Foam Making Sense

behavioral additive deposition and stigmergic agency for integrated surface tectonics

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This thesis research deals with the architectural project from an interdisciplinary point of view, integrating biomimetics, additive fabrication, computer vision, and robotics. The work focuses on the feedback interaction loop among robotic additive fabrication, a stigmergic agent-based system and the self-organizing properties of the material. The aim is to explore the morphological, constructive and expressive potentials generated by the mutual influence of computational design, construction behavioral rules, and physical material behavior (whose complexity exceeds current simulation capacity).The proposed approach leads to the creation of surface-based tectonics, enhanced with a fiberglass-coated dendritic ridge formation that integrates functional, ornamental and structural performances. The process can be extended to larger architectural scales with the creation of bespoke EPS molds via robotic hot wire cutting; the presented case study leverages the aforementioned process on ruled surfaces for the generation of translucent delimiters, used to create heterogeneous spatial organization.

Keywords: *behavioral fabrication, stigmergy, agent-based system, robotic hot-wire-cutting, additive fabrication, sensors*

INTRODUCTION

The strategy behind the work is deeply connected with the paradigms of complexity and self-organization, it is based on an integrated vision of tectonics (behavioral tectonics) and on an ecosystem of information in which the procedures and operational criteria of the production systems become an integral part of the creation process, as they are encoded in the algorithm that generates the simulation. The use of simulations, iterative algorithmic processes, and the ever-increasing computing power broaden the limits and the spectrum of possibilities within the design space by accessing a complexity that exceeds the human capacity for its conception and deployment (Erioli, 2018). The resulting systems are intrinsically coherent, which allows their readability and assessment of their performances. Simulation algorithms are based on the definition of interaction rules among basic elements within a geometric / mathematical model - rules that do not necessarily aim to imitate an existing phenomenon. Their reiteration generates forms, organizations and outputs that reveal themselves only when the system is enacted, as they are the consequence of the rules in action but not their literal reflection, but allow a certain degree of control and steering for design purposes, due to the internal coherence of the system. This approach challenges the idea that conception is a single defining moment, independent and pre-dating development, in which a project is imagined as a whole and details descend from it in a progressive zooming in of scales. Details are instead encoded within the interaction rules, and their iteration produces higher level (self)organized assemblages. Computation has made quantitative iterativity accessible, accelerating and amplifying it, while sensorization allowed the connection and integration with the physical realm in the process, challenging the idea of manufacturing as a purely subordinate phase to the conception. This research explores the expressive possibilities deriving from these premises and investigates their application in the architectural field.

BEHAVIORAL FABRICATION

Design and manufacturing are typically conceived as two distinct phases with a linear and unidirectional transition from one to the other. Carpo (2011) traces the origins of this separation back to Alberti, who aimed at the reproducibility of otherwise unique pieces (sculptures, maps, buildings); a particular strengthening of such gap happened with the second industrial revolution and the first intensive introduction of automated processes and mass production. In architecture, conception progressively strained so far from production to become almost entirely self-referential, object-centered and devoid of process: once the design of one object is completed - regardless of the method of its conception - its qualities are reverse-engineered into a series of standard-compatible instructions for its passive reproduction, generally losing any systemic feedback or influence with the design phase and the related information structure. With the introduction of cyber-physical systems in the manufacturing industry, production machines are increasingly able to perceive, process and interact in real time with each other and with the physical environment. Behavioral programming fosters a design process that, instead of being entirely predetermined and self-contained within the digital domain, unfolds and iterates across the physical realm through an exploratory path that we can define as computational construction - in which geometry and forces mutually restructure each other and organize by processing and exchanging information over time, producing higher level formations which properties that exceed those of their constituent parts. Due to their programmable nature, the same technologies developed for industrial automation thus open the possibility for behavioral-based manufacturing processes. Performance assessment undergoes a similar challenge; shifting the focus from the object to the process. Standardization in the industrial world is the cornerstone to guarantee quality in mass production by establishing a set of expected qualities for the outcome and discarding any deviation; product reliability and consistency comes at the cost of sacrificing differentiation and adaptability. A behavioral approach focuses on the design of behaviours (actions) performed by agents (regardless of their nature: digital, mechanical, biological, or else - as long as they can be programmed) which iteration over time leads to the emergence of higher organization. Such approach allows the granular encoding of intentions and qualities as an intrinsic part of the system, erasing the necessity of a touchstone; variation becomes a trigger for design potential rather than a precision issue or a deviation from the norm. Material systems become an active component of design, not only through their increasingly accurate encoding in digital simulations - but especially by accounting for their real-world behaviour as a design driver: in additive fabrication, materials undergo a change of state at the moment of deposition, and, in their process of stabilization over time, properties such as volume, stiffness, and shape are prone to change with a degree of complexity that digital simulation alone is yet unable to capture. This means that new information must be constantly gathered, and new features

