**Fibrous Aerial Robotics**

*Study of spiderweb strategies for the design of architectural envelopes using swarms of drones and inflatable formworks*

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This thesis research presents an integrated workflow for the design and fabrication of large-scale architectural envelopes using swarms of drones and inflatable structures as formworks. The work lies at the intersection of architecture, biology and robotics, incorporating generative design with digital fabrication techniques. The proposed approach aims to investigate the tectonic potential of computational systems which encode behavioral strategies inside an agent-based model. It is from local interactions taking place at the micro-scale of complex systems that a new set of architectural tendencies seem to emerge. The authors focused on the strategies developed by colonies of social spiders during the construction of three-dimensional webs. Their communication system and the characteristics of the material structure have been then modelled and translated in a digital environment. A physical fabrication process, in which the simulated agents become drones in a real world environment, was concurrently developed. The goal was to investigate the architectural possibilities given by an autonomous aerial machine depositing fibrous material over inflatable formworks and its potential usefulness in specific sites where overall conditions don’t allow traditional construction techniques.

**Keywords:** tectonics, robotics, multi-agent systems, stigmergy, drones, inflatables

**INTRODUCTION**

The strategy underpinning the work is deeply connected with the logic of swarm intelligence, the collective behavior of decentralized, self-organized systems, natural or artificial (Beni and Wang 1993). Self-organization, intended “as a process in which pattern at the global level emerges solely from numerous interactions among lower-level components of the system” is a key element when it comes to design robust and decentralized systems (Camazine 2003). Swarm intelligence studies systems in which a complex action arises from a collectively intelligent group of individuals as it happens for many insects colonies, flock of birds, schools of fishes or mammalians groups. The design of simple rules and behaviors governing the individual agent actions at the local level can lead to the formation of swarms that cooperate in building complex yet reliable struc-
figures. Collective species display decentralized self-organization, swarm behaviors and intelligence - intended as making an effective use of environmental resources through the construction of buildings and artifacts which sophistication (both in morphology and metabolism - i.e. the passive thermal regulation dynamics in termite mounds) greatly exceeds the intelligence potential of any single individual. Insects, in particular, exhibit great potential when it comes to share information and use them in a clever way. Ants, termites and spiders are common examples of societies capable of generating complex collective organization taking advantage of their elaborate communication system (Figure 1).

BIOLOGICAL MODEL

Social spiders. Of all the spider species in the world, only about fifteen can qualify as social spiders. The individuals live together, share the same web and cooperate in a diverse set of activities such as brood care, web weaving and hunting (Bourjot et al. 2003). Spiders are gathered in small clusters throughout the web, under the vegetal sheets enclosed by the web itself and are distributed on the whole silky structure. Despite their apparent individual simplicity, these spiders are exhibiting interesting collective behavior during prey capture and web weaving. The authors focused on the architectures built by social spiders and the type of cooperation involved during the related construction task. These insects are able to collectively build silk structures bigger than 10 m3 consistently endowed with architectural qualities in different environments. Adversely from solitary spiders these colonies seemed to be aware of the global scheme of the structures they were to build or the task they were to realize. This hypothesis was nevertheless difficult to accept because of the intricacy and sometimes impressive size of the structures or complexities of actions compared to the apparently reduced cognitive abilities of the individuals involved. The theory of stigmergy developed by Grassé (1959) for termites lifted the veil on this mystery. Stigmergy is a mechanism where the structure created by an individual acquires stimulation properties that can control the behavior of a congener by reducing its degrees of freedom. A stimulating configuration acti-

Figure 1
Colony of Anelosimus eximius, a species of social spider.[1][2][3]
vates a response of another element of the system, transforming the original configuration into a different one that may trigger in turn another, possibly diverse, action performed by the same element or any other agent in the colony. Although each step in the sequence of interactions is based on rigorous stimulus/response dynamics involving only local information, this distributed system enables a broader plasticity at the global scale and the emergence of the phenomenon of self-organization, which unlocks the generations of higher forms of internally coherent complex organizations.

