

Aerial Robotic Construction Towards a New Field of Architectural Research

Jan Willmann, Federico Augugliaro,
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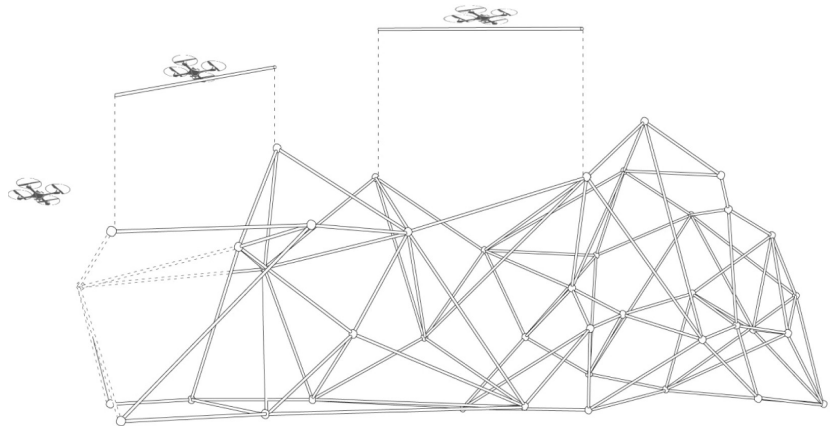
Abstract

This paper takes a first step in characterizing a novel field of architectural research - aerial robotic construction (ARC) - where aerial robotics is used not only for construction, but as a guiding principle in the design and fabrication process. Featuring autonomous flying vehicles that lift small building elements and position them according to a precise digital blueprint, ARC offers a comprehensive new approach to architecture research and technology. Developed by the research groups of Gramazio & Kohler and Raffaello D'Andrea at ETH Zurich, ARC offers unique advantages over traditional approaches to building: it does not require scaffolding, it is easily scalable, and it offers digital integration and informational oversight across the entire design and building process. This paper considers 1) research parameters for the individual components of ARC (such as module design, connection methodologies, vehicle cooperation, and construction sequencing/synchronization), and 2) the architectural implications of integrating these discrete components into a systemic, unifying process at the earliest stages of design. Fidelity between the design concept and the full-scale construction is of particular concern.

I. INTRODUCTION

Robots are extremely useful to the field of architecture [1]. Not only can they lead to significant time and cost savings, but their ability to connect digital design data directly to the fabrication process enables the construction of non-standard structures. Yet traditional ground robots (such as industrial robots or CNC machines) have predefined working areas that limit their scale of action and thus constrain the size of the work-piece they act upon [2]. However, *aerial* robots, such as quadcopters, can operate dynamically in space. As a result, their use opens up entirely new possibilities for robotics in architecture (see Figure 1). Aerial robotic construction (ARC) is a new form of dynamic construction that is not limited by the same constraints of ground-based robots; its most evident and radical consequences are the ability to digitally oversee and control a large number of aspects of the design and construction, and the ability to freely position building components in space.

► Figure 1: Conceptual model of a space frame structure assembled by flying vehicles.



ARC research is in its infancy, and presents many theoretical, practical and methodological challenges. Obvious examples are wide-ranging and include the need for digitally controlled, non-standard assembly of building parts [3], building materials and constructive systems that are both robotically transportable and configurable at heights, and the integration of flying vehicles into the building process. In order to develop a schema for addressing these challenges, two research groups from ETH Zurich – Gramazio & Kohler’s Architecture and Digital Fabrication group [4], and Raffaello D’Andrea’s group at the Institute for Dynamic Systems and Control [5] – collaborated to create a first experimental setup for ARC [6]. This prototype, called Flight Assembled Architecture, resulted in a six meter tall, 1500-module tower, dynamically assembled by a fleet of autonomous

quadrocopters, and required many innovations, including the development of new computational and material construction systems, and insight into the control of aerial robots as they grasp and carry payloads, and cooperate in assembly tasks (see Figure 2). While it remains to be seen whether ARC will emerge as a viable dynamic building technology, the Flight Assembled Architecture prototype successfully illustrates how an ARC approach makes empty airspace tangible to the designer, and addressable by robotic machinery.



