[VOILES | SAILS]
Self-Assembling Intelligent Lighter-than-air Structures

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Abstract

Through the use of flying automata (aerobots), the [VOILES | SAILS] project aims to port to the physical world some of the functionalities observed in artificial life systems, with a particular focus on simulations of assemblages and behaviors derived from the observation of animal societies (coral reefs, anthills) that can collectively produce high performance structures with extremely limited abilities at the individual level. It involves a swarm of cubic robotic blimps floating in a large indoor space. Four aerobots (one 180 cm prototype and three 170 cm beta versions), equipped with sensors, ducted fans, wireless communication and a 40 g fully functional UNIX computer, are currently flying. The current phase of the project aims to implement 6 to 12 self-organising cubic aerobots evolving in a semi-spherical indoor space within which an immersive environment will be generated through the use of a 360 degrees panoscopic projector. The cubes will interact between themselves, and to the local temperature, color, and luminosity conditions within the sphere ; complex structures and behaviours will emerge from these interactions, creating flying architectonic structures for which we coined the term aerostatiles, in reference to Calder's mobiles and stabiles.

1. Introduction

For more than two decades methods of design have emerged, made possible by the decreased costs of powerful computation, in which the designer does not specify the shape of the objects he or she wants to create, but instead declares a set of intentions, criteria or constraints with which the object must comply. These intentions must be formalizable, which means that they must be quantifiable in some way ; they are then input to a computer equipped with appropriate software tools, which will generate whole families of digital objects that supposedly enforce the required criteria. Many of these methods, such as genetic algorithms or cellular automata, are now familiar to most of the generative artists. Though they may look like cutting-edge contemporary techniques, they are often based on simple principles, and rooted in analogies with phenomenon that can be traced to very ancient natural or cultural processes. Genetic algorithms try to replicate the model which explains the reproduction and evolution of gendered organisms ; they are hundreds of millions of years old. Cellular automata simulate many kinds of biological, geological or cultural processes in which the collaborative action of individuals with limited abilities generates sophisticated collective behaviours, or results in structures with a high degree of complexity. Examples can be found in phenomena as different as coral reefs, anthills or fault propagation. The ones that have been at the origin of our current works are much younger : six to eight thousand years. They correspond to the very roots of urban genesis, somewhere in Middle-East, in current Turkey, where for the first time houses made with age-resistant materials were agglomerated to form a single urban object of high complexity level. This accretive model has crossed the ages. Besides today's contemporary cities that grow according to a grand, simple geometric scheme, thousands of villages and neighbourhoods still evolve through accretive processes in which the location of buildings (houses and other types of constructions) is not determined by reference to a pre-existing grand plan, but through local rules of assembly, involving neighbourhood conventions, compatibility of activities, relations between individuals or groups, access to sun, air and paths, and socio-cultural norms that are not always explicit. Most of these rules are simple, but their conjugate action generates very complex patterns that are almost impossible to decipher through standard geometrical analysis. As the reader may have noticed, this last sentence also describes one of the main characteristics of cellular automata.

2. Origin of the project

Like many other research teams (Batty and Longley,[1] ; Clarke & al.,[2] ; White and Engelen,[3]...), we attempted to use cellular automata in order to better understand the formation and evolution of complex urban shapes, focusing on an urban phenomenon that represents today one half of all urbanization processes on Earth, namely the exponential growth of slums and squatter settlements. Many studies demonstrate that in certain circumstances, now rather well elucidated, they tend to consolidate and transform in official urban neighbourhoods. This evolution, which takes about forty years, has be seen by many researchers as presenting numerous similarities with traditional processes of urban growth that used to take centuries, an observation that is of the greatest interest for architects and urban planners.

After a few tests and studies, we came to realize that by playing with the parameters of our simulation tools, we could generate architectures and urban morphologies that had nothing to do with existing cities, but presented a tremendous potential on their own. To these potential architectures, we gave the name « computer architectones », in reference to Malévich's architectones in the 1920's. We then developed many generative tools, some based on cellular automata, others on genetic algorithms, other on different algorithmic processes, that were explored in many projects, including « Computer Architectones » [4], « The Cloud Harp project » [5], « The Sixth Diffractal » [4] (see Fig. 1, 2, 3 and 4). All these works, presented in the form of architectural drawings, digital pictures, video animation, stereolithographies or large architectural sculptures, were intended to port to the physical world the potential of these « digital objets trouvés » discovered by exploring digital territories with these new tools and processes. It was during a meeting at Caltech in July 2000 between A. Martinoli, N. Reeves and G. Théraulaz (via tele-conference) that the idea came to port not only the results obtained by using these processes, but the processes themselves, to the physical world ; more specifically, to get the generative processes out of the computers and to have them implemented by physical robots, instead of digital entities. This led to the development of an international arts/science/technology research program, called [VOILES | SAILS], aiming at the realization of flying rigid robots (aerobots) able to develop collective behaviors and to achieve autonomous self-reconfiguration through swarm-intelligent processes. Once completed, a robotic society of this kind will become a platform for both scientific research and artistic creation, and a testbed for explorations in advanced collective robotics.