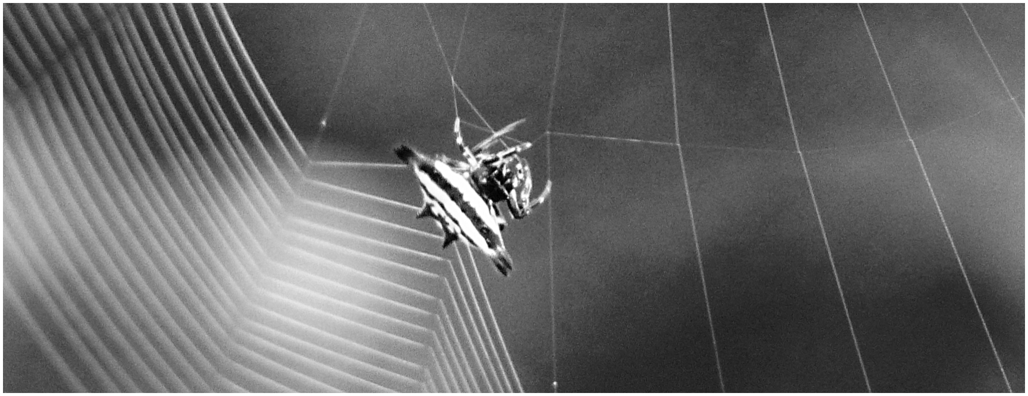


Figure 1
An orb spider weaving a web is an example of behavioral construction in biology. © 2009 Jee & Rani Nature Photography. Creative Commons Attribution-ShareAlike 4.0 International License.

can be perceived at each stage, informing the next: design evolves iteratively, digital and physical realms affect each other and partake equally in the process.

SELF-ORGANIZING SYSTEMS

The transition to computational construction challenges the aforementioned typical conception/construction segregation, and together with the absence of a blueprint for the final outcome finds close affinities with biological models: the constructions occurring throughout the animal kingdom (such as beehives, wasps nests, weaverbirds nests, spider webs, beaver dams - to quote the most commonly known) are the result of inherently behavioral iterative processes in which agency, material behavior, and self-organization play a crucial role. Self-Organization is a process where global organization in a system (emergence of patterns at the global scale) arises by means and as a consequence of local interactions. These interactions can occur directly among the agents themselves, or indirectly (carried out through the environment). Despite the deterministic nature of local interactions, the dynamic and non-linear nature of the organization at the global level allows the emergence of properties that transcend the characteristics of the individual parts. Interactions affect both the internal organization of the system and the environment, and their respective changes affect each other mutually. The system evolves in space-time, achieving dynamic stability by means of feedback interactions: positive feedback disrupts the system and promotes change, while negative feedback stabilizes it and acts as a regulator. The coexistence of both systems and their reciprocal influence allows the system to self-regulate and self-organize. Agent-based modeling is a particularly promising approach, as it allows designers to instrumentalize self-organization for the exploration of the space of possibilities in the context of architecture and construction, aiming for the level of complexity and sophistication expressed by the biological cases.

STIGMERGY: FROM MULTI- TO ASYNCHRONOUS AGENCY

Self-organizing systems require some sort of coordination, usually implemented as simultaneous interaction (i.e. the typical flocking model); this approach, however, does not comply with the use of a single robotic arm or machine (as in the present case study) or any non-simultaneous swarm of machines (as in the majority of real-world cases). Stigmergic systems are of particular interest for these cases: they are based on an indirect coordination mechanism in which the trace left by an action on a medium stimulates a subsequent action. Introduced by the French entomologist Pierre-Paul Grassé to describe a coordi-