◀ Figure 2: Flight Assembled Architecture: A quadrocopter placing a polystyrene module.

First, because aerial robots fly and mount construction parts directly to their required position, ARC does not require scaffolding and is less constrained by height and bottom-up accessibility. Second, ARC structures can be built according to highly complex designs: aerial robots operate under the explicit guidance of a digital architectural design, and can place and manipulate material according to a precise digital blueprint. Third, ARC work capacity is easily scalable: while conventional machines are limited to operating on a small component of a traditional structure, many aerial robots can operate on an ARC structure at the same time, either individually or cooperatively. Each of these characteristics lends ARC the potential to pave the way for new forms of spatial load-bearing structures that are not currently possible with standard robotic systems.

In the next section (Section 2) we present the context of our work from both a theoretic and a technical perspective. Section 3 presents a schema for research into ARC, and suggests parameters for investigation, including modules and assemblies, connection and construction methodologies, features of flying vehicles, and grippers, connecting devices and pickup stations. Section 4 explores issues on computational design, and Section 5 discusses the challenges of ARC and suggests strategies for addressing them. In Section 6 we present a detailed description of a first experimental setup for ARC, Flight Assembled Architecture. Our conclusions are presented in Section 7.

2. CONTEXT

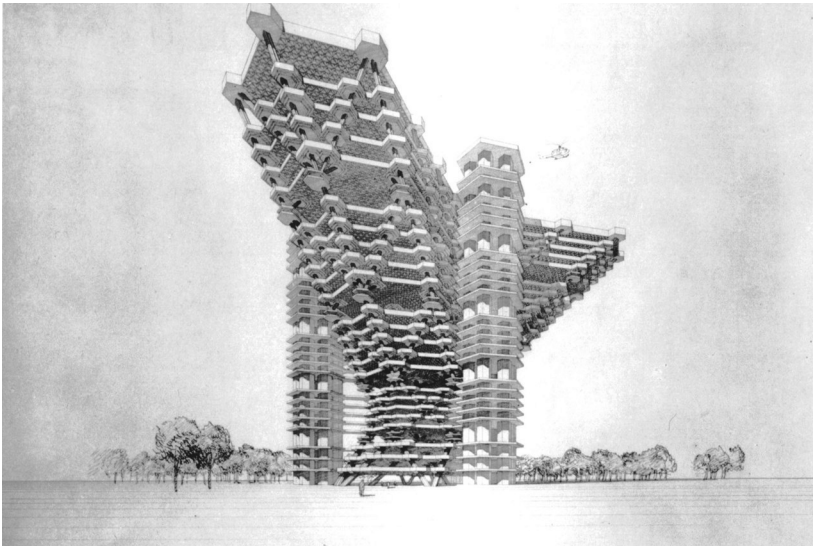
ARC is a novel area of research, and little published research currently exists. We begin this section with a discussion on the influence of flight and airspace in architectural theory. Next we discuss the technical context our research, and describe previous attempts to develop mobile construction robots in general, and aerial robots specifically.

2.1. Flight, airspace and mobility in architectural theory

Flight, building and machines have been linked since Leonardo da Vinci's flying experiments during the 15th century. Since then, students of architecture have marveled at the beauty of flying. Modernists, for example, held a fascination for aviation, which they saw as a new utopian ideal of dynamic architecture directed onto culture and technology. Treatises such as Le Corbusier's *Cinq points de l'architecture moderne* (1926), suggested lifting buildings off the ground in order to control space, leading the collective imagination to formulate ideas of mechanistic power and attainable reality, and symbolizing an ideology of progress and function [7]. Around the turn of the 20th century in particular, the debate received fresh impulse through the shift towards new post-war economic, geopolitical and social order, radically expanding the notion of information and space [8]. A new hyper-technological language evolved, flowing from the visionary extrapolation of modern functionalist precepts and ever more clearly shaping post-modernist culture [9]. This climate of progressive politics allowed protagonists such as Yona Friedman, Archigram, Buckminster Fuller and Kisho Kurokawa or Kenzo Tange to generate the radical idea of a nomadic utopia, describing endless reconfiguration scenarios of buildings and cities, opening the way for a new understanding of weightlessness, mobility and communication [10].