Fig. 1 (above left), « Coirault – First Mutation of the White Doe (1999), a computer architectone generated by an algorithm whose parameters coded the melody of a very old traditional song ; rendering by G. Credoz (Ateliers-U, [6]). Fig. 2 (above right), « Gestatio o Slum / Opera » (1994), stereolithography of a computer architectone generated by seeding a cellular automata with a coded sequence of Monteverdi's « Orfeo » ; stereolithography by N. J. Iverson (Pure Fluid Magic, [7]) ; Fig. 3 (below left), « The Sixth Diffractal » (2001), architectonic sculpture with mirrors and prisms generated by an algorithm whose parameters coded Bach's XVIIIe Goldberg Variations. Fig. 4 (below right), a Cloud Harp (2001-2004), a gigantic musical instrument converting real-time the height and density of passing clouds into musical sequences ; the sculpture was obtained by coding an algorithmic design process with the geometry of a stratus cloud. All works by Nicolas Reeves and the NXI GESTATIO Design lab.

3. Related studies

Many experiments have been made during the last years in different labs in the field of collective robotics, but experiments with full 3D systems are far less frequent. Basic considerations of weight, energy, inertia and moments of inertia, resistance of materials, autonomy, trajectory computation, quickly develop into a wealth of sub-problems, of which many are still being explored. Attempts can broadly be divided in two categories : first, modular self-reconfigurable robots, in which simple modular robots self-assemble to construct a large automata ; different configurations of the small robots allow the large one to implement different tasks or to play different roles. To this category can be related 3D robotic experiments such as Hamlin and Sandersons' Tetrobots [8], Murata's Fracta [9], Rus and McGray's Molecule [10], Bojinov and al's Proteo [11], Michael's Fractal Robots concept (not implemented) [12], Yoshida's self-reconfigurable miniaturized robot [13], Ünsal and Khosla's I-cubes [14], Kurokawa's semi-cylindrical reconfigurable robots [15]. Second, swarms of robots, which again collaborate for task implementation or role playing, but are not necessarily connected by a physical link. They can separate and reassemble, but still act in a coordinated manner, like a swarm of insects. A good example in the 2D space of such a system is represented by the artefact generated in the Swarmbot project [16].

Some examples of robotic swarms with full-3D capacities are provided by Morse and Belhumeur's attempt to generate a school of robotic fishes [17], and by the IAS lab's flocks of robotic blimps [18]. But to our knowledge, no attempts have been made to achieve self-reconfiguration within a 3D space. The [VOILES | SAILS] project aims to build a platform pertaining to both categories : the aerobots can either act as swarms of separated individuals, or as a reconfigurable systems where large robotic entities can be generated by « polymerisation » of individual ones.

All the experiments listed above have their own difficulties and constraints, which all point to some of the problems inherent in porting digital robotic organisms to the « reality platform ». A few examples : the Tetrobots are not completely autonomous, since some of their parts must be manually connected. The fracta is a nice piece of technological jewelry : units are made from a cube with connecting arms at the center of each face. They can assemble and climb on each other, and can actually implement 3D self-reconfiguration. However, their size (about 25 cm), weight (more than 7 kg) and cost/complexity prevent the realization of large societies. Because of their size, Yoshida's miniaturized robots have limited torque and short range of movements. Though another example of full 3D self-reconfigurable system, Kurokawa's robots use magnets for connections, which limits their number and strength. In collective robotics, the Morse and Belhumeur's fishes evolve in a full 3D environment, but need to be immersed in a liquid in order to counteract their weight by Archimede's force. The IAS lab's blimps nicely implement collective translation, but their geometry does not allow for self-assembly or reconfiguration.

Technologically speaking, our cubic aerobots are relatively simple ; they mainly use off-the-shelf robotic components. Their shape allows for in-flight reconfiguration and assembly. If their current size and load-bearing abilities limit the range of their potential applications, their characteristics allow us to use them for two different purposes : first, since they are subject to very low weight and inertia constraints, they allow us to study and evaluate swarm-intelligent processes that will eventually be ported to other robot *species* ; second, flying cubes of this size can be directly used in many artistic or design applications.

