TOWARDS SWARM CONSTRUCTION

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Abstract. Swarm intelligence has primarily been explored in architecture as a form-finding technique with resulting material articulation using advanced 3d-printing technology. Researchers in engineering have developed swarm robotics for construction and fabrication, typically constraints to small scale prototypes as the technology matures within the field. However, a few research explores the implication of swarm robotics for construction on the building or urban scale. This paper presents a novel swarm robotics construction method using mole-like digging technology to construct new architectural language using machine intelligence. The research discusses the role of swarm intelligence behaviours in design and synthesis such behaviour with machine logics. The paper addresses the conference theme through the speculative projection of future construction methodology and reflects on how automation can impact the future of construct and design.

Keywords. Swarm; Digital Fabrication; Robotic.

1. Introduction

The research proposed a novel robotic system that challenges the typical agent-based design techniques as form-finding (Snooks and Jahn, 2016) towards an agent-based fabrication system using swarm intelligence. The paper hypotheses on the use of multiple tunnelling swarm robots deployed to manipulate earthwork with resulting void spaces filled with self-compacting concrete to create structural form through design research methodology. Local communication with sensors (Schranz et al., 2020) allows swarm robotics to avoid colliding in the tunnel and generate feedback when implementing the staged earthwork. The swarm robotics works as a collective network instead of linear feedback, making the system robust, scalable and adaptable with the changing environment. Later part of the paper discusses the swarm robot design, including its control system and workflow in detail.

The research is tested through a series of construction scenarios as research outcomes through the synthesis of swarm behaviours with machine constraints and construction methodology. It demonstrates the potential to shape and challenge traditional construction cut and fill techniques in earthwork with application to create landscaping components striving for digital naturalism (Spuybroek, 2016).

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2. Background

2.1. RESEARCH GAPS: BEHAVIOUR, FORM, MOTION AND TECTONIC

Most of the swarm application in architectural design focuses on emergent characteristics of form. It mimics natural behaviour as a form of organicism (Spuybroek, 2016) with single robotic fabrication (Snooks and Jahn, 2016). These form seeking techniques tend to be self-referential in its data generation. The FIBERBOT (Kayser et al., 2018) designed at MIT Media Lab uses swarm robotics to build the tubular structure in emergent events and TERMES (Petersen et al., 2011) designed at Harvard University introduce an autonomous collective construction at a small scale. This paper intends to fill the gap of translating multi-agent algorithms directly to the collective swarm robotic construction. It is a novel design and construction system, from behaviour to form, and from form to motion, which informs the final tectonic outcome.

2.2. RESEARCH APPROACH: SWARM BEHAVIOUR STUDY

The research takes a systematic approach. The swarm behaviour is the fundamental principle of the system in generating form and defining robot movement. Based on the study of Craig Reynolds' theory (1987), in Figure 1, each agent or Boid's movement is defined by the basic forces as aligning, cohering and separating. The agent can be released with or without initial velocity. Vision radius (dashed circles) determines how far each agent can research its neighbour. This basic parameter decides the character of local behaviour which later inform the size and type of the global organisation.

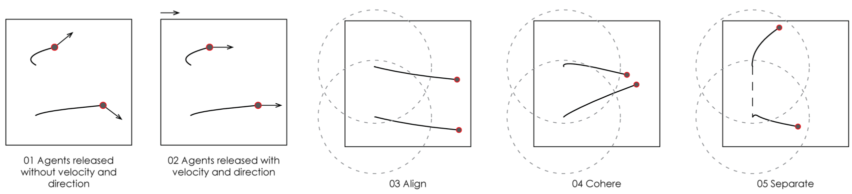

Figure 1. Basic swarm behaviour.

One type highlighted in this research is path tracking behaviour, which is used to generate later architectural geometry. It attracts agents to steer along a given path. Additional parameters further define tracking behaviour. As illustrated in Figure 2, projection distance refers to how fast agents move towards the path while the polyline radius determines the range of moving.