◀ Figure 3: Archigram's "Instant City"-collage from 1968 (Image © Peter Cook, Archigram).



◀ Figure 4: The "Helikopter-Haus" designed 1961 by the Austrian architect Wilhelm Holzbauer (Image © Wilhelm Holzbauer).

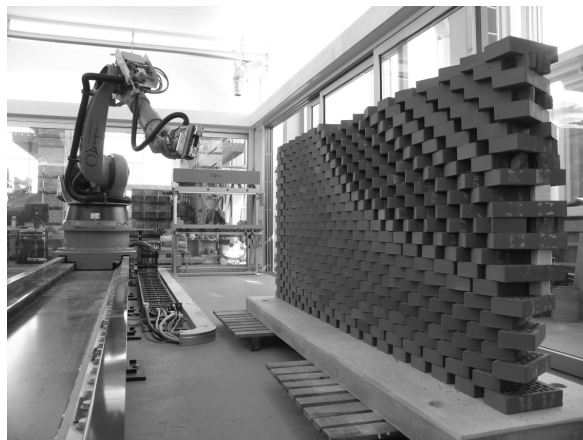
In the face of this physical and mental liberation, Geodesic Domes, Instant Cities (see Figure 3) and Megastructures (see Figure 4) can be seen as strategic objects that were no longer defined by a foundation or the physics of space but rather by the order of information and networks. As such, conquering the sky resurfaced as an important leitmotif that was dictated by prevailing explorations of technological autonomy, both on an urban and cultural scale [11]. In this way, the modern fascination of airspace has been

transformed into a post-modern interest in space, information and control that favors a new regime of experimentation, and embodies the utopian dream of a permanent conquest of space through rationality. Today, as we shift from the mechanical to the digital age, these experimentations return to the subject of architecture, and appropriate for it a new autonomy, free from purely physical constraints. It is in this light that ARC can be seen as not only as a new field of architectural research, but also as a return to a long standing subject of architectural interest: the fascination with airspace.

2.2. The development of mobile construction robots

Several attempts have been made to develop mobile construction robots, the most advanced of them being the ROCCO [12] and the BRONCO [13] projects. This research dates back to the early 1990s, when the motivation was to improve the productivity and economy of building construction, mainly by utilizing the machines' ability to handle an increased payload in contrast to humans [14]. Although highly advanced, these developments did not find full access into practice since they were not flexible enough to adapt and to react to different design situations. In the course of the recent shift towards digital technologies in architecture, universities such as Harvard GSD [15], Carnegie Mellon [16] and University of Stuttgart [17] have set up research facilities for construction with industrial robots. Together with ETH Zurich (see Figure 5), they have fostered promising architectural case-studies and prototypical elements, elevating robotic assembly to the role of a constitutive design and fabrication tool [18]. Such novel technologies now motivate new approaches to the design of architectural structures, and advanced constructive systems that use robotic technology are clearly feasible [19]. For example, a team at the GRASP Lab, University of Pennsylvania, recently investigated the possibility of quadcopters to autonomously build tower-like cubic structures from modular parts [20]. The recently launched ARCAS project focuses on aerial assembly by helicopter equipped with robotic arms [21].

► Figure 5: Robotic fabrication of a non-standard brick wall at ETH Zurich, 2006 (Students Michael Knauss, Silvan Oesterle © Gramazio & Kohler, ETH Zurich).