The following sections of this paper will briefly present the physical characteristics of the aerobots and the methodology we adopted to develop their behaviors, then show the results of recent experiments, and finally describe some of the artistic applications that we currently foresee for them.

4. The design of the aerobots

The acronym SAILS, coined by team member Alan Winfield, stands for Self-Assembling Intelligent Lighter-than-air Structures. The word VOILES is the French translation for « sails ». The Mascarillons are the first aerobots developed for this project. Like their non-robotic ancestors, they are made from a polyurethane helium bladder stretched between the inner edges of a cubic, ultra-light structure. All robotic and mechatronics equipment is located within the structural trusses.

Fig. 5 – Photograph of a Mascarillon M170 ready for take-off, May 2005. The white bladder is filled with helium, and is stretched within the ultra-light basswood structure.

The design is determined by a number of constraints, among which the weight-to-lift ratio holds the most important place and influences all other characteristics. The lifting force of helium at sea level, at normal pressure and temperature, is roughly 9,81N per cubic meter of helium, which means that one cubic meter of helium can lift roughly 1000 g. For instance, a large non-robotized blimp built in Moncton in 1998, based on a 3,30 m-edge structure, could lift about 32 kg. The total weight of the blimp, made of extruded styrofoam, was about 30 kg, so the lifting force was 2 kg, more than enough to keep it flying.

The size of the first robotized Mascarillon is 180 cm (hence the model name, M180) ; the lifting force is about 5300 g. This may seem a lot ; the M180 is actually quite large, and was designed as a prototype to allow multiple software and mechatronics tests with minimal concerns about flying abilities. The real challenge is actually to built the smallest possible blimp : reducing the edges by a certain factor decreases the lifting power by about the third power of this factor, and the following models, the M170, see its lifting power reduced to about 4500 g. Considering that the load includes the structure (about 1000 g), the films (about 1500 g), the CPU, the motor controllers, the sensors, the wireless card, the batteries, the motors and the motor ducts, the cameras, the docking devices, and all the wires and cables, it is easy to see that each element must be very carefully chosen in order to maximize its general efficiency. Apart form theses hydrostatic considerations, several major concerns have to be considered :

1) - **The necessity to obtain a perfect cube**, with straight edges and flat faces. This is primarily an art/architecture concern, since it relates to the intention of creating perfectly geometrical flying shapes ; but it is also induced by the fact that the cubes need to assemble while flying. If the edges are not perfectly straight, or if the faces become convex due to the internal pressure of helium, the cubes will not assemble properly.

2) - **The self-assembly properties**. When two cubes connect to each other, they must still be able to use their motors to move in space. The thrusts of the motors of many connected cubes must add up in order to provide enough power to move them all. This led to the decision to place the ducted fans at the midpoint of each edge, and to guide the air streams towards the corners of the cubes with thin plastic or paper tubes.

Fig. 6 – Ducted fan in the middle of a triangular horizontal truss, showing the polycarbonate tubes that guide the airflow towards the corners of the cubes.

3) - **The axial symmetry of the cube**s. The cube is oriented in space : it has a top and a bottom. The mechatronics components are located within the bottom edges and corners, except for the four z-axis ducted fans, which are placed at the middle of the vertical trusses. In order to preserve horizontal stability and to balance the angular momentum of the whole cube, all elements are located within the center section of the trusses and/or at the corners of the cube. Each element must be counterweighted by another element located in the opposite corner or truss center. No helix configuration is allowed : no element can be located off the corners or off the middle section of the trusses, since his would introduce asymmetries in the angular momentum.

4) - **The location of the sensors.** This is a critical concern. The cube is by no way an optimal shape when it comes to sensory aptitudes, especially with large cubes such as the M180. Obstacle avoidance would ideally require 24 sensors (one for each axis on each edge), which is hard to implement for reasons of cost and energy requirements. The optimal sensor configuration is still being studied ; three 14-sensors Mascarillons are flying since August 05.

5) - **The need for assembling and disassembling the cubes**. Transportation of the cubes is a

major concern : these big, hollow shapes would be very costly to move for a demo or an experiment, and since the trusses are also quite fragile, the structure must designed in order to allow the disassembling of the cubes, and their storage in small protective cases.