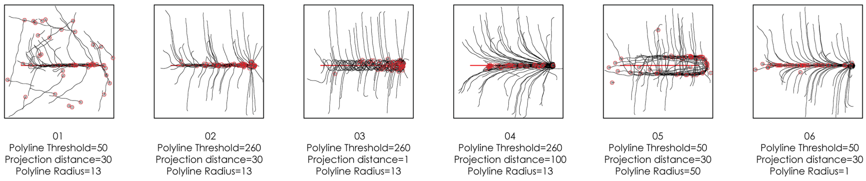

Figure 2. Path tracking behaviour.

Site surface datum levels (both existing and desired) are critical parameters that give the spatial organisation architectural meanings. Figure 3 shows one example of the serial architectural catalogues examined. The width and clearance of the road define the boundary of the interface. Groups of agents are released from or above the ground floor plane moving towards the path. The red spheres in figure 3a represent the individual agent's moving position while the black lines show the trajectories created with resulting geometry (Figure 3b). The moving slope decides the type of vertical elements such as column, staircase and ramps (Figure 3c). In this virtual prototype, the swarm technique proves its potentials in generating architectural elements via the site conditions. The new synthetic structure applied with swarm technique further facilitates the flood management on the site in the later urban landscape proposal.

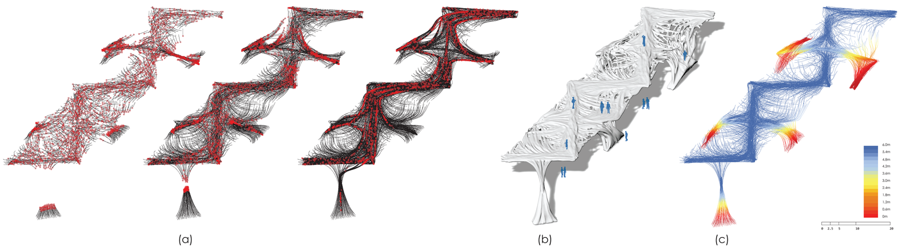

Figure 3. Architectural elements generated. (a) Generation process. (b) 3D outcome. (c) Height evaluation.

2.3. SUBTRACTIVE APPROACH - MOULD FOR CASTING CONCRETE

Figure 4 shows the logic of translating motion into tectonic outcome using a subtractive fabrication approach. The red sphere represents the individual robot that drills through the stock. Each trail generated in tracking behaviour is extracted to become the paths of the robots. The resulting void spaces become the mould for casting. So, the form generation process is directly translated into the fabrication process.

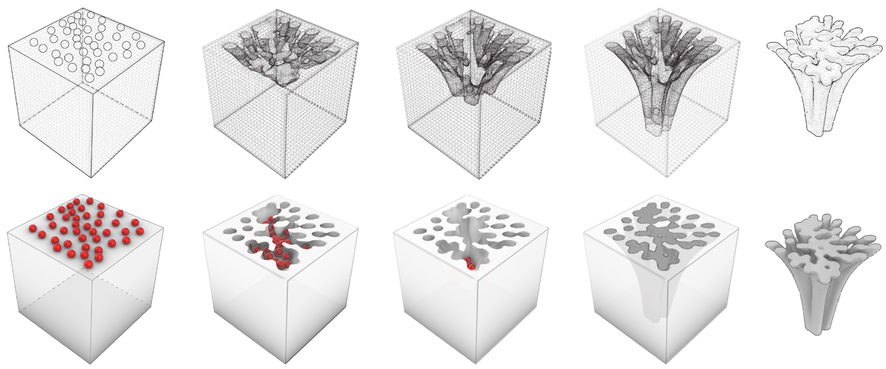

Figure 4. Translating swarm movement into tectonic outcome using the subtractive approach.

