by a layer of mesh fabric embedded in the silicone. Many different material properties of silicone have been taken advantage of during the design and prototyping phases of the project to showcase the versatility of the chosen material and emphasize its strengths.

For example, silicone rubber also becomes more transparent when it inflates. This was used in the final design to enhance the architectural effect of the assembly. As such, the creatures could inflate all of its cells simultaneously to greatly reduce the opacity of the skin and allow more daylight in through the creature-composed "facade" of the assembly. To further test and optimise this effect, I made a series of prototypes of silicone "bubbles" with varying thicknesses and sizes to test how much each one could inflate, how transparent they would get when inflated as well as the weight difference.

Moreover, a pump and multi-valve pneumatic system was designed to allow different groups of cells to be inflated or deflated simultaneously to allow for different morphological states. For example, in order to tightly connect multiple creatures together, every other column of cells would be inflated, which would allow two creatures to form a "zipper joint together. Small magnets were then embedded in the liquid silicone cells to enable a stronger connection between creatures while maintaining the inflatable and elastic property of the material.

Sensor-Actuator

I then turned my focus on the sensor-actuator system to operate this inflatable skin with pump-valve system. This involved the physical layout of the components and the design of the rest of the creature's body. All of these were done with the goal to optimize flight time, weight, thrust, and acoustic performance.

These sensors measure the local environment conditions (daylight, wind direction and speed, rain conditions, and sound levels) and observe the world around them using a vision system composed of multiple cameras and ultrasonic sensors which allow creatures to know their proximity to other objects in multiple directions.

Additionally, sensor-actuator feedback loops enable the creatures to be aware of their own states and share it with other creatures to achieve various architectural effects. In the case of the inflatable skin for example. which inflates more or less depending on its mood, its position in the structure, the current environmental conditions and user interaction. As such, pressure sensors can be installed in the inflatable system giving information about the state of the inflation back to creature. This can be used for the creature to better understand its environment: it could know for example if it is pressing against something, if it is under too much pressure, or if it squeezed by something. It can also be used by the creature to know if it is correctly responding to the current environmental conditions such as sunlight or rain, and then share this information to nearby creatures to imitate it.

Avionics

The avionics design required to take into consideration the overall weight of the creature as well as the its acoustic performance as it will be flying alongside a swarm of other creatures. In order to set high safety goals and to achieve a relevant architecture effect each drone need to accommodate a large battery to ensure a long flight time.

On the one hand, as the battery is the heaviest part of the drone, this would be a governing factor in the overall weight. In this case it accounts for around 50% of the total weight at 1.2kg for a flight time of about 2-3h. This would require a high thrust to lift the creature in the air. On the other hand, in order to reduce the noise from the drone, I had to do go followed three principles: reduce the number of motors, lower the motors' rotation speed, and increase the propeller size.

These two principles guided the design away from a standard quadcopter towards using a coaxial motor configuration. This setup halves the number of motors and propellers which reduces the overall creature weight. It also allows for larger propellers to be used, and based on scientific studies, the total noise reduction is around 30% when using this configuration as opposed to a quadcopter.

Moreover, by adding a duct around the propellers further contributes to noise reduction by guiding the air in a more aerodynamic fashion. Finally helium balloons are also integrated around the ducted propellers giving the creature its overall shape while reducing the weight of the creature with the lifting force of the helium whose weight compensates for that of all the electronic components (expect the battery).

GENERATIVE DESIGN, EMERGING ARCHITECTURE AND REPRESENTATION

Design and Feedback

This time based and robotically enabled architecture of emergence forces a shift in the role of the architect from a top-down planner to a bottom-up thinker, focusing on processes and change rather than prescriptive approach to design. This involves encoding the architectural intentions and evaluating their success instead of directly designing the outcome.

I was inspired by soap bubble aggregations as the basis for the overall shape of the creature-formed structures. In order to translate this architectural intention into code, it has to be deconstructed into an input-output sequence of steps. Each one the steps then represents a space for architectural inputs which govern how that step will modify its input into something that is closer to the desired result.

The complexity and speed of the algorithm therefore depends in how many steps it has, and its number of inputs. While increasing the number or the complexity of the sequence of steps may provide more control over the sequence, it also slows down the script which is supposed to be run by a large number of robots in realtime.

Moreover, by grouping the input points and by sequencing the script into larger chunks, the changes in input become more apparent to the architect’s eye. As such, these steps act as feedback loops for the architect, allowing for the evaluation of the result and the modification of additional inputs. These steps also represent the invisible architectural layers on which the architectural performance relies. They define the aesthetic of the overall system and the logic followed by the creatures.