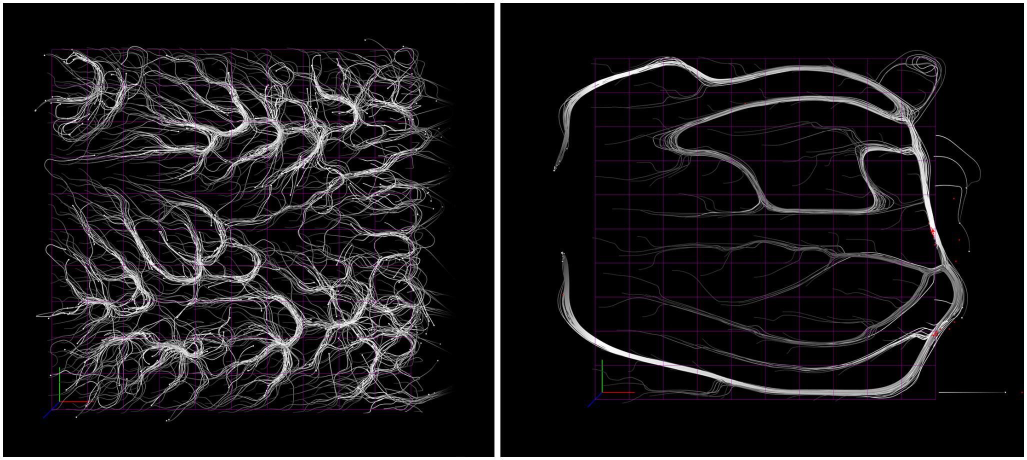


Figure 2
Left: example of synchronous stigmergic simulation. Right: one of the first tests on asynchronous agents behavior.

nation mechanism used by insects (Heyligen, 2016), in stigmergy the environment takes a central role as both source and recorder of information. This model suits particularly well with the single actuator scenario and the inclusion of material behavior: at each iteration, the deposited material becomes a part of the environment that will be read as information for the extrusion in the following iteration. This mediation through the environment ensures that the activities are carried out in the right order, without the need for planning, control or direct interaction between the agents. Coordination among agents can thus be asynchronous, considering one agent at a time (Snooks, 2016a). To achieve this, traces left in the environment must be persistent or their decay proportionate to the manufacturing times. Persistent traces lead to asynchronous stigmergy: agents do not have to be simultaneously present since the trace can influence them at any time. Conversely, transient traces lead to synchronous stigmergy: agents simultaneous presence is required for self-organization to happen. In the proposed approach, traces in the environment do not decay: the iterative process is free of synchronous time limitations, its implementation is simplified, and a coherent, direct coupling between the digital agent and the physical actuator is achieved.

VISION SYSTEM AND ACTUATOR SIMULTANEITY

The physical actuator is equipped with a Kinect to register step-by-step environmental changes as a point cloud representation of the working space. At each iteration, color, geometry (via mesh curvature analysis) and other relevant information are extracted from the raw model and fed to the algorithm, which then operates between the external inputs obtained from the scanning system and a series of structural and functional objectives to define the depo-

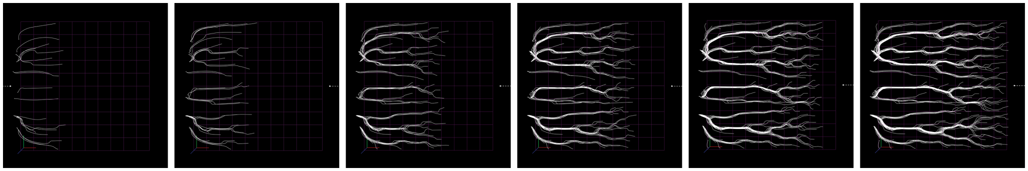


Figure 3
Asynchronous stigmergic pattern formation sequence.

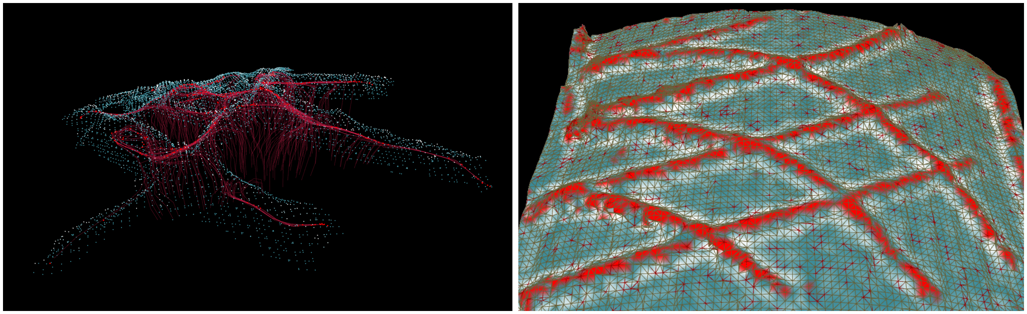


Figure 4
Left: agents behavior influenced by the surface curvature datas stored in the tensor. Right: visualization of the curvature analysis values.