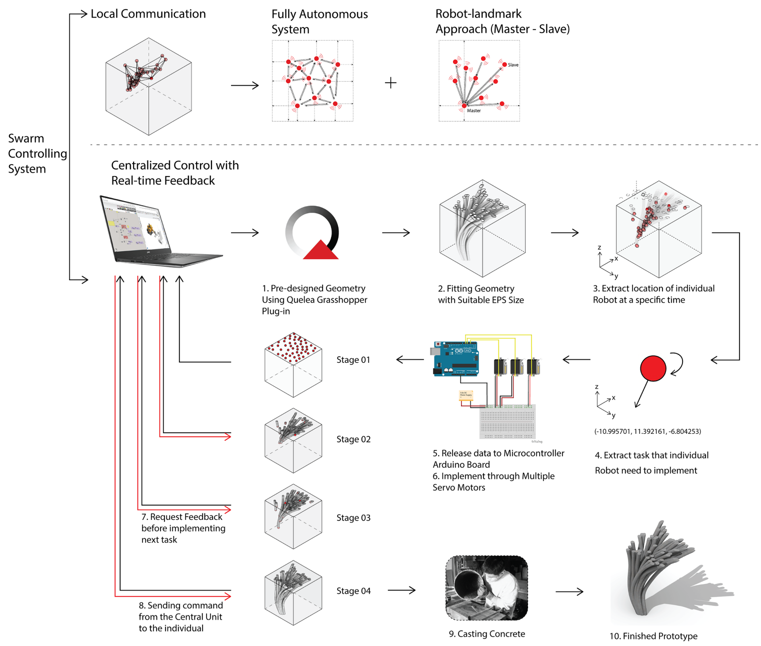

Figure 5. Swarm Controlling System.

2.4. SWARM CONTROLLING SYSTEM

Some researches identify decentralized decision making in swarm robotic application as a fundamental principle (Schranz et al., 2020). To maintain the agent’s autonomy while reducing risk in real-time construction, the paper presents a new controlling system. The form-finding process is fully autonomous while the central unit with real-time feedback-controlled the fabrication procedure. To be Specific, after geometry is generated with animated swarm behaviour, the X, Y, Z coordinate, velocity and moving directions are extracted and sent to the microcontroller of the individual swarm robot (see Figure 5). In each stage, the robots send the position to the central unit for calibration before implementing the next task.

2.5. COLLECTIVE CONSTRUCTION VS SINGLE ROBOTIC CONSTRUCTION

Swarm intelligence operates through simple behaviours to create emerging complex forms (Scribner, 2001). The simple mechanism makes the robot able to act independently and implement its own task. Under collective action, swarm robotics can generate a complex geometry. The project proposed a mole-like digging robot to perform the tunnelling action. Individual robots consist of microcontroller, senses, actuator and mobile power. Like Terms (Petersen et al., 2011), the complex structure can be built at a scale larger than an individual robot. With sensing capabilities, swarm robotics are interconnected and able to interact with each other and environment, which characterizes the system's main advantage as scalable, robust and adaptable. Compared with single robotic construction, having a collective of smaller and more mobile robots operating at the same time contributes to a faster and more efficient construction method.

3. Robotic System

3.1. DESIGN AND RESEARCH

The proposed swarm robot is based on Mole-like Drilling Robot (Lee, Tirtawardhana & Myung, 2020), which was originally designed for tunnelling through soil. The proposed design, titled Dig-bot, further expanded on the engineering design and adopted it for architectural purposes. As shown in Figure 6, it consists of the expandable drilling bit (01), forefoot (02) to remove soil, wheels (11) to manoeuvre and a pneumatic fibre mesh (13) to hold the soil. The paper will not explain the detail of the mechanism that has already been documented in engineering research (Lee, Tirtawardhana & Myung, 2020). Instead, the paper emphasis on the application of choosing mechanisms appropriate to architectural design and construction. The expandable mechanism using the rack and pinion system allows the drilling blade to expand and contract by rotating the inner shaft driven by the stepper motor. The soil removing mechanism is the design based on the scapula and humerus interaction of a mole. With a fixed point of connection, it can transform linear movement into the rotational movement to remove soil to the side. The fibre mesh attachment is able to inflate the plastic tubes lining inside through pneumatic pressure, similar to the Earthworm Soft Robot by Calderon et al. (2019).