In this case, the design algorithm starts by identifying individual people in a large crowd and group them into small to medium-sized clusters. The algorithm then draws a box around each group, divides this box into smaller boxes if it is bigger than a certain size. It then finally draws single “bubble” around each box and computes the aggregation of all the drawn “bubbles”. The final the bubble aggregation is the overall shape that the creatures will conform to.

This solution directly links the final shape of the assembly to the position of the people it shelters. This means that the structure will continuously shift through time as the people move in space. The algorithm also provides feedback to the creatures as to whether the structure is tightly-packed enough, where there are large gaps and allow creatures to verify that they are correctly positioned and responding accurately to the environmental conditions.

My tutors further helped me optimize and refine my algorithms in order to make them usable in a real-time scenarios by considerably speeding up the algorithms making them finally usable by the creatures in flight to form assemblies and make them evolve through time.

Moving forward, machine-learning algorithms could be developed together with the creature’s cameras to be able to recognize and cluster people into groups in order to compute the bubble aggregation surface of the assembly.

Representation

Similarly to how Deleuze describes the diagram as a better tool to represent change in action compared to a static architectural drawing, the robotically-enabled architecture developed in this project challenged the conventional forms of representation in architecture. Indeed, this architecture is constantly evolving and morphing through time, and is thus defined by how and why it changes. This presented the opportunity to explore new drawing conventions and representational methods such as frame animations or videos looking at how a single view changes through time.

This form of representation also provides the architect with another point of evaluation and for potential input. This is another feedback loop for the architect to exert some control over how the assembly transitions between one state and another. This representation technique thus reveals how the architectural intentions are consistently and coherently expressed and carried out through time. Therefore, by representing the architectural drawings as being in constant motion, one does not evaluate the result at a single state of the assembly in time, but rather by looking *how well* it adapts to the people below it.

CONCLUSION

Looking back at the research, design and prototyping phases of the project, I believe that this project has challenged me in terms of the trying my best to understand the functioning of autonomous robots and how to translate architecture intentions for multi-agent robotically-actuated autonomous systems. The multidisciplinary of the project, touching on swarm robotics, avionics, biomimetism, emergence and algorithmic design was an exciting starting ground for the project. I believe that combining all of these fields into a single system provides a better understanding where their interface lies and detailing one of these interfaces in a holistic manner. This is showcased by the variety of the methods used to develop the final solution, which include critical theory, interviews with experts, material studies, sensor-actuator prototyping, coding, scripting and simulations as well as time-based architectural drawings.

The first challenge was understanding how these robotic creatures are more akin to humans, that can learn and be taught, that can have feelings and desires, allowed me to widen the scope of the project to also touch on non-architectural aspects of these creatures that would allow them to be better integrated in the built environment. These resulted in architectural interventions to place the infrastructure required for these robotic systems to be an integral part of the urban fabric. They include a detailed a strategy for the inclusion of moods and their expression through the creature's morphology, as well as a series of designs for street-light structure that double as charging stations for the drones which evoke the bird-like nature of the creatures.

The second part of the project consisted in establishing behavioural and architectural intentions and defining how they are expressed in the creature's body. This entailed research and interviews with experts in the fields of soft robotics, and inflatable architecture for the design of an inflatable skin. In order to breathe life into this inflatable skin, a series sensors have been embedded throughout the drone to be able to dynamically adjust the different inflatable areas of the skin based on its context, environment conditions, or emotions. By prototyping this inflatable skin, I was able to experiment with material combinations such as fabric and silicone, as well as controlling the inflation of this skin through sensor-actuator systems to showcase the responsiveness of the creatures to this variety of external conditions and personal states. Moreover avionics research and interviewing experts in the fields of swarm robotics allowed me to take the avionics design of the creature to a new level: a coaxial propulsion system was therefore conceived for the creatures as well as. Finally It also involved the inclusion of feedback systems to enhance the creature's self-awareness and ability to dynamically react to its environment.

Finally the development of a generative design algorithm for an architecture of emergence was both a challenge and a great opportunity to explore and document best practices for this relatively new type of rule-based design methodology. The translation of these architectural intentions at the scale of a swarm was done by developing a series of algorithms that provide a set of rules for the creatures to autonomously form temporary shelters within certain constraints, as well as morph between different states through time. It also includes feedback loops which allow for architectural inputs at different points in the execution of the algorithm. Such loops also open up discussions related to the role of the architect in this age of algorithmic and robotic architecture.