**Silk.** Like many other animals, spiders communicate through chemical signals or pheromones. This ability is often used to find prey but also functions in social and sexual communication. Silk plays an important role by influencing how the information travels along the elements of the colony. For example female specimens may deposit chemical traces on the ground or on the substrate by combining sex pheromones with the filament of the same thread in production. The male is then able to identify the silk thread produced by the adult female and monitor it using chemical and mechanical information. In a similar way spiders are able to perceive their local environment thanks to the specific nature of the silk they are depositing and existing structures play an important role as the spider is able to extrapolate useful information from preexistent silk. Stigmergy theory allowed the understanding of the cooperation mechanisms among social spiders, providing at the same time an operational model upon which the design exploration is based. Self-stigmergic processes (Krafft and Cookson 2012) suggest the involvement of a process similar to the stigmergy described by Grassé for explaining the construction of nests and termite mounds, except that the pheromone influence acts on the emitting specimen itself rather than its congeners. Pre-existent structures guide the spider’s subsequent behavior in the cases of both flat and three-dimensional cobwebs. The position and consistency of these pre-existing pheromone-charged wires influence the construction of further fibrous elements.

**Figure 2**
The diagram shows the influence of the stigmergic separation parameter over the final morphological result.

**Figure 3**
The diagram shows the influence of the surface mapping parameter over the final morphological result.

**MULTI-AGENT SYSTEMS**
The building strategies investigated in the biological role model were then encoded as rules of a custom written simulation program developed on the open source platform Processing [4]. Agents are modelled as constructors, with enough degrees of abstraction to allow the simultaneous interpretation of their role as both simulated colonial spiders and robotic units performing coordinated construction tasks in space.
The explored behaviors can be outlined in three principal classes. The first one evaluates all the aspects related to distributed communication systems and swarm logics among the units, taking into account the stigmergic process. The second one examines constraints and opportunities of the robotic units chosen for the fabrication stage (i.e. quadcopters) so that each simulation can provide reliable data for further implementation. Finally, material features provided the basis to encode micro-scale behaviors into the system. The whole simulation is made up by a set of constructive units interacting with each other and the surrounding space depositing fibrous material on a previously modelled and analyzed reference surface. A series of input regarding the environment data and the initial surface geometry are provided at the beginning of the simulation, then the collaborative construction takes place. While the simulated entities don’t carry a representation of the whole, they are able to share data with each other, the environment and the already built structure as well as manipulate the system by depositing new material. The constant stream of information is the key to build a feedback system in which every agent is constantly able to read the local state of the construction process and start/stop releasing material whenever certain conditions are fulfilled. When the global construction reaches stability (the surface is considered structurally sound and the expected fibrous density values are met) all the simulated units stop moving and the material behavior simulation begins: all the strands in direct contact with the surface undergo a stiffening process that simulates the “starching” procedure performed during material experimentations. The core behaviors underlying the setup of the simulation system can be outlined as follows.

**BEHAVIORS**

**Separation.** Agents, conceived as robotic units, have physical dimensions and well-defined areas of action so that in the simulation builders can locally recognize the distance that separates them from other elements and avoid interfering with each other by respecting their influence area.

**Material deposition.** A key factor for the construction system is represented by the ability of the agents to modify the environment. During their movement they release a linear thread or filament formed by a chain of spring-particles blocks. These structures represent the spider silk and they are responsible for the main attraction forces for the agents. (Figure 2)

**Motion trajectories.** When developing windings, agents maintain a constant reference to the inflatable surface in order to develop helicoidal trajectories along the development axis of the surface. Therefore, the robot element is programmed to distinguish the main axes of the solid shape. The other fundamental component of motion is the tangential one. The agent extracts the value of the tangent to the surface for each position in the simulation space. By combining tangential and axial force, agents can determine the trajectory for the correct winding force. (Figure 3)

**Environmental conditions.** Each robotic element in the simulation interacts with the environment and specific elements within it. The reference surface plays a key role in the construction process: real world behavior of inflatables surfaces was achieved by using a mesh that binds the position of the particles released by the agents during the simulation. Agents are capable to detect the presence of the
surface within a defined distance range. Once entered into the inflatable structure’s influence area, they work out its principal axis and start a helicoidal motion. This type of movement coupled with the agent’s ability to release material engenders to a series of windings that occur around the inflatable object. Simultaneously, the surface becomes also an attractor: data from geometric features and environmental analysis is mapped on its geometry for the agents to retrieve and process.

**Scalar field.** A volumetric scalar field was embedded in the environment, acting as an attractor towards the reference surface in order to limit any uncoordinated agent movement and avoid any construction happening far from the inflatable structure. While moving in space, the agent samples the field at each frame from its future location and calculates the average of the values found in its proximity at the center of gravity of the positions of the samples considered. Each selected value is stored in the voxel evaluation space. The agent then only considers values belonging to a specific optimal range for construction.