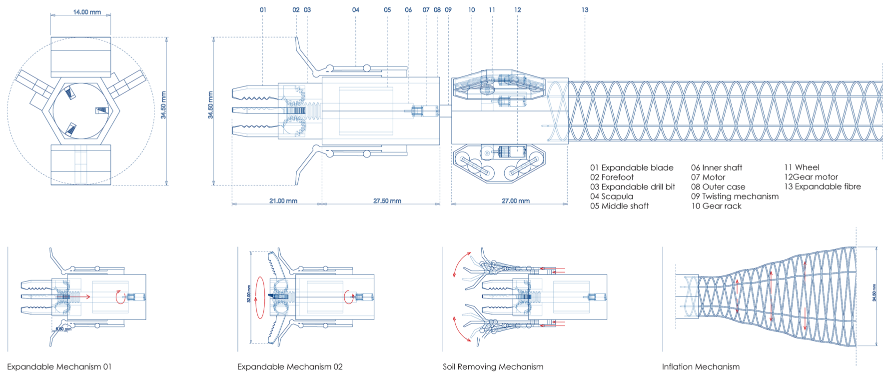

Figure 6. Mole-like swarm robotic component and key mechanism.

3.2. DIGGING PROCEDURE

Figure 7 illustrates the digging procedure starting with the initial position (7-A) where the forelimbs are located at the side of the robot. By rotating the motor counterclockwise, the folded drill bit moves forward, expanding the blade (7-B). The expanded blade keeps rotating to crush the soil while the robot advances forward (7-C). After a sufficient amount of soil is crushed, the motor rotates clockwise to retract the drilling bit to the starting position, providing enough space for soil removing (7-D). The forelimbs are pulled forward with linear actuators and spread left and right to remove soil to the side (7-E, F). After forelimbs are pulled back, the fibre mesh is inflated to hold the void space (7-G, H). While the same digging process is repeated, the waist mechanism allows the robot to change direction (7-I, J). The resulting void space will be supported by fibre mesh. This acts as a mould for concrete casting (7-K, L).

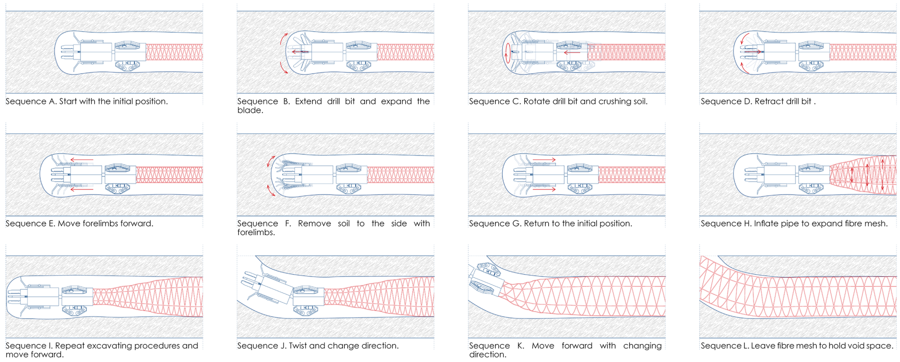

Figure 7. Digging process diagram of the system.

4. Urban Speculation

The performability of the swarm technique is tested in a speculative design, titled Digital Naturalism. The proposal is an infrastructure mediating flooding issue for a new university campus proposal. The site in consideration will be affected by increasing stormwater flooding due to climate changes. It is predicted that the site's mean sea level will rise by 0.8 meters by the year 2100 (Pty Limited et al., 2018). Facing the future challenge, the design emphasis on several water management strategies. The agent's flow is used to generate a water channel diverting rainwater from the bridge to the wetland (Figure 8). The structure indicates the procedure of swarm construction. Figure 9 also highlights the foundation shift on material and introduction of a new building type. As a passive structure to integrate with nature, the water and soil are considered as live elements of the system. The gravel with bio-resin fills in the gaps between structures which allow rainwater to flow through. Height difference in structure contributes to the varied depth of soil components, which allows the native ecosystems to coexist with the structure. The swarm becomes a technique to weave the form, material, ecology and infrastructural function together.