3. AERIAL CONSTRUCTION

Research on ARC is based on specific components and strategies to manage and perform complex construction experiments. We have identified three general categories of research: (1) computational design, (2) material and constructive systems, and (3) robotic systems. Once the concept of ARC is computationally identified, the physical requirements for experimental research can be examined. The essential feature of ARC is therefore to introduce the unique integration of different material and robotic systems, so that account is taken of their overall capabilities and limitations regarding the physical building performance. Important parameters of investigation range from building modules to particular construction techniques, and is completed by the investigation into flying robots, grippers and pickup stations. This can be outlined as follows:

Modules and assemblies - In the context of ARC, one important key is to develop modular components that are suitable to aerial construction and are architecturally lean. Hence, these elements must be geometrically generic while allowing an optimal architectural and structural performance. For the purpose of experimentation, building elements must be as precise as possible in order to avoid buildup of tolerances and unstable situations, and to ensure reliable connections between them. In ARC, industrial precision is needed in order to produce such building modules. The weight of materials is of particular interest if one wishes to ensure fidelity for full-scale implementation: On the one hand, robotic constructive assembly processes are by nature “additive”, they are scalable and can incorporate variation in the assembly to accommodate not only economic and programmatic efficiency, but also complex information about individual elements and their position [22]. On the other hand, however, the payload of flying vehicles is very much limited, whereas materials with high strength and high density favor the use of ARC. Here, the volume of the element’s structure must be low in relation to the total volume that is supported [23]. This fosters investigation into structural geometry, specifically the efficiency with which particular levels of strength and weight can be achieved. Consequently, this research focuses on the construction of elements, on lightweight material composites and on complex space frame structures, in order to match the lifting capabilities of flying vehicles and to ensure efficient use of energy and resources. Because the overall shape of these building modules is also determined from aerodynamic considerations, these must be designed according to the specific assembly techniques and building capabilities of the flying machines. The building modules, therefore, must have particular geometrical characteristics so as to meet the required levels of the flying vehicle’s complex aerodynamics, and thus, its building performance [24]. The consequence is a design that is never monotonous or repetitive, but rather specific and adaptable to different architectural and aerial characteristics. It is both comprehensive and versatile all at once [25].

On that scope, any optimized form of the building elements contributes positively to the performance of the flying vehicle. This “information” logic between dynamic contingencies – such as the requirements of aerial transportation and the physical constraints of production – must be seen as integral; consequently, construction, weight and form must be allocated a very high priority in the design of building elements. In addition, in order to permit the identification and assessment of factors affecting fidelity of implementation, one must meet particular architectural and structural requirements: the modules, for example, must allow complex assemblies with multiple degrees of freedom. As long as they can be physically placed in a stable manner, they can be individually positioned and rotated by flying vehicles. This creates a set of rules and parameters that informs a varied design for the overall structure, in terms of both the horizontal and the vertical aggregation. These rules and parameters, together with usability and structural requirements, provide a framework for researchers to investigate the issue of fidelity and the role it plays in implementing ARC at full scale.

Connection and construction methodologies – While ARC enables the assembly of complex architectural artifacts from a large number of elements, it also creates the problem of how these elements will be connected. New connection and construction methodologies that make use of additive layering are needed. Individual modules must not only be displaced in relation to each other (so that the structure gains a geometrically differentiated figure as a whole), but they must also lend themselves to a constructive formation that can be assembled from either identical or individual parts. As a consequence, this connection technology must encompass tolerances of both the buildup material and the robotic placement of it. It must also account for discrepancies in material properties, such as weight and friction. For example, connecting a large number of building elements layer by layer requires a connection type with minimal tolerances so that the actual buildup corresponds to the digital design data given to the flying vehicles. As a consequence, glue connections are most adequate for this task and would allow for multiple degrees of freedom in placing, but without preserving full fidelity for full-scale building processes. Another idea is to use interlocking connections. Here, the arrangement of building elements must be chosen in such a way that, without resorting to mechanical fasteners or adhesives, each block is prevented from moving by its neighbors. A main issue of concern for ARC is the relative imprecision of flying robots when placing a building element. As such, the benefit of interlocking connections – the origins of which can be found in ancient structures such as the arch or the dry stone wall – is that they compensate for assembly imprecision while jointing the single elements. Building elements with simple convex forms would allow plate-like assemblies of a certain number of elements, for example. Also, traditional joinery techniques, such as is found in woodworking, would be possible. In