sition trajectories to be performed by the physical agent at the next step (Snooks, 206b). Several market grade robotic systems already allow real-time communication and control, achieving effective digital/-physical simultaneity. Despite the impossibility to access such technology, the workflow developed for this research aims to approximate that situation as closely as possible.The technique is similar to continuous curve approximation by means of small discrete intervals: shortening the timespan of each iteration phase (digital trajectory simulation and physical deposition) should approximate the simultaneity condition in which agents are affected also by their own deposition. At the time of this article it was not possible to prove the accuracy of this technique, but this does not affect the validity of our results as simultaneity is a desired, yet not necessary, condition.

BEHAVIORS

As an initial benchmark, a one meter side square-shaped plate - fixed on one edge and subjected to a uniform distributed load on the opposite - was chosen, shape and size set to simplify as much as possible the scanning process and the mapping of the digital space within the physical one. A finite element analysis was carried out using Karamba3D, (a parametric structural calculation software), in order to extract the relevant information for the stigmergic system: the scalar values of the principal stresses and their direction vectors at given sample points (stored as tensor points), and the stress curves along the mesh surface sampled through the same locations. The underlying behavioral rules of the system were defined as follows.

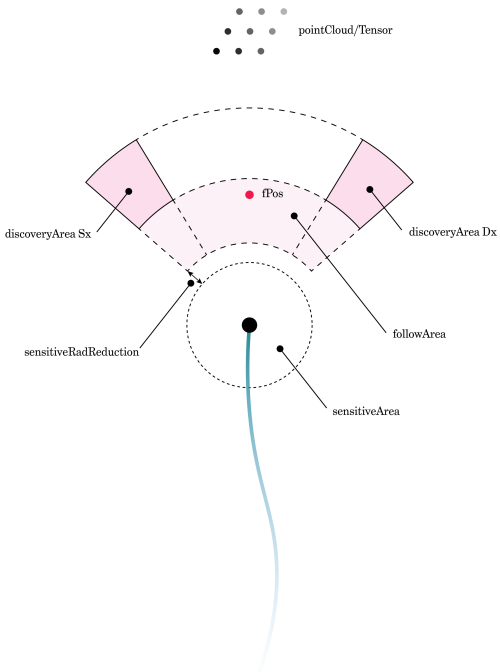


Figure 5
Agent in the discovery phase. The search radius increases to see if there are traces released by other agents in nearby areas.

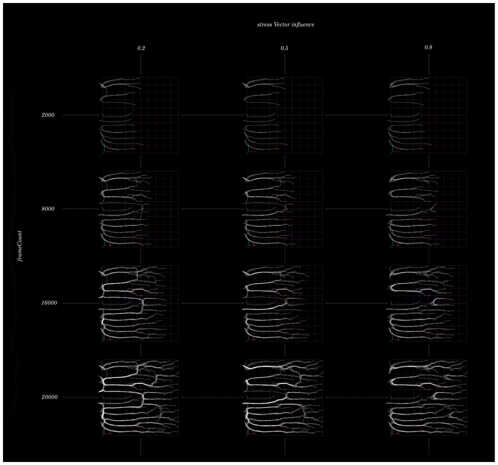


Figure 6
Influence of the stress vector magnitude over the final morphological result.

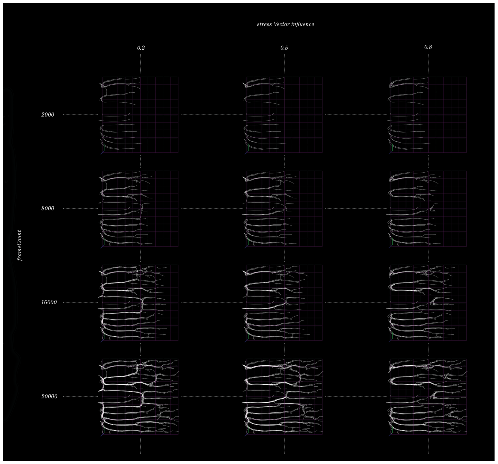


Figure 7
Influence of the start point spacing on the x axis over the final morphological result.