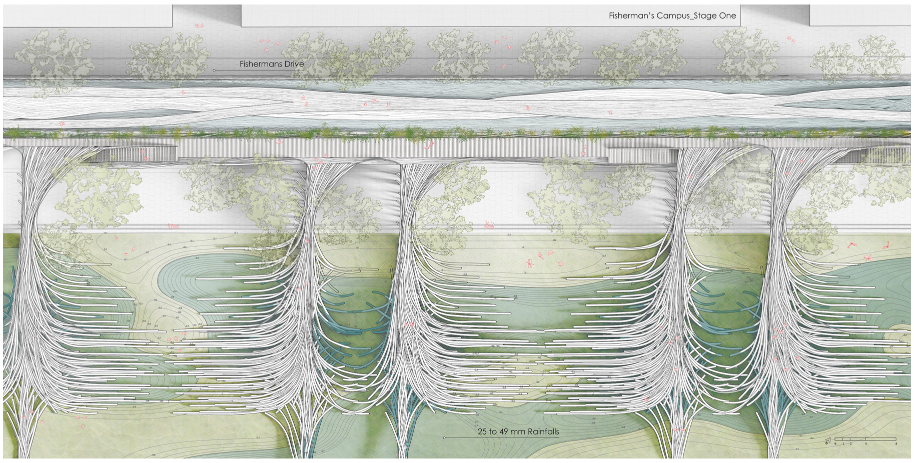

Figure 8. Plan: Proposed structure mediate flooding issue on Fishermans Bend site, Melbourne, Australia.

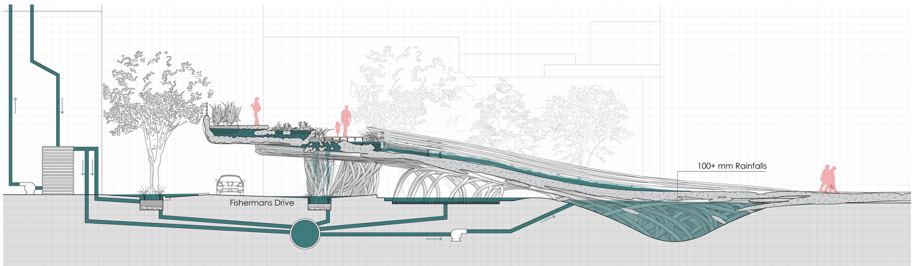

Figure 9. Section: Proposed structure mediate flooding issue on the test site.

Figure 10 highlights new swarm topography in the background of the existing urban environment and future university campus. The structure humbly sprawls from the ground and flows between the building and nature. The paper recognized that both nature and architecture are synthetic. The intent is to create a synthetic environment for nature and architecture to coexist, and facilitate each other overtimes, as a reinterpretation of naturalism in the digital age.

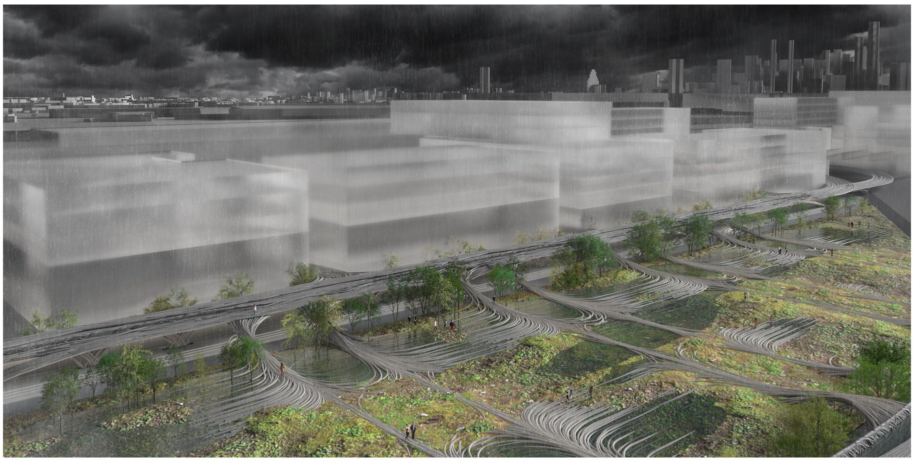

Figure 10. New swarm topography.