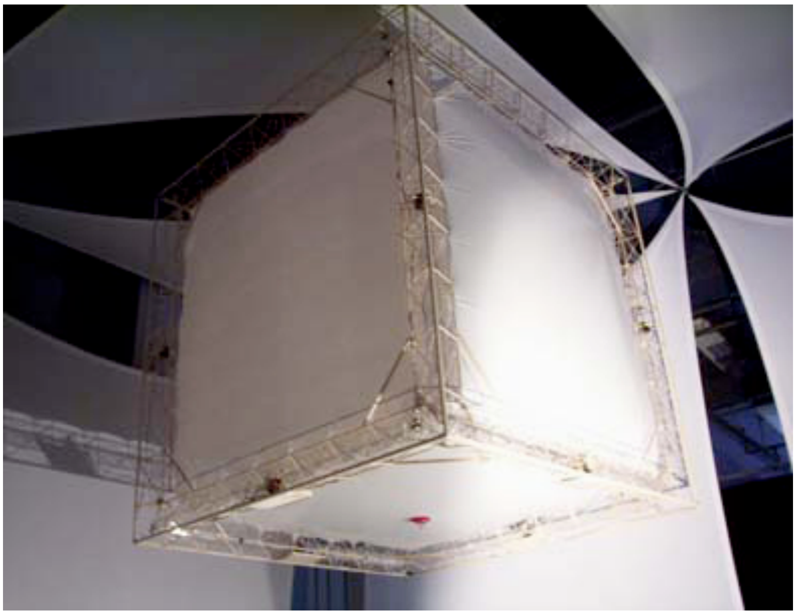

Fig. 7 - A flying Mascarillon. The ducted fans can be distinguished at the mid-points of the trusses. The red inflating valve appears on the lower face.

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5. The structure

Like all rigid flying objects, the structure of the [VOILES | SAILS] aerobots has to fulfil lightness, rigidity and stability criteria. It must also be dismountable, in order to allow easy transportation of the aerobots for experiments, demonstrations or shows/performances. Many materials and configurations have been explored, from extruded styrofoam to carbon fiber. Extruded styrofoam (Fig. 1) shows a surprisingly good behaviour to shear constraints, and has strong load bearing capacities for such a light material ; its cost and availability could have make it a primary choice for the project. Unfortunately, its stability over time is rather poor. Carbon fiber has unmatchable resistance and rigidity properties, but it was not suitable for this phase of the project because of its density (around 1,6) and price ; it is also difficult to work with. We are still planning to develop optimal fiber carbon structures for later aerobots. Considerations of cost, availability, and workability finally led us to concentrate on light woods for the first flying cubes. Balsa structures were then tried. They were incredibly light, and showed a satisfying rigidity. But their fragility made them almost impossible to handle : some of the wood pieces were so thin that they could be involuntarily broken by someone who would not even notice touching them. Next models were balsa-basswood composites ; they were abandoned for the same reason. The final trusses are made completely from basswood. On the M170 model (Fig. 7 and 8), each truss weighs barely 80 g each, which amounts to slightly less than 1 kg for the complete170 cm-edge structure.

Needless to say, we could not find in hobby shops pieces of wood with the proper dimensions and shapes : no shop would hold pieces with a 3 mm-side equilateral triangular cross-section. We had to buy large beams that were cut on saw benches, with a 75% loss, since most of our pieces are thinner than the thickness of the saw blades.

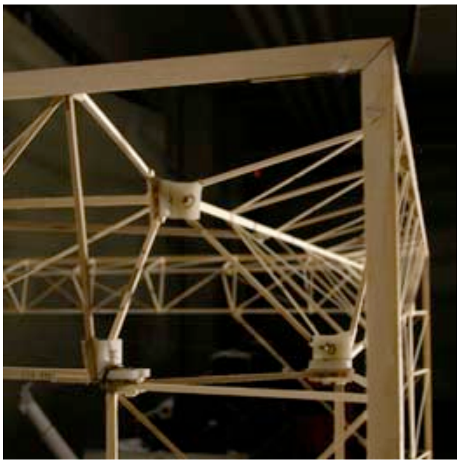
 

Fig. 8 and 9 - Final design for the Mascarillons structure, made of twelve identical basswood trusses. On Fig. 8 (left), two 170 cm structures waiting to be equipped. On Fig. 9 (Right), details of a corner showing the nylon connectors that allow to assemble and disassemble the aerobot. The complete structure weighs about 1000 g.