Adherence to the point cloud. Each agent, based on their vision angle and range, sees a portion of the point cloud environment and its encoded information; operating a weighted average on the position of the vertices a target is calculated and the agent tends to follow it, keeping its trajectory adherent to the surface.

Environment Influence. The information stored in the tensor points (such as the principal stress direction vectors), the movement constraints, and the boundary conditions are interpreted by the agents in the algorithm to choose their future direction. This table (figure 6) schematizes the the stress vector influence (called stress vector influence) on the system. For high values of tensMag agents trajectories follow the principal stress directions and cross connections are absent. Conversely, for lower values, agents tend to favor cross connections due to stigmergic behavior.

Starting Points Spacing. Spacing influences the density of agents trajectories on the surface. It can be noticed (figure 7) how decreasing the distance between consequent starting points also increases the number of points needed to cover the surface. For very small distances the system becomes much denser and the main branch progressively loses importance in favor of secondary branches.

Cross Connection Behaviour. The analysis of the first batch of experiments on the stigmergic pattern morphogenesis showed how the formation process is extremely effective in developing and responding to the principal stress directions . As a countereffect, there aren't almost any cross-connections among the branches thus causing a lability in the direction of the perpendicular principal stress. Agents are then given a sensitivity radius (figure 5): each agent, based on the values read in the closest tensor, can widen its vision area and try to connect with the adjacent branches. If a branch is found below a certain threshold the agent will leave the current trajectory to connect to the new target.

MATERIAL STUDIES

Expanding polyurethane foam (EPF) was chosen as a deposition material because it facilitates experimentation across a spectrum of material behaviors: by controlling its expansion rate (via a bespoke effector), the material can behave either in a highly predictable or highly volatile fashion. This behavioral variability depends only on the pressure exerted to extrude the two chemicals that mix in a nozzle to form the foam; the effector was designed and built to finely control the extrusion pressure by means of a gear rack and a

Figure 8
Scheme of the behavioral iterative feedback loop and fabrication process.

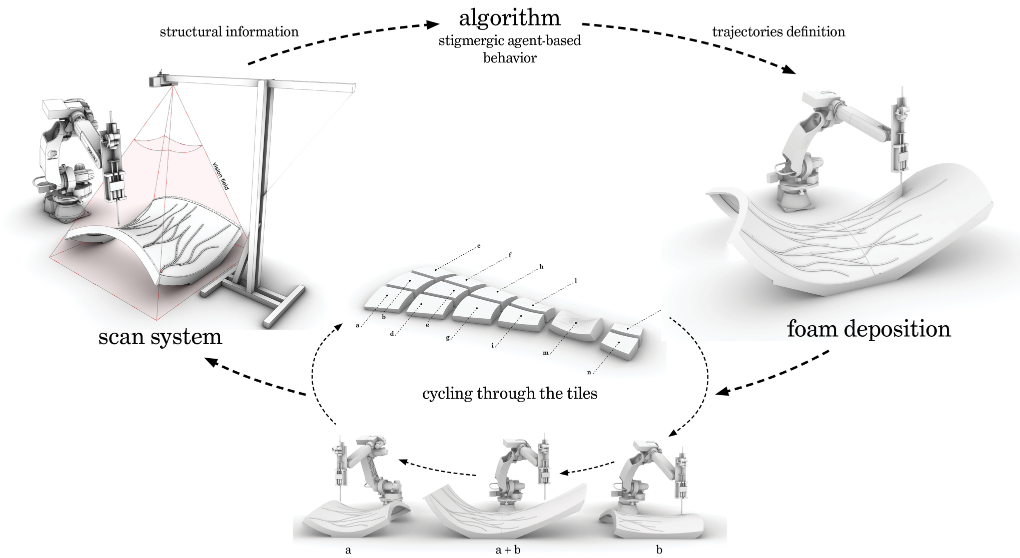
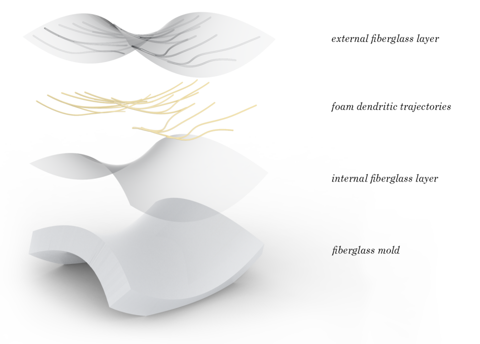


Figure 9
Fiberglass layer structure.



motor speed control system, thus managing the extruded material flow and map its behaviors in a parameter space.