4.1. ON-SITE CONSTRUCTION

The project utilized the novel swarm robotic as an on-site collective construction (Figure 11). The construction procedures are designed largely based on existing construction systems with two sizes of the robot operate simultaneously. The swarm of Robot A constructs the primary structure, while the swarm of Robot B defines the surface texture. Soil is held in place using the standard Peri(TM) system, while earthwork is moved into place for robotic excavation (11-1). Swarm robots are released and tunnel inside the soil, leaving the fibre mesh to hold the void spaces (11-2). Self-compacting concrete with micro-reinforcement is pumped into the meshes and unifies all void spaces as one structure (11-3). After the concrete is consolidated, most of the soil is removed with a hydro vacuum extractor, and some are left for planting (11-4).

Some researches also have examined the same casting technique. Montana's tippets rise art centre by Ensamble studio (2020) is a sculpture cast from the terrain. It traces the geological transformation process and is used as a way to reinterpret the terrain. The swarm construction proposed here also shared a similar aesthetic but with a unique automated construction process. As discussed in Section 2.5, collective construction provides high efficiency with small and simple robot working simultaneously. The same data used to generate form can be directly translated into the machine movement contributing to a high coherent workflow. The research project the future of design and construction, embedding the autonomy of natural system into form generation, using data to communicate between human and machine, machine and material, archiving a synthetic structure that facilitating an on-going mutual relationship between nature and architecture.

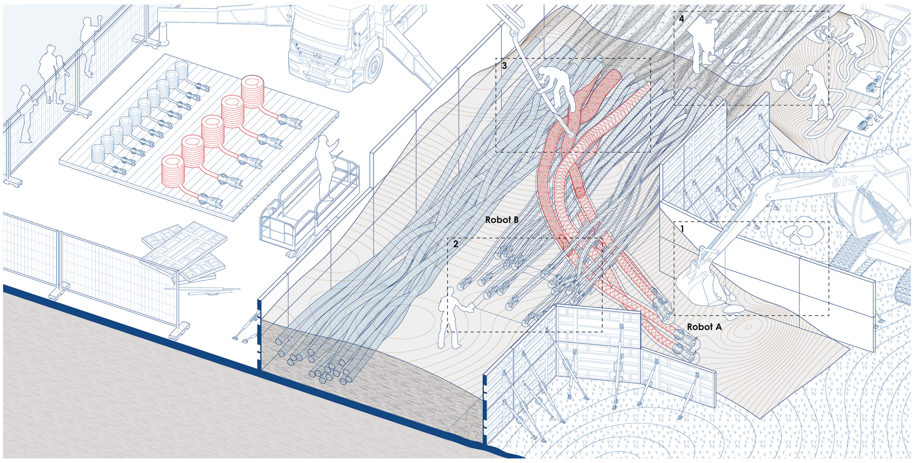

Figure 11. Swarm Robotic Construction on site.

4.2. ROUGHNESS - NEW AESTHETICS OF SWARM CONSTRUCTION

Roughness is a unique aesthetic highlight in this swarm construction. The research considers the notion of roughness as an approach to engage with nature. This thematic has been widely explored by architects such as Ensamble studio (2020), and Lina Bo Bardi (Veikos 2015). The rough quality of the surface records the process when the earth meets the concrete. The project presented in this paper extends the notion of roughness as surface quality and a digital construction strategy. In swarm construction, the robot's organization and routine are fixed while the tectonic outcome is not, allowing a certain level of change and imperfection. Besides, roughness also indicates the unfinished condition of the structure. The gaps created allow nature to infill over time, creating a live ecological system, constructing a synthetic environment for nature and architecture to coexist.

5. Conclusion

In conclusion, the paper proposes a novel form-finding and collective construction method inspired by swarm intelligence. The research has a few constraints requiring future investigation, namely physical prototyping and the feasibility of designed robot. The autonomous construction system is also worth further exploration, particularly how the form emerges from the local communication through a central control interface. Overall, the paper finds its position in projecting the future design and construction informed by swarm intelligence. It proposed an implementation of a new digital naturalism - a condition where architecture and nature not just coexist but facilitate each other as one synthetic system in an on-going period.

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