6. Mechatronics and software development

The Mascarillon's « brains » is the KoreBot card [19], a miniaturized full-UNIX computer, which weighs about 40g. Each blimps has its own IP address, turning it in a flying internet node. The fourteen sensors are sonars with a six-meter range and a one-centimeter resolution ; six of them (one per face) have light-sensing ability. Eight small ducted fans are located at the midpoint of the vertical and lower horizontal trusses. Airflows are guided to the ends of the trusses through clear polycarbonate tubes.

Fig. 10 - The KoreBot card from K-Team, a full-UNIX computer with internet and wireless abilities weighing 40 g.

Communications between the aerobots components uses the I2C protocol, while communication between ground and aerobots is ensured by a standard Wireless Local Area Network (WLAN). In their current state, the aerobots do not communicate with each other : they can only detect each other. The difference between fixed obstacles and other aerobots is determined by the software, by comparing information coming from different sonar sensors.

Tasks that are straightforward to implement on ground robots become real challenges in flying ones. Immobility is a good example : to make a ground robot stay still can hardly be considered as a « task », but it is actually a dynamic process for an aerobot, involving constant measurements and height adjustments. The same can be said for stopping a robot at a given position : reading from the sensors, the computer must anticipate the final position and stop the motors so that the inertia of the aerobot will be exactly compensated by the resistance of air, and so that the aerobot halts at the desired position. More complex tasks require more sophisticated algorithms ; their study on real aerobots involves a good deal of time, large experimental spaces, as well as human and material resources.

To optimize this development process, we decided to undertake the development of the aerobots on several experimental levels simultaneously. Besides the real-robots experiments, two levels of simulations have been implemented by one of us (J. Nembrini, see [20]) with the Webots platform, a software tool which allows us to simulate a robotic system with different degrees of abstraction [21]. On Fig. 11 below, the aerobots are represented by simple geometric cubes ; this elementary model allows us to explore different behaviour rules, and to evaluate their potential for the emergence of self-organization processes. Application of a particular set of rules leads to the formation of linear structures. This demonstrates how local rules have the potential to generate large-scale structures with a high degree of organization or complexity : no single cube knows what is a straight line, but the repeated application of a same, single local process generates straight lines with many cubes. In the second example (Fig. 12), the simulation becomes more precise ; it incorporates physical parameters such as mass, moments of inertia, range of sensors (the sensors beams are clearly visible), motor thrusts and so on, as measured from the real aerobot. Among other things, it has been used to implement stabilization algorithms (vertical and horizontal), and to allow two aerobots to stay side-by-side at a very short distance (a few centimeters), a process that is essential for the future development of docking procedures.

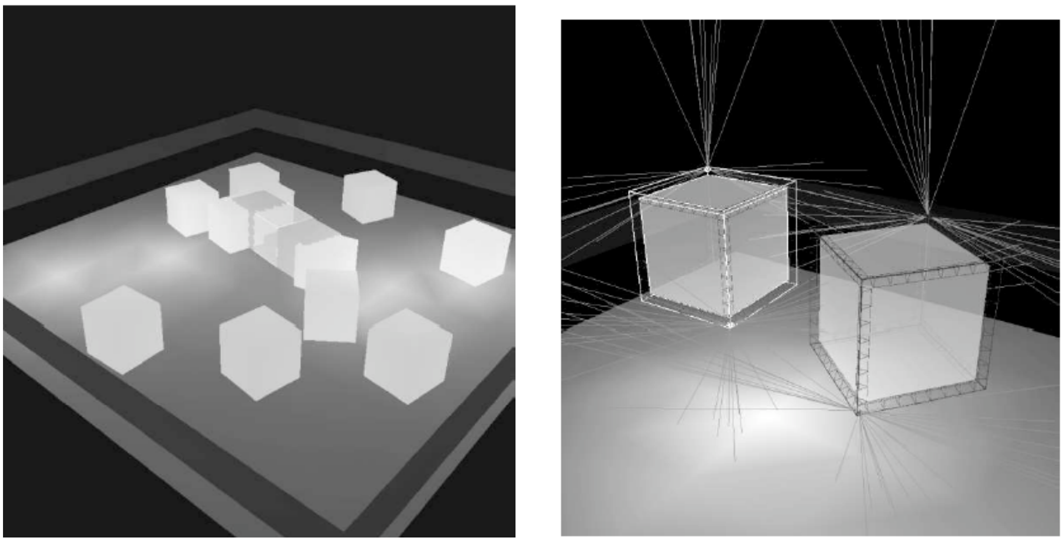


Fig. 11 and 12 – To different levels of simulation. On the left (Fig. 11), simulation at a "microscopic level". The aerobots are represented as simple cubes with no physical properties. This model is used to study different strategies for generating self-reconfiguration. On the right (Fig. 12), the model gets closer to the real aerobots, and the simulation takes in account parameters that have been measured during experiments, such as weight, inertia, motor thrusts, sensor response... Macroscopic level simulations, where the cubes are represented as clouds of points, are planned in the next phase. All simulations are implemented on the Webots platform [21]. Simulations by J. Nembrini.