this case, one would need to pre-determine and digitally control both how the interlocking device is assembled and how it behaves under mechanical and dynamic impact. If connection and construction methods are developed such that they allow aerial robots to connect parts autonomously, scaffolding for workers and materials would not be required. Overall, this constructive thinking fosters the creation of architecture that profoundly reinvents its constructive repertoire. Traditional connection techniques or as yet unknown systems could thus lead to profound changes in the design, performance and expressive language of architecture.

Flying Vehicles – Hover-capable vehicles, such as helicopters and quadcopters [26], are fundamental to aerial robotic construction: flying vehicles must be able to accurately maintain and adjust their position as required. Small Unmanned Autonomous Vehicles (UAVs) are nowadays a research topic for many groups, and their abilities have drastically improved in recent years [27]. Research results demonstrate the possibility of carrying payloads with quadcopters [28] and helicopters [29]. This new field must be further explored: Adaptive control strategies, for example, can be used to control a UAV as it interacts with its environment, or picks up and places a building element. In addition, the development of an aerial robotic construction system requires multi-vehicle cooperation. Possible tasks requiring cooperation include planning trajectories, lifting payloads and fault-handling. Currently, high-accuracy flight still relies on external localization methods, but advances in sensor capabilities (cameras, GPS, laser range finders, etc.) and their growing miniaturization drastically improve the possibility of on-board perception and state estimation, allowing, for example, autonomous flight using onboard processing for computer vision [30]. At the moment, most small UAVs have limited payload capabilities, and are thus suitable for scaled research only. However, multi-vehicle cooperation and progress in vehicle design allow them to achieve higher lift capabilities.

Grippers, connecting devices and pickup stations - To realize such complex structures using UAVs, construction parts must be accurately moved in space. Thus there is a need to develop physical gripping systems that allow hover-capable UAVs to connect to objects, steadily fly with them to a target point in the space and place them with a given orientation. This depends largely on the vehicles' capabilities and on the degrees of freedom a chosen construction method allows. Hence, the design of a particular construction system is directly linked with the design of its tools. Solutions for this are mechanical grippers, which either insert pins in the materials or feature small gripping brackets. This could be a suitable solution given the use of deformable building materials or small scale elements. Also, dexterous hands or magnetic grippers would present an important field of study, even though such complex tools are in most cases too heavy to be built into UAVs. Another way to carry payloads is to hang them on cables. The

advantage of using cables to lift a payload is that they enable multiple flying vehicles to co-operate; payloads that are too heavy or awkwardly shaped for a single UAV to lift on its own could be managed by a group of UAVs working together. Placing an object at a specific location using cable, however, has some limitations: it is more difficult to apply specific forces or torques on the part when assembling a structure.

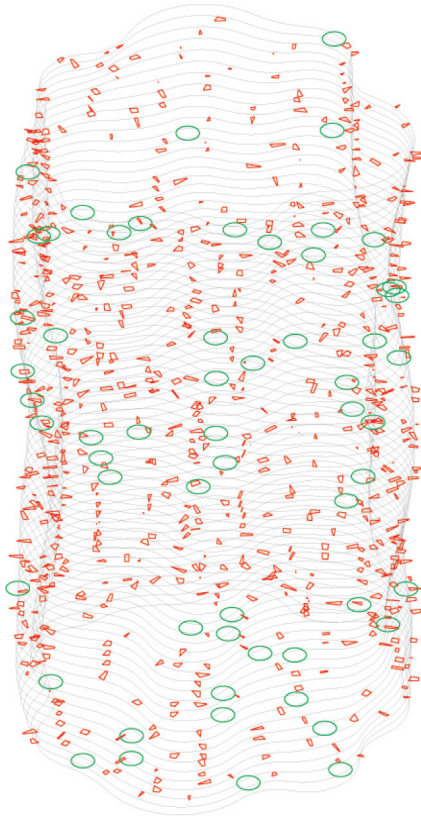
Research on ARC also applies to infrastructure and logistics. The location of the pickup station is, for example, a key element of such a complex assembly apparatus. So is the number and kind of parts it furnishes. Indeed, construction parts can be stored ahead of time, allowing pre-defined assembly sequences to run continuously. This makes it necessary to develop a physical scenario where a variety of building elements can be picked up by the flying machines as needed. The station, therefore, must continuously operate and be adapted and controlled not only according to the digital design and assembly data, but also according to the ever changing supply and demand of material. Overall, the infrastructural environment and material logistics heavily influences the buildup of the ARC structure, and hence its geometrical freedom. This also depends on the degree of pre-fabrication, particularly if the flying vehicles pick up an aggregation of multiple parts instead of a single building module. For this research, it is essential to ensure a safe and reliable interaction between the pickup station and the flying vehicles.

In sum, concurrent to ARC is an explicit interest in the development and integration of different physical building components. When linked with innovative robotic machinery, modular material systems satisfy the requirements for economic construction while providing a high degree of freedom for differentiation [31]. Also, the fact that complex architectural structures contain a large number of elements – and therefore require advanced design and planning processes – can now be addressed by the exploitation of powerful digital planning and fabrication tools [32]. In fact, this encourages the use of constructive assembly techniques since singular elements can be precisely controlled and accumulated where needed, enabling the implementation of an additive principle on a tectonic scale [33]. To conclude, our focus is not only to precisely examine the impact of new material aggregations, but also to progress with criteria of components and tools. With advanced physical building systems such as ARC, material implications (such as load-bearing capacity, implanted information, reproducibility and programmability for digitalized assembly of elements) directly inform the design act.

4. COMPUTATIONAL DESIGN

With ARC, writing a computer program is on a par with the drawing of plans and sections. This convergence of digital data and physical materiality allows for the creation of highly complex geometries, and more importantly,

non-standard architecture [34]. At the same time this requires new computational methodologies and tools that can exploit the coherence between parameters used in computational design and the physical degrees of freedom available to flying robots in airspace. This coherence can be characterized by parameters that translate directly from digital to aerial space and vice versa. In the Flight Assembled Architecture prototype, for example, the imprecision of the aerial robotic placement had a significant impact on the computational design of the structure. With a maximal tolerance of 25 millimeters, the designated design features had to remain readable without the structure taking on a random appearance. Therefore the design was evaluated not only as single structure, but also through a simulation of different assembly tolerances. In addition, a local evaluation of the structure's connections was conducted in order to find critical solutions that could be optimized computationally. To provide the building design with an adequate architectural and computational fitness, gravity and tolerances were calculated with a customized algorithm that generated the convex building envelope by adding the tolerances and overlapping zones of single building modules (Figure 6).



◀ Figure 6: Computational optimization of geometrical formation for Flight Assembled Architecture, optimizing curve radius and curve length as well as checking missing overlapping areas (marked in green) or too small overlapping areas (marked in red).

Such an approach enables the exploration of the full design space where the structural integrity of the final form, the feasibility of its building parts, and the integrity of the buildup process can be evaluated. In such a system, the building height is indicated in layers and elements instead of a metric coordinate system. The reason is that actual deposition height of the individual modules must be registered by a camera or measuring system when placing the modules. The placement height of the building elements, therefore, stems from the physical aggregation of the modules instead of being a pre-computed coordinate. This principle yields future potential in digital design and construction; consequently, materially-based procedures must be tolerant to incongruences between physical reality and digital model. This is an important step towards a dynamic building process that is sustainable in its entirety [35], where computational tools allow not only for intuitive formfinding while maintaining optimized structural and economic performance, but also enable an ideal breakdown of the form into the best number of elements and smart assemblies [36]. A specific case is presented in Section 7.

In this context, a key research goal for ARC is not only the design of architectural structures and their constructive sequencing, but also the simulation and analysis processes. This includes real-time assessment of critical overlapping zones, tolerances and load-cases during the design process, and the integration and development of specific structural analysis software for complex modular building structures. As such, the vision of ARC draws from the explicit relation between digital design techniques in architecture and the complex capabilities of flying robots. Only in this way can a new (computational) design ontology evolve to envision architecture as not only a final geometric form, but as a complex and refined generative process of digital materialization [37].

5. CHALLENGES OF AERIAL ROBOTIC CONSTRUCTION

Developing flying vehicles that co-operate to lift and place building parts is an inherently difficult and challenging problem. It is therefore difficult to obtain a universal principle model of an ARC system. It is possible, however, to isolate important characteristics, evaluate fidelity and describe new constructive typologies.

The integration of architecture and robotics - Tremendous advances of digital technologies and their capabilities in architecture have come from the close interrelation of computational design and digital manufacturing. Industrial robots enable the implementation of complex constructive material systems on an architectural scale. When freed from operating within the predefined parameters of specialized machinery, robots can allow a wide range of manufacturing possibilities. It is also possible to design a robot's specific set of "manual skills", to determine its movements,

and to assign it particular types of assembly sequences. However, when exploring the link between performative design and robotic fabrication, the differing characteristics of architectural material systems and robotic fabrication are a prominent issue. Three principal factors determine the integration of architecture and robotics: (1) tolerances influencing the manufacturing processes; (2) the need for interfaces that provide a seamless digital information chain (in the case of the Flight Assembled Architecture prototype, computational design decides the quadrocopter's desired placing location, but it will not manage the trajectory and control of the vehicle); and (3) knowledge of different research methodologies and disciplines influence the research process and determine how comprehensively the research can be undertaken. In fact, the different research areas are faced with many problems, considerations, and conflicting issues, as is to be expected when pioneering a new field of research.

Determination of parameters, scale and fidelity requirements -

ARC is a multivariant field of research with no *a priori* set of parameters. Given the degree of its constructive differences, and difficulties relating to its fidelity for full-scale implementation, specific experiences for this research are not presently available. However, general conclusions can be made regarding varying levels of fidelity in small scale, and how these influence the outcome of different types of experiments. Thus, experimental research in ARC is challenged by the determination of a particular experimental scale and the selection of specific tasks that can be transferred to full-scale construction. The basic idea of scaling the experiments relates to performing research with the most realistic impact possible; it includes flying vehicles, material and construction system, fabrication and assembly sequences, and not least, the architectural design. Given these characteristics of full-scale fidelity, it can be accurately stated that ARC can be transferred to specific building tasks, and that these capabilities are definitely necessary when conducting this research.

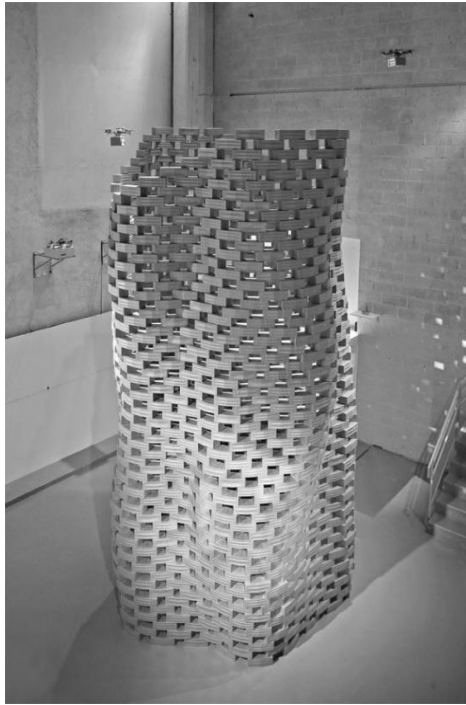
Multi-vehicle cooperation and dynamic structuring of space -

Multiple robotic agents can perform a desired action collectively in an intelligent dynamic constructive cooperation. In addition to direct collaboration, their work capacity is also to a large degree scalable, a trait that digitally controlled flying robots share with many other digitally driven technologies. In fact, flying vehicles can cooperate in many ways: as mentioned before, they can collaborate to lift heavy loads [38]. In addition, cooperation can be exploited during the assembly process. For example, two vehicles can carry two building parts (such as modules or bars) while another one helps them with the assembly. Consequently, multi-vehicle cooperation will allow the development of a flexible aerial construction system, but requires the investigation of the possibilities of collaboration between vehicles when defining the connection and assembly strategy at the very beginning of the constructive design. For this reason, the manufacture

of non-standard tectonic systems using multiple and autonomous flying machines requires a dynamic structuring of space. Here, the placing of building elements must be pre-determined, but must also be adaptable to building tolerances, interaction between vehicles, wind gusts and payload changes.

6. FLIGHT ASSEMBLED ARCHITECTURE

The installation Flight Assembled Architecture was developed as a collaboration between Gramazio & Kohler, the Professorship for Architecture and Digital Fabrication and the Institute for Dynamic Systems and Control. It takes a dynamic approach to construction, and provides a first experimental setup for the research on ARC. The project was exhibited at the FRAC Centre Orléans from December 2011 to February 2012 and included a utopian urban architectural vision, featuring particular aesthetic, structural and programmatic characteristics. It was the first architectural installation to be assembled by flying machines (see Figure 7). Conceived as a 600 meter high architectural structure (see Figure 8), the experiment used four quadcopters, building a scaled 6 meter tall tower out of 1500 polystyrene modules. Each module had a size of 30 cm x 15 cm x 10 cm, such that the thrust of the propellers would not be substantially blocked. Through the resulting porous arrangement of modules and the off-set of individual layers, a geometrically differentiated outer building envelope emerged that allowed a large degree of freedom for the spatial arrangement of the modules, their associated outside spaces, and the spaces between the modules. Similarly, the multiple folds in the formation resulted in the structure being self-stabilizing. The first conceptual design decision for the Flight Assembled Architecture project was to maximally use the height of the given exhibition space volume. This height is easily accessible by the flying vehicles without any human intervention or auxiliary construction but, even at this small scale, would be far beyond the reach of any ground-based articulated arm robot. To build the structure, glued modules were manually put into the pickup station. Then, the first available quadcopter landed on it, gripped the module and flew above the desired placing location to place the module. The overall flight behavior of the four quadcopters was generated by an algorithmic translation of digital design data: a network of intercommunicating computer programs used a real-time camera system [39] to guide the vehicles to specific locations for pickup and subsequent non-standard placement of each of the individual modules [40].



◀ Figure 7: The 6-meter tall tower of the Flight Assembled Architecture installation, assembled from 1500 lightweight modules by four quadcopters (Image © Francois Lauginie).



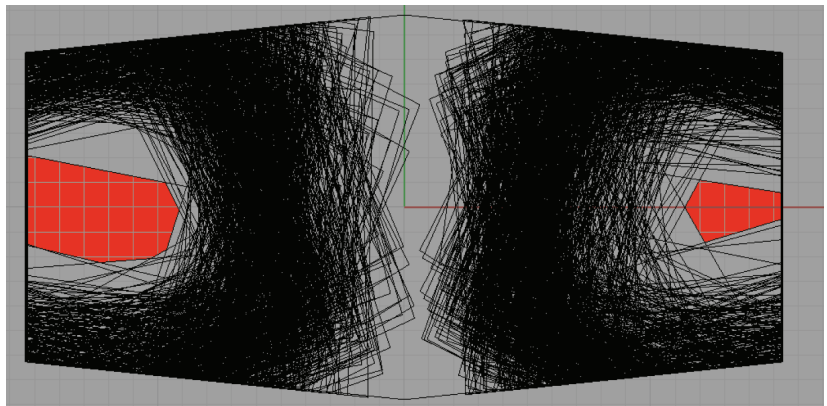
◀ Figure 8: The architectural concept of Flight Assembled Architecture – a 600 meter high “Vertical Village” for over