**Stigmergy.** The first force, called stigmergic separation, is represented by the interaction between the fibers already released (modelled as springs in the simulation) and the moving agent. The agent detects the fibers’ particles in its cone of vision (oriented along its moving direction) and steers away from the calculated average position. Stigmergic separation avoids excessive fiber accumulation and overlapping, thus preferring a deposition that follows distinct trajectories. Stigmergic cohesion reverses the previous behavior, attracting the agent towards the fibers. Cohesion tends to create areas with abundance of material, highly redundant and sometimes chaotic. A proper modulation of these two behaviors can unlock extremely elegant and expressive solutions. (Figure 4)

**Material behavior.** As already mentioned, the system of particles and springs released by the agents mimics the behavior that fibers exhibit when impregnated in a liquid or viscous matrix. The term bundle refers to the strong forces that act on the scale of the material and manifest themselves through attractions and repulsions between adjacent material portions. In the present case the springs that came into contact with the inflatable surface are considered. Once the apprehension (hardening of the fiber in the real case) begins, the particles start a proximity check, moving towards the average position of found neighbors if any are within a given threshold. In a real case scenario the spider web modifies its properties over time due to environmental exposition; likewise, a stretched wire impregnated in a matrix (resin, for example) undergoes a significant alteration of its mechanical characteristics. Accordingly, in the simulation the wires deposited over the inflatable lose their elasticity over time by increasing the springs stiffness value.

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*Figure 5*

Process of preliminary analysis of the structure, extrapolation of one module and simulation of the construction system.
Figure 6
The resulting configuration is assembled on site thanks to the cooperation of a set of drones. On the bottom right. Side sectioned views of the structure.

ARCHITECTURAL APPLICATION
The generative system under construction was then tested at the architectural scale to verify the potentialities previously noted. To exemplify one of the possible fields of application for the system an architectural proposal for a suspended structure in an alpine site was elaborated. The site characteristics do not allow the installation of a conventional construction site, therefore, to organize the circulation of material and people, the inflatable structure previously tested (cylinder, toroid, etc) has been modified and extended in order to achieve complex spatial organization and to accommodate connections between different part of the envelope. Taking into consideration the computational issues encountered in the simulation of structures with a large amount of elements and the opportunities offered by the use of drones, the process was split in parts. A first analysis and evaluation of the surrounding area is then followed by the generation of an inflatable surface. Sub-
sequently, it was decided to divide the structure into seven parts and simulate the process on each module individually, preserving border conditions. At the end of the construction process all the artifacts produced are transported and mounted on site by the same flying robots. (Figure 5 and 6)

![Image](image1.png)

**Figure 7**
The image show a planned trajectory given to the drone in order to achieve a complete helicoidal motion around the inflatable formwork.

**MATERIAL STUDIES**
To explore the possibilities of the constructive process and verify the physical behaviors of the system, a series of material experiments was developed from two basic components: the fibrous element (thread) and the supporting structure around which it is wrapped (an inflatable formwork). Cotton and wool threads (impregnated with a bonding resin) were employed mainly for their availability and cost over other kind of materials with equal properties at the testing scale. The inflatable elements were made with variable-sized latex balloons. The first models were needed to understand the limits and possibilities of the materials in question. At the same time the expressive characteristics of the obtained results were used to develop the most interesting features in subsequent experiments.

**FABRICATION PROCESS**
Quadcopters represented a viable option to work with in order to translate the simulated construction system into the real world. The size of the space they can act upon is substantially larger than theirs. This feature, along with their unrestrained capacity to move in 3D space, is one that no other computer-controlled construction machine has nowadays and allows the construction size to transcend the one of its constructor. Flying machines perform construction tasks and build structure by releasing fibrous material on inflatable formworks; the developed pipeline codified the agent’s trajectories and writing the code that was then fed to the robotic units. The quadcopter used in all the phases is a Parrot AR Drone 2.0 which, since its launch in 2012, has been vastly used in academic environments. It was chosen for its flexibility of use, the presence of a variety of built-in sensors and its affordable price. Despite its lack of payload capacity (an important issue for this research) it still represented the best option on the market thanks to a vast community of people already working on identical drones. The key challenges in this case were to locate the robot only through the data provided by its own sensors and then navigate in a robust manner even in the presence of temporary signal leakage. This required a solution to the simultaneous localization and mapping (SLAM) problem for estimating and controlling the robotic unit. These challenges are even more important considering issues such as low-cost actuators, noisy sensors, significant communications delays and limited computing resources on the robotic unit. To solve the SLAM problem on these aircraft, various types of sensors such as laser scanners, monocular cameras, stereo-cameras and RGB-D sensors have been explored in the past. The adopted system, developed by a research group at the Munich Technical University, determined a solution through a monocular system which enabled the robot to operate in small spatial environments as well as in open spaces. (Figure 7)
Environment. The drone dimensions and the monocular vision control system required the preparation of a suitable working area to work properly. A set of support structures was provided: a grid on the floor for constant tracking of the robot’s motion trajectories, a textual map with black elements on a white background to create a visual reference and a system of three supports for the anchorage of the fibrous elements. The components layout was adequately traced for accurate reproduction in the simulator. (Figure 8)