7. Results obtained ; planned and future work

To comply with the general paradigm of swarm-intelligent systems, in which complex phenomena emerge from individuals with limited abilities, we began by equipping the aerobots with only one kind of sensor (sonars), and tried to get maximum results from these before adding other sensory modalities. In their present state, our aerobots cannot detect their orientation, nor their position relative to the ground ; they do not communicate between each other. Despite these handicaps, a clear software strategy allowed us to obtain the following results, which have all been observed during a public demonstration in Montreal, in October 2005 [22] :

- Obstacle avoidance ;
- Vertical stabilization with less than 10 cm oscillations ;
- Stabilization at a fixed distance from a wall with very small oscillations ;
- Stabilization at fixed distance (about 10 cm) from another aerobot. A chain of three aerobots maintained this configuration for more than ten minutes.

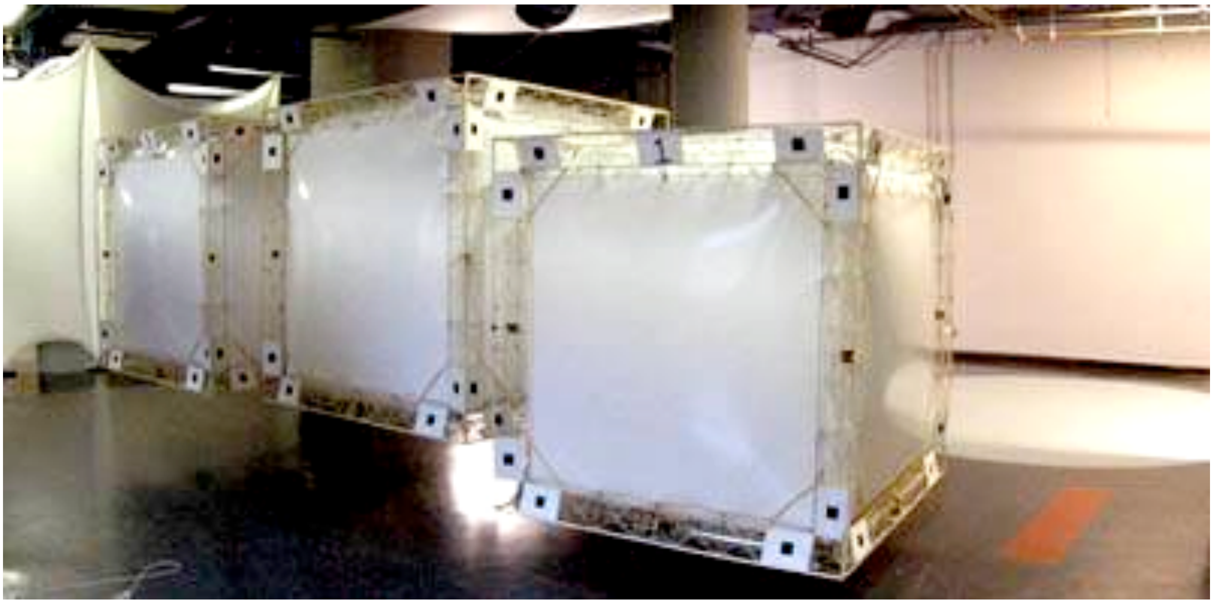


Fig. 13 – Three M170 Mascarillons aerobots in the process of stabilizing at a short distance from each other. This configuration was maintained for more than ten minutes, a result that opens the door to the next implementation of in-flight docking procedures.

Many other experiments are planned with the current configuration. Future models will get progressively smaller in size (we are undertaking the development of a 160 cm model with a composite materials structure), and more capacities will be added once the experiments with sonars have been completed. In particular, the need for the aerobots to measure their own positions relatively to fixed elements of the environment proved critical : they are very sensitive to micro-atmospheric and convection currents, which generates important positional drifts. An inclinometer and a compass will also be installed in the next models, allowing more sophisticated behaviors.

The [VOILES | SAILS] platform is dedicated to scientific and technological development in swarm robotics and to research and creation in arts, design, and architecture. Besides its remote origins in the study of complex urban shapes, it presents a more direct connection with architecture : an assemblage of cubic aerobots represents a flying construction that relates to the mythical idea of flying architectures, such as the Vimanas of ancient India, the celestial city that many cathedrals try to evocate through stone, light and stained glasses, the Albatros airship in Jules Vernes' Robur le Conquérant, Krutikov's constructivist flying cities.

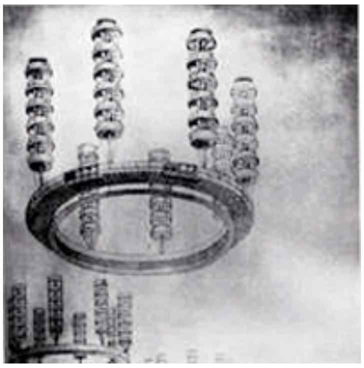
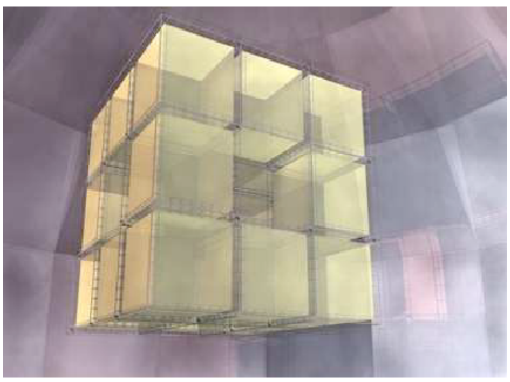


Fig. 14 – Left, Krutikov's constructivist flying cities ; Fig. 15 - Right, "La Ville Volante", en engraving by G. Trignac. All flying architectures echoes the mirages of cities floating over the deserts, sometimes hovering over their own reflections.

The next phases of the [VOILES | SAILS] program involves the construction of aerobots with different shapes, including asymmetric ones, that can be used to generate more complex reconfigurable flying structures, to create full-size models for architectural projects, or even as sculptures made from many aerobots floating still in the air, constantly readjusting their position to keep a given assigned configuration. To these sculptures we gave the name « aerostatiles », in reference to Alexander Calder's mobiles, suspended objects that are extremely sensitive to the smallest air movements and for which immobility is almost impossible to achieve. On the performance side, the Mascarillons aerobots will be used for hybrid choreographies, during which a swarm of aerobots will interact with a group of dancers, and where the nature of human-aerobots interactions will change or evolve according to data sampled from the environment.



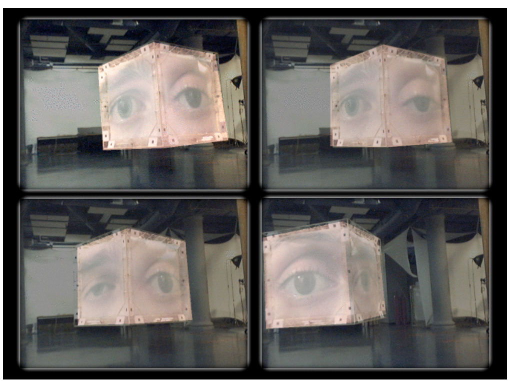


Fig. 16 (left) : prospective view of a self-assembled 20 Mascarillons. Fig. 17 (right) : dynamic projection of video sequences (blinking eyes) on a moving Mascarillon . The images follow the displacements and orientations of the cube.

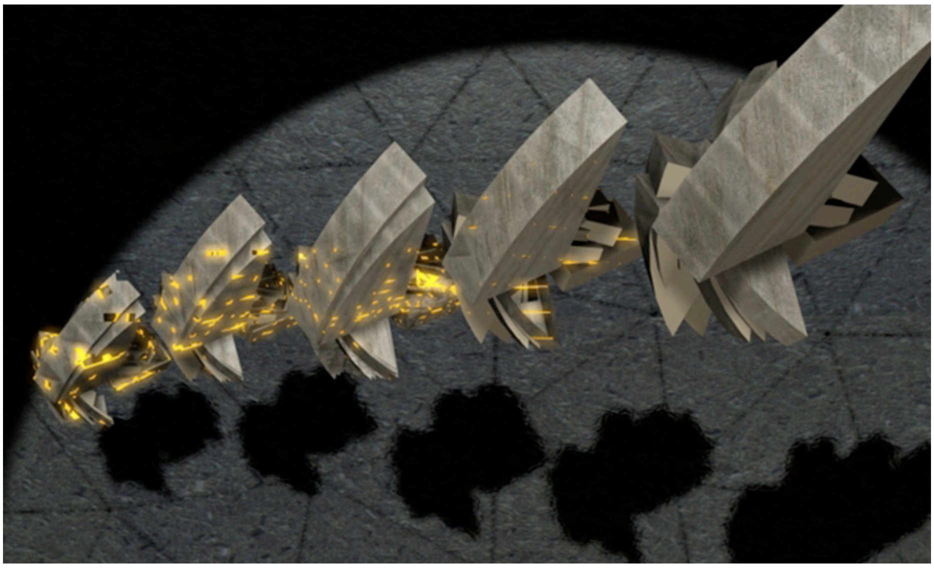
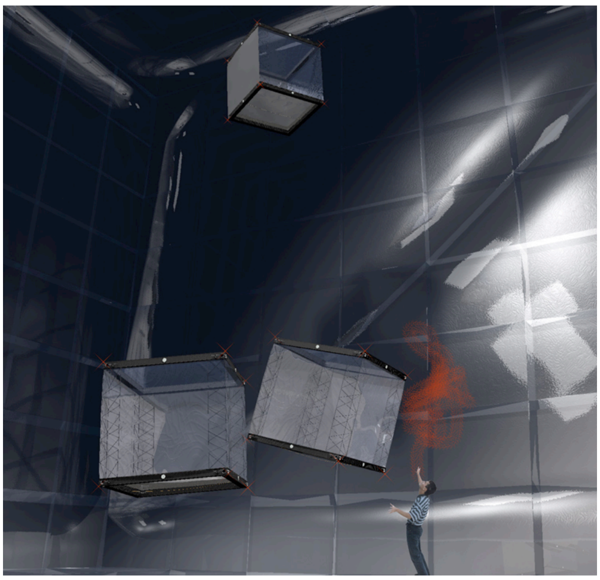


Fig. 18 : prospective view of an aerostatile, a sculpture made with different non inter-connected aerobots. Lighting effects can easily be added. Rendering by Ateliers-U [G. Credoz].

The Mascarillons, as well as the next aerobots of the [VOILES | SAILS] project, will also be used as flying screens for adaptive dynamic video projections, using a software developed by one of our Montreal collaborators. Through the very short projection of calibration grids, this software can adjust in real time images and video sequences on distorted, undulating or moving surfaces, in order to constantly generate a perfect picture. Mascarillons assembled in many rows and columns will thus constitute a gigantic projection surface, which will be able to fragment in small elements that will eventually reconfigure elsewhere ; the images and films will follow their displacements and rotations everywhere in space. Finally, covering some faces with metallized membranes will transform the aerobots into flying reflectors that can be located anywhere on a stage, allowing unseen lighting effects.



Fig, 19 – Prospective view of a dancer interacting with a flock of Mascarillons aerobots. In this kind of performance, the modalities of interaction can evolve according to data sampled from the environment : level of noise, temperature, lighting...

8. Outlook

Reconfigurable structures have long been a vision for architects and designers. The concept of an architecture/object which can self-adapt to environmental or programmatic changes (autopoiesis) and whose identity can differ according to the context (variable ontology) emerged in the last century, and is now underlying many exploratory works. As mentioned above, many researches using artificial life methods have attempted to understand, simulate or predict urban growth to evolve architectural shapes or to grow structures through algorithmic processes (Dollens [23]) ; most of these attempts either remained at the level of computer simulation, or led to virtual structures that were transposed to material ones only after termination of all processes. Simultaneously, attempts to develop ground robots with self-assembling properties occur in different labs, but did not yet reach a point where applications to architecture/design could be realistically foreseen. Positioning itself at the crossroads of these attempts, the [VOILES | SAILS] research program aims to port the processes themselves - not only their results - to the physical world, first for gaining insights for future projects on reconfigurable architectures, but also to develop a first set of functional and reliable swarm intelligence based design/art objects, something that has never been done, and will also constitute one of the first out-of-the-lab applications of swarm-intelligent systems.

9. Acknowledgements

The [VOILES | SAILS] program is supported by the Hexagram Institute (Montréal, Canada), the Natural Sciences and Engineering Research Council of Canada, the Canadian Council for the Arts, the Quebec Fund for Research on Society and Culture, the Society for Arts and Technology (Montréal, Canada), the University of Quebec in Montreal, the École Polytechnique Fédérale de Lausanne (Lausanne, Switzerland) and the University of the West of England (Bristol, UK). Alcherio Martinoli is currently sponsored by a Swiss National Science Foundation professorship.

More information on the [SAILS | VOILES] project can be found at www.mascarillons.org.

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