ROBOTIC HOT WIRE CUTTING AND FIBER COMPOSITES

Once the system rig and workflow have been tested on the benchmark, the research presents a nexus of possible paths: from the intensification of the autonomy of the process (which points in the direction of basic research) to the possible applications (of more or less direct implementations) at the architectural scale. This research aims at the latter direction; as a consequence, the need for a certain degree of control dictated a very low number of iterations, and foam alone proved inefficient (primarily - but not only - in terms of the construction size/required material ratio) to tackle the required change of scale. Instead of working alone, foam is then used to design ridges infills for fiber composites surface tectonics: foam deposition forms an intermediate layer between sheets of fiber composite material, working as an integrated beam at the intersection of the structural and ornamental condition (Snooks, 2016b). Fiber composites however require a mold, and one technique that provides a sound answer to the design questions of size, modularity and variation - and has already architectural scale commercial applications - is Robotic-Hot-Wire-Cutting (RHWC). This technique uses EPS foam and a hotwire arc effector mounted on a robotic arm to create large, bespoke molds in a relatively short time (Søndergaard et al., 2018); examples are the Lushan Primary School bridge by Zaha Hadid or the Kirk Kapital by Olafur Eliasson (in both projects the formworks are produced by ODICO). The main constraint is a grammar of possible shapes limited to ruled surfaces - a limitation which still allows great morphological variation and loses relevance as size increases, since for larger surfaces the approximation is less problematic.

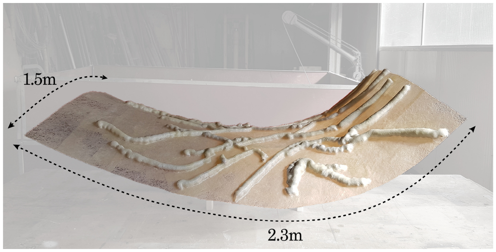


Figure 10
Self-standing fibercomposite prototype (2.5kg)

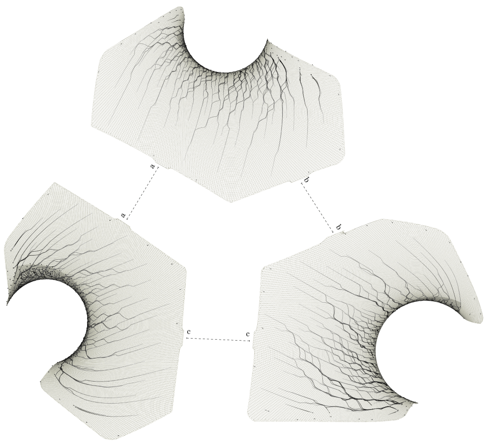


Figure 11
Top-view of the joints connections between the fiberglass surfaces.

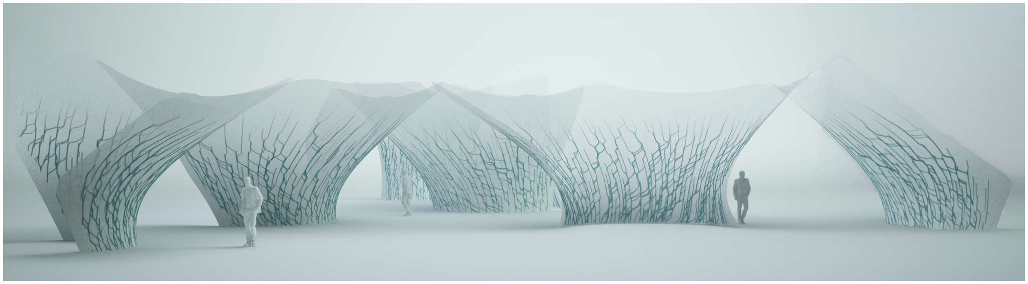
PROCESS

The final version of the process consists of the deposition of a single or double foam layer in dendritic trajectories over a ruled surface mold coated with fiberglass fabric. The base fabric and the deposition are then coated in an external layer of fiberglass, in order to obtain integrated "beams". One of the classic problems of automating construction at the architectural scale is the size limit of the machine versus the required size of the outcome. One of the fundamental properties of stigmergy provides an efficient workaround: the possibility of partitioning the process in different moments and locations, as long as the global environment is shared by all agents. It was then possible to subdivide the global surface in accordance with the robot's reach and deposit material on one sub-surface at a time, making the whole process modular. The total area can then be subdivided, each part manufactured through RHWC, the foam deposited, fiberglass coated and then reassembled at a later time.