Movement. The first test flights necessarily focused on the definition of the robotic unit trajectories. The drone was able to generate an effective localization map and, hence, an ad hoc reference system for space navigation. Once defined, the origin of the system can be provided with a series of spatial coordinates. The quadcopter waits at each point of the trajectory for the instructions transmission to complete. The control system therefore allows the definition of a unique trajectory once the origin of the reference system is identified. The trajectory execution is accurate and customizable through initial control parameters. In fact, it is possible to set the minimum distances between the position of the drone and the spatial coordinate to reach as well as the minimum amount of parking time around the desired point. The same type of experiment was then made by hooking the end of a wool coil to the quadcopter. The turbulence created by the drone propeller moves the wire during the flight. Although the effect was visibly significant, it did not show a worrying intensity for the continuation of the experiments.

Inflatable construction. In order to build a feasible pneumatic surface a plastic sheet (made by several pieces seal-taped together) was used, while a...
connected fan ensured a constant pressure within the surface. The system proved to be flexible to small damage and suitable for the intended purpose. A support structure was also prepared to hold the inflatable structure in place while the drones performed their tasks. The support wires position was changed several times to prevent them from becoming obstacles in the drone’s trajectories.

**Winding technique.** After the preliminary tests, the constructive process started. First, a specific simulation for the system was performed by extrapolating the agents’ trajectories coordinates; these were then inserted into the drone control operating system. The communication with the drone happened via text files in which, in addition to the coordinates, safety parameters were set in case the drone entered emergency mode. The first results of the winding process are visible in figure 9. Initially, problems due to the friction force generated by the strands on the inflatable surface showed up; for this reason in some cases manual assistance to the drone in certain winding steps around the inflatable was necessary. In most cases, however, the robot was able to realize the structure independently based on the information provided by the digital process. Once the construction task ended the stiffening procedure started. A mixture of glue and starch was then applied on top of the strands on the pneumatic surface. At the end of the strengthening process (when the strands dried out), the inflatable formwork was pulled out and the fibrous structure reached its final state. (Figure 9 and 10)

**CONCLUSION**

The construction system fully exploits the ability of flying machines to reach any point in space, allowing robots to move fibrous elements to location otherwise not accessible by conventional construction machines, manoeuvre in or around existing objects and interact with the already built elements. The outcomes are the result of a mediated approach capable of mixing top down strategies, necessary to intuitively steer the system towards articulated functions, and bottom up tendencies which, on the other hand, foster a variety of generative tectonic solutions while maintaining reliability and robustness. These assemblages are structurally non-linear: hierarchies emerge through transformative variations in intensity, capacity and density. They resist categorization as either pure surfaces or strands only, since the fi-
brous elements bundle and weave to form surfaces, while surfaces split into strands losing the traditional distinction between skin and structure, as the system operates structurally within a redundant, highly intricate assemblage endowed with intrinsic ornamental patterns. The fabrication method introduced addresses the potential offered by quadcopters in the field of architectural construction through the deposition of fibers on inflatable elements: this process can be advantageous in scenarios where traditional building systems and techniques cannot operate (e.g. Mountain gorges, forests, etc.). Experimental results provide a proof of concept and feasibility of the construction system, providing a useful reality check on economic and technical constraints for future developments. From the architectural as well as from the robotic perspective, various aspects of the approach deserve further experimentation: during the development of the work, critical elements of the inflatable system and fibrous assemblages emerged; specifically, the fabrication method for the inflatable formworks greatly limits the final morphological and typological result. A refined method would provide more reliable and complex structures able to address a wider range of needs. At the same time, the fibers and the stiffening solution have shown significant limitation in strength and robustness that require additional attention for large scale models. Further developments could also involve the robotics manufacturing system, implementing the possibility to engage multiple robotic units inside the constructive process. The exchange of information between the units and the ability to read data from the structure being created could significantly improve the tectonic results and the construction technique.

REFERENCES
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