MASCARILLONS : FLYING SWARM INTELLIGENCE FOR ARCHITECTURAL RESEARCH

Julien Nembrini[*+φ]*, Nicolas Reeves*[+]*, Eric Poncet*[+]*, Alcherio Martinoli*[*] *and Alan Winfield*[φ]

[*]Swarm-Intelligent Systems Group, École Polytechnique Fédérale de Lausanne, Switzerland
[+]Nxi Gestatio Design Lab, École de Design, Université du Québec à Montréal, Canada
[φ]Intelligent Autonomous Systems Laboratory, University of the West of England, Bristol, UK

ABSTRACT

Initiated by N. Reeves, the Mascarillons project stands at a crossroad between Art and Science[1]. It aims to bring together researchers in both artistic and scientific domains to collaborate towards the production of a robotic environment dedicated to architectural research, with a major potential for multi-media performance. Because of the tight constraints of the project, a multi-level design methodology is proposed, consisting of the parallel development of real robots and increasingly abstract modeling tools. The interaction of these experimental levels is expected to hasten the progress towards an efficient solution by taking every technological and physical constraint into account.

1. THE ARTISTIC PROJECT

Taking its roots in numerous biological examples, the swarm intelligence paradigm provides an alternative way to consider complex architecture design. Indeed, the characteristics of termites' or bees' nests are incredibly complex in comparison with individuals' abilities. Instead of central coordination, it is through the interaction of simple behaviours that such structures emerge. As demonstrated by Bonabeau and Theraulaz in their investigation of self-organised nest building [2], local rules are sufficient to produce complex structures through the help of stigmergic interactions. By carefully observing several insect societies that build nests, they were able to deduce behavioural rules as reactions to the insect's local environment, whose implementation on numerical models led to surprisingly similar levels of complexity [3].

Following his interest in studying the formation of urban landscapes in unplanned settlements as well as the use of Artificial Life models in producing architectural shapes, Nicolas Reeves has chosen to study the potential for swarm-intelligence models to produce self-organised three-dimensional structures of architectural relevance [12, 13].

[1]see www.mascarillons.org for more information

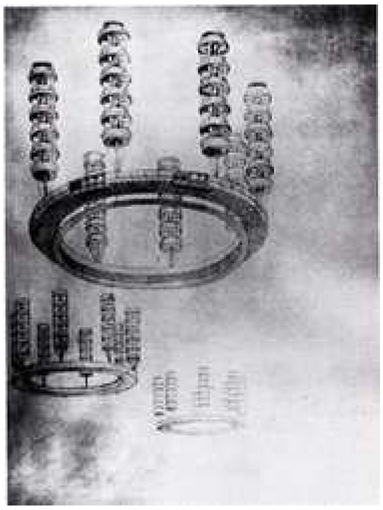

Figure 1. Gregory Krutikov's constructivist flying cities

In this research, instead of concentrating on designing a final result, the process of architectural creation is transformed into the design of rules governing the assembly of components. If the number of these components is high enough, their interaction will eventually lead to the formation of complex hovering structures, last descendants of a very old lineage of flying architectures such as the *vedic vimanas* from ancient India, Jules Vernes' *Albatros* in *Robur-le-Conquérant* [17], Gregory Krutikov's constructivist flying cities (see Figure 1), or even Archigram's *Instant City Airship*. For the first time however, and as opposed to its mythical or visionary ancestors, this flying architecture will emerge from the collective behavior of a set of individual agents ('flying bricks'), a flock of proactive elements taking the form of flying robotic cubic blimps, the *Mascarillons*, which are currently being developed at the University of Québec in Montréal. They will be used to study both the processes and the outcomes of self-organising systems.

In the final stage, the project will involve 12 to 20 self-organising flying robotic cubes, situated in a semi-spherical

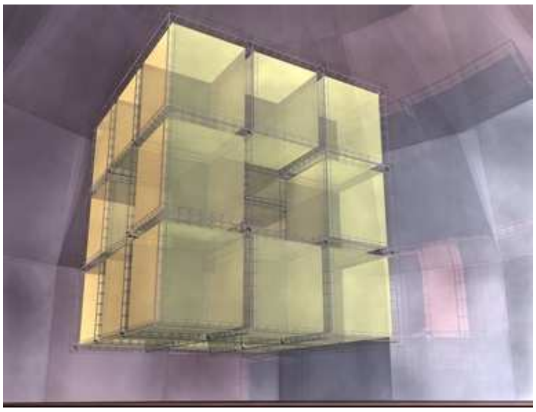

Figure 2. Prospective view of self-assembled Mascarillons

indoor space within which an immersive environment will be generated through the use of panoscopic projectors. The cubes will both interact with each other and react to the local color and luminosity conditions within the sphere. Complex structures will emerge from these interactions with robots self-configuring into a pattern and then *re*configuring into another (see Figure 2).

Because of the performance nature of the project, assembly time becomes one of the critical constraints: self-organised processes have to be perceptible within the spectator's attention limits. In order to balance this constraint with other constraints charcteristic to flying blimps, we adopt the interaction methodology described in section 3.

2. RELATED STUDIES

If the area of self-reconfigurable robotics is now being thoroughly studied by different groups throughout the world, they mainly concentrate on physically attached modules that connect and reconnect to produce function from shape [8, 7]. In [15] a distributed algorithm to coordinate the movement of several such modules into a locomotion task is presented. In an interesting subsequent paper, Støy presents results of using gradients and Cellular Automata to let cubic elements self-organise into any three-dimensional shape [14].

Some examples, however, present the behaviour of autonomous units able to move by themselves, occasionally assembling to form patterns [4, 6]. In the work most related to this study, Taylor investigates the potential of communicating underwater robots to assemble into complex shapes [16]. Like our work this has a fluid dynamic context but the high value of water density places less constraint on the payload. A study involving formation control of underwater gliders is also presented in [5]. Also, while there are several experimental studies on flying robotic blimps [18], the use of flying elements in a reconfiguration task has not to our knowledge been attempted until now, not least because of obvious technical difficulties.

In order to meet the technical and scientific challenges presented by this project, a joint international effort has been appointed, involving the collaboration of the artists' research group Nxi Gestatio at the University of Québec in Montreal (Canada), and two engineering groups, the Intelligent Autonomous Systems (IAS) laboratory at the University of the West of England (Bristol, UK) with its expertise in flying swarms and the Swarm-Intelligent Systems (SWIS) group at École Polytechnique Fédérale de Lausanne (Switzerland), specialised in swarm-intelligent algorithms and their implementation in distributed, embedded, real-time systems.

3. INTERACTION DESIGN METHODOLOGY

To tackle the difficulties inherent in this project, an alternative design methodology has been adopted, such that the development of the Mascarillons is undertaken in parallel, on several experimental levels (see schematic figure 3):

1. by physically building the cubic blimps;
2. by modeling them in the dynamically realistic sensor- and actuator-based simulator Webots [10];
3. by the microscopic modeling of self-organising cubes with a kinematic point-simulator keeping each robot's individual states separately and
4. through the use of macroscopic modeling, where in contrast to the microscopic model, the swarm is modelled as a whole (not yet implemented for the specific set-up mentioned here).

In so doing, it is possible to gain insights from all implementations to benefit the others, with each experimental level having its own descriptive power and corresponding computational cost (see Table 1). The interaction of all levels of exploration is expected not only to speed up the design process, but also provide us with a strategy to tackle the strongly constrained design space of interacting flying blimps.

Limitations in volume, power and weight are a constant concern when improving the sensory-motor capabilities of the flying cubes. In such a context, the potential of a given implementation to achieve self-reconfiguration must be thoroughly explored in terms of sensor placement, information sharing or movement control before considering any improvement of the robotic capabilities. The interdependence of the implementation with a specific self-organisation algorithm distributed in the swarm is, in this case, crucial to the goal.

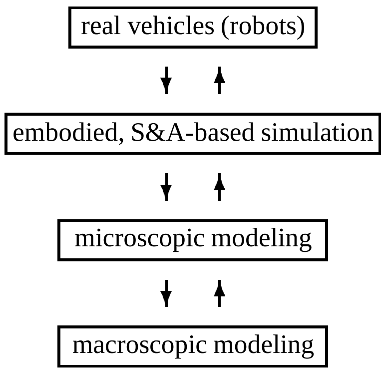

Figure 3. Schematic view of different levels in the interaction methodology

In order to assess the performance of a given implementation, we will consider several metrics that must be measurable on all experimental levels. These metrics can be subsequently aggregated in order to enable direct comparisons. Time of completion, energy consumption, robustness to noise are the most important ones; a way to measure availability and quality of information will also be useful.

With the proposed set of experimental levels, it is possible to decompose the problem considered into several interdependent tasks:

- Realistic macroscopic models usually rely on Markov formalism; they represent the swarm as a whole and capture self-assembling as a probabilistic process determined by the local interaction between vehicles and between vehicles and their shared environment. The advantage of this level of abstraction is that, in addition to being computationally independent of the number of units in the system and in general several order of magnitude faster than any other level of implementation, it often allows for mathematical tractability and analysis of the overall system dynamics. If the macroscopic model is implemented in an incremental way, as for instance demonstrated in [1, 9], it allows for quantitatively correct predictions without the use of free parameters. However, the parameters used in macroscopic models often summarize general interaction mechanisms and do not capture details of possible design choices to be performed at the level of the implementation of real units.

- To investigate the 'time of completion' constraint, the microscopic modeling provides a fast tool that does not need to take low-level motor control into account in detail. It allows us to study the quality and availability of information needed to self-assemble in reasonable time. It usually represents a compulsory step towards the macroscopic level of abstraction: the representation of the individual units is much simpler than that used by a realistic simulation but the elementary level of a unit of the system is maintained (one robot corresponds to one agent in the microscopic model).

- The realistic sensor- and actuator-based simulation provides the opportunity to investigate lower-level system parameter influences and control loops taking into account aerodynamics, inertia and noisy, non-linear sensors and actuators. The broad strategies resulting from the microscopic model will here be thoroughly tested before implementation. Restrictions appearing from this testing will in turn be included in the microscopic simulation to increase its accuracy.

- The target system of this project is a multi-robot real platform. Therefore, the real robots implementation is crucial for the parameterisation of all levels of abstraction. It dictates the limitations of a given implementation that need to be echoed in the abstract models. It also provides a testbed for confirmation of results.

Because of the strong interdependencies between the different tasks, each experimental level is expected to outline specific constraints, which must be subsequently considered in the other levels in modifying descriptive parameters. As a results each level contributes to global progress towards the design of the flying self-organising swarm.

4. THE MASCARILLONS

The Mascarillons are currently being built in Montreal in Nicolas Reeves' research/creation laboratory Nxi Gestatio. Already several versions have been built in the effort to reduce structure size and weight while maintaining cubic shape and sufficient payload.

4.1. Description

Each Mascarillon is basically a helium blimp constrained within a rigid, ultra-light structure, whose size varies from 1.8 meters (prototype) to 1.65 meters (final version). The helium is contained within an inner polyurethane envelope, while an outer envelope made from a thermoshrinkable polymer is tightened on the structure, resulting in truly cubic blimps with perfectly flat faces that can assemble in a building block manner. The design of the structure was a challenge in itself, since it had to be rigid enough to withstand the tension of the stretched membranes while being light enough to maintain a sufficient payload. Many materials have been evaluated and tested (polystyrene, balsa wood,

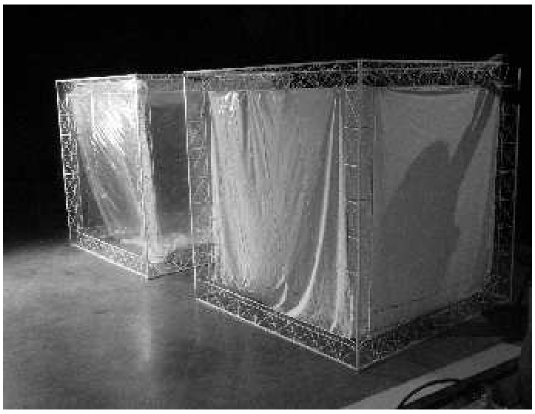

Figure 4. The real Mascarillons

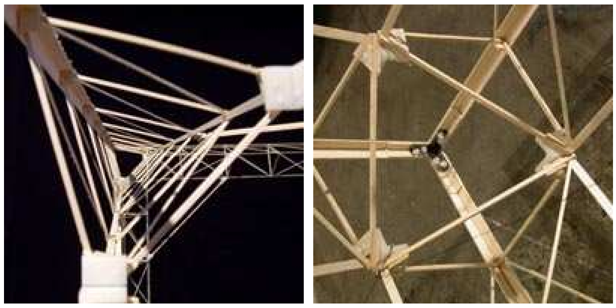

Figure 5. Details of the structure

polycarbonate, carbon fibers) and many structural configurations have been tried. At this time, we have obtained the best results in terms of rigidity, lightness and cost efficiency with twelve similar triangular beams of constant equilateral section, made of basswood and housing all the in-board devices. The weight of the completed structure is about 1100 g for a 170cm Mascarillon. In comparison, the total lift for the same model is about 4000g, which is enough to bring the current blimps and their various elements (structure, membranes, batteries, motors...) to aerostatic equilibrium with some spare payload. It is to be noted that the elements are assembled with small steel and nylon connectors so the blimp can be dismantled to allow its transportation for display or demonstrations abroad with minimal losses in materials (only the outer envelope will have to be replaced).

The mechatronics equipment is currently composed of ducted fans located within the structure's edges, sonar sensors spanning each direction and a Korebot CPU[2] running Linux with wireless LAN. A compass and inclinometer are currently being added. Intrabot network relies on an I2C infrastructure: all embedded components communicate over a flat-ribbon four-wire bus that carries logic, power, data and clock. We had to insert a set of I2C buffers/debuffers in order to cross the theoretical maximum length officially defined as "a few meters". This circuitry basically increases the bus current by a tenfold. Extrabot network uses WiFi capabilities of the KoreBot, thus allowing it to exchange data with a ground station (uploads, control and status). Interbot network will use the very same WiFi capabilities in order for the cubes to trade local and global information with each other. This network has yet to be developed, but it will most likely rely on threads implementing either a client-server or peer-to-peer protocol over TCP sockets. Mechatronics is powered by Lithium-Ion/Polymer batteries, offering optimal capacity-over-weight ratio. A future version will include an I2C agent that polls the battery level and raise an emergency landing alarm. This will prevent both freezing of the logic and damaging of the batteries by going below a safe tension threshold.

With this implementation the Mascarillon is balanced at the aerostatic equilibrium and uses motors only to avoid possible obstacles, to perform some task oriented move, or to adjust for micro-atmospheric movements. The wireless network also enables direct exchange of information. At the present time, a prototype (M-180) and 3 preliminary versions of the Mascarillons (M-170) are already built (the model number refers to the length of the edge, measured in centimeters). The final swarm will be composed of at least 12 M-165 flying cubes.

To be able to achieve self-configuration, the addition of a docking system involving electromagnets is under development, as well as additional sensor capacities such as onboard vision.

From this primary implementation, aerodynamic modeling information is gathered such as damping coefficients, moments of inertia and added mass constants. These modeling parameters are then used to build a realistic model of a Mascarillon in simulation.

4.2. Challenges

In order to act as effective building blocks, the Mascarillons must be strictly cubical. As mentioned above, a particularly rigid — and comparatively heavy — structure is needed in order to constrain the helium blimp that would otherwise tends towards a spherical shape. All remaining components such as batteries, motors and sensors, must then be carefully chosen to fit within the volume imposed by the structure and be sufficiently light to meet the payload requirements. For instance, most blimps used in robotic research usually fit all components in a gondola hanging under the balloon. In our case, the aim of 3-dimensional self-assembly prevents the use of such a solution.

Considering that one of the aims of the project is to reach the smallest size possible, and that volume — and hence

[2] see http://www.k-team.com for additional information

available payload — reduces to the cubic order of the edge length, each possible amelioration in the structure or components weight is welcomed. In this context, any further extension to the mechatronics in order to give the Mascarillons greater behavioural ability is highly constrained.

More particularly, the choice and placement of sensors is of great importance for the performance of the assembly strategies. The use of more abstract levels of modeling are expected to give meaningful insights in an attempt to choose the most efficient sensor and actuator configuration given the constraints.

Also, the realisation of an effective docking strategy is, in itself, a challenging task. Indeed, while the problem of efficiently guiding the cube already presents great difficulties because of the non-aerodynamical cubic shape, approaching another cube accurately will raise serious issues. Indeed, when two light objects in comparison to air density try to meet on their flat surfaces, aerodynamic perturbations will strongly influence the robots' behaviour. The use of electromagnets to guide and clamp the robots together is currently being considered [16]. However, the cost on the payload for an efficient device is uncertain.

5. REALISTIC SIMULATION MODEL

Because of the multiple challenges of the Mascarillons project, building, modifying and testing the potential efficiency of successive generations of flying blimps would consume significant time and resources. Due to the rather large size of the robots, physical experimentation also requires large spaces that are not necessarily available when needed. In this context, the realistic capabilities of a dynamical simulation featuring noisy and non-linear sensors and actuators can be of great help in exploring the implications of different design choices within a short time.

In addition, the aim of collaboration with researchers in the artistic domain calls for an interactive 3-dimensional visual interface, providing us with a common understanding and enabling the shared elaboration of solutions. With such a tool, the different needs of the project's protagonists are more readily taken into account.

Despite these advantages, simulation results must be taken with great care and validation through subsequent implementation onto real robots is an absolute requirement.

5.1. Description

Insights gained from the construction of the Mascarillon robot enables the definition of a aerodynamic model of a flying cube, which is implemented in the realistic robotic simulator Webots [10]. Based on previous work in blimp modeling by Zufferey [19], the model currently takes into account air resistance damping, aerostatic restoring force, added mass and added Coriolis effects characteristic to the problem of solids moving in a fluid environment. The model is then parameterised through extensive tests of the real robotic blimp's dynamic behaviour, actuator thrusts and sensor response.

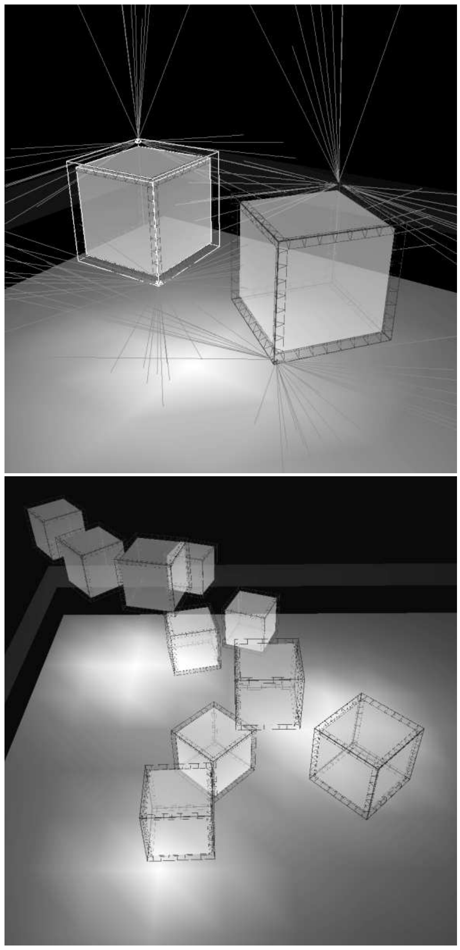

Figure 6. Mascarillons realistically simulated with Webots

Through its implementation in Webots, the model can take full advantage of this physics based simulator using the ODE dynamics engine[3], and profit from its realistic simulation of sensor and actuator responses, especially considering noise. This simulator has the advantage of being realistic enough to produce results consistent with the behaviour of the real robots. Webots is used in more than 200 universities worldwide and is therefore strongly validated as a simulation tool.

5.2. Challenges

Because of their light weight relative to the air density, the Mascarillons are very sensitive to small perturbations of the

[3] see http://ode.org

surrounding atmosphere. Even the perturbation of a person walking by is sufficient to influence the trajectory of a robot. On top of that, the cubical shape is certainly not the most aerodynamical one, a characteristic which tends to render trajectories even more unstable. These considerations call for the modeling of the fluid-solid interactions between the robots and the air in order to be able to draw meaningful conclusions from the realistic simulation of the Mascarillons.

However, the modeling of quantitatively accurate dynamical interaction between fluid and solids is highly computationally demanding. The modeling of multiple interacting flying cubes with Webots has to make strong simplifications by minimizing the impact on the quantitative agreement with real world results. To this extent the physical realisation of a few flying blimps is crucial to determine the parameters that are especially relevant to the faithfulness of the simulation. Such an aim also involves a deep understanding of aerodynamical modeling.

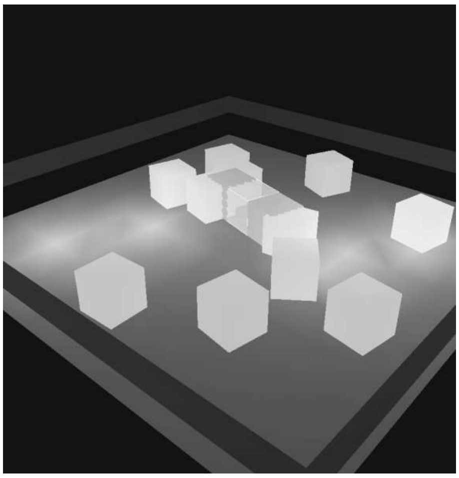

Figure 7. Webots' visualisation of the 2D microscopic modeling showing self-assembling Mascarillons

6. MICROSCOPIC MODELING

Because of the time constraint of the problem considered, it is not clear that strictly local information will be sufficient to allow the Mascarillons to self-organise fast enough. In order to study the influence of the availability of information on the self-assembly time, we go further into the abstraction to reach the third level of the interaction methodology (see Figure 3).

6.1. Description

Instead of dynamical modeling of the robots, the model is now a kinematic point-simulator that maintains only trajectory and orientation information to characterise the robots. Here the difficult problem of starting or stopping a flying blimp is not considered, but merely the problem of self-assembling cubes from an initially spread swarm. We also reduce temporarily the dimensionality from 3D to 2D.

Despite the strong level of abstraction of this simulation, parameters are realistically represented in order to keep the behaviour of the simulated cubes in reach of the real Mascarillons. To this end, translational and rotational speeds are constrained and safe distances are kept. Thus far, the microscopic simulation is deterministic. However, the introduction of noise or probabilistic state change might be needed to let the model better correspond with results from real robots or the realistic simulator. The simulation process can be displayed on the 3D interface of Webots or run in batch mode for faster speed.

With such a simulation, it is possible to tune the information available to the robots and even compare between centralised and distributed solutions to the problem. Already, a centralised planner and a distributed behaviour relying on total availability of information within a definite radius have been implemented for the assembly task. We are now systematically investigating a realistic way to reduce the available information, and the obvious next step will be to extend the behaviours developed to a three-dimensional space.

The results of this level of abstraction will serve as a guide for the design of the sensory system of the real Mascarillons, with prior confirmation through the realistic model described in section 5.

6.2. Challenges

The rationale of research using this more abstract simulation is to investigate two different problems at the same time. Firstly, the problem of self-assembling a robot swarm into an interesting pattern is a demanding task in itself and has been already studied by several groups [16, 11].

Secondly, the potential for the swarm intelligence paradigm to generate solutions that can meet real world constraints still remains to be shown. In our case the tightest constraint appears to be the time of completion: surely the public does not expect to wait several hours to see the process reach an assembled state. And even so, the power consumption of the blimps would not allow for such a protracted denouement. Thus, it appears impossible to let the robots wander around randomly until they come across each other in order to self-assemble. While it would be possible with the help of a central planner and absolute information about the units location and heading to assemble the swarm in a given configuration, this project aims at exploiting self-organisation as the main mechanism for self-assembling. All the key ingredients of self-organisation (positive feed-

simulation level	real-time factor
realistic (visualisation)	0.25 – 1.36
realistic (webots batch)	2.3
cinematic (visualisation)	1.57 – 8.77
cinematic (batch)	44.5

Table 1. Computing time comparison for different simulation levels in the interaction methodology (10 simulated robots on a 3.0 Ghz desktop station)

back, negative feedback, randomness, and multiple interactions) should be exploited for achieving the desired performance in terms of efficiency and robustness. In particular, the careful design of a positive feedback mechanism might lead to an interesting solution in term of time of completion. As a result, the sensory and communication capabilities of the robots as a means to extract information about a meaningful direction to follow become crucial parameters.

Also, the flying robot swarm will have to have a means to determine its assembly state in order to trigger self-reconfiguration after reaching a distinctive pattern.

This kinematic modeling abstraction leads to the possibility of investigating, in a very general way, the expected behaviour of the flying swarm, for a given level of availability and quality of information for the cubic blimps. More particularly, the potential to reach interesting configuration patterns within the problem's time constraints can be tested against the level of the sensory and communication capabilities of the robots.

7. DISCUSSION

Systematic results for the proposed methodology are still to come. Nevertheless, it is already possible to comment on the respective computing speeds of the differing levels of abstraction (see Table 1). Indeed, the realistic model, even though it does not yet implement solid-fluid interactions, is quite computationally demanding as the number of robots increases. The use of batch mode slightly improves the performance but remains too slow to enable a systematic search of the design space, through, for instance, machine-learning techniques. The microscopic model, and especially its batch mode, is therefore very useful for rapid exploration of solutions.

A further level of abstraction — and improvement in computing speed — could be achieved by implementing a macroscopic probabilistic model, as presented in [1]. As in other case studies dealing with multi-robot platforms, the purpose of such a model would be to provide a mathematically tractable representation and computationally efficient tool for the analysis of the overall dynamics of the system. However, the strongly constrained design space and the highly complex aerodynamical interactions characterizing this problem might significantly reduce the impact of macroscopic models on the design process.

8. OUTLOOK

The Mascarillons project will result in the development of a multi-robot platform that can be used as a testbed for the relevance and robustness of general self-assembly algorithms. It will also embody a validation test for an interaction design strategy in the engineering of solutions to difficult problems.

In the broader sense, the Mascarillons project combines the challenges of the self-assembly of moving elements, the technical difficulties of flying indoor blimp swarms and the theoretical modeling of the dynamics of actively interacting intelligent units in fluid environments. It also involves the collaboration of traditionally differing fields of research and therefore fits well into the current trend towards more interdisciplinarity in scientific research.

9. ACKNOWLEDGEMENTS

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