ARCHITECTURAL APPLICATION

The experimental results led to the conception of the demonstrative project at the architectural scale in the case of outdoor spaces organized by large ruled fiberglass surfaces. The geometric study on the surface shape - limiting the field of research to ruled surfaces only - led to investigate the hyperboloid of revolution due to its double curvature (a very important property for implicit structural resistance) and the relative simplicity of execution given by the axial symmetry. These characteristics allow its subdivision into a matrix of identical panels and the creation of a complete hyperboloid (potentially of 360°) starting from a single panel mold. Once the mold is made, it can be reused as many times as necessary to obtain the final surface shape and size. Operating on geometric proportions, the surface border shape, and the combination of several paraboloids in a modular system, it is possible to achieve great variability which translates into a potential architectural versatility. In the proposed architectural case study the hyperboloid allowed the realization of large sheds that smoothly transition into enclosures, the cuts have been studied in such a way as to leave maximum space for the circulation flows; the shape of the ground connections allows instead to delimit more collected spaces

Figure 12
Perspective view of the architectural application composed of six surfaces.



suitable to host more private functions and services. Each surface is fixed at the base and has a support joint at the intersection points with the others. This punctual element, also made of fiberglass, allows to significantly reduce the size of the joint to the ground. The fiberglass native translucency ensures light diffusion and a certain degree of visual permeability through the space, mediated by the variable density of the foam venation which exceed pure structural performance, integrating aesthetic characteristics and other potential functions (i.e. flow circulation, lighting - not implemented in this case but already compatible with the current system setup).

Figure 13
Front and top view of the modular system.

CONCLUSIONS

The obtained results are an attempt to bridge the design-making gap by interacting with the fabrication process and material behavior unfolding over time. The extrusion of polyurethane foam has shown how the introduction of cyber-physical system within the design process opens up new manufacturing potentials for materials that until now have been neglected from the point of view of standardization. On the contrary, in the case of foam, volatility becomes a design element and complex emergent behavior that exceeds simulation capacity can be reinterpreted and assimilated by the system. The properties of stigmergic behaviors enable asynchronous processes, loosening time and space constraints as long as a shared communication environment is maintained; the manufacturing system can be discretized in parts and subsequently reassembled without renouncing continuity in the design process and the final result. The extrusion of the bicomponent foam through the developed effector proved to be more effective in long and continuous deposition trajectories even on slanted surfaces (tested up to 45° from horizontal plane) and small extrusion nozzle angles (30° from the Z axis), while more difficult to control for short stretches since the continuous interruption of the deposition tends to increase exponentially the volatility of the material behavior. With regards to the architectural application, while the system flexibility can express a high degree of versatility and variability from the ornamental to the spatial tectonic scale, it is still limited to open surfaces and has a scale

Figure 14
Perspective view of three modular surfaces assembled.

limitation dictated by the material performance and current setup. Further work in all directions is required to enhance and broaden its applicability scenario, nonetheless the system's potential, coupled with RHWC outline a promising way for the development of automated manufacturing processes that can make designing with complexity bridge the gap from the laboratory to real world architectural applications.

REFERENCES

Carpo, M 2011, *The Alphabet and the Algorithm*, MIT Press

Erioli, A 2018, 'Anexact Paths: Computation, Continuity and Tectonics in the Design Process', in D'Uva, D (eds) 2018, *Handbook of Research on Form and Morphogenesis in Modern Architectural Contexts*, IGI Global

Heylighen, F 2016 'Stigmergy as a Universal Coordination Mechanism: components, varieties, and applications', *Vrije Universiteit Brussel*

Snooks, R and Jahn, G 2016a 'Stigmergic Accretion', *Robotic Fabrication in Architecture, Art and Design 2016*

Snooks, R and Jahn, G 2016b 'Closeness: On the Relationship of Multi-agent Algorithms and Robotic Fabrication', *Robotic Fabrication in Architecture, Art and Design*

Søndergaard, A, Feringa, J and Stan, F 2018, 'Robotic abrasive wire cutting of polymerized styrene formwork systems for cost-effective realization of topology-optimized concrete structures', *Construction Robotics*, 2, pp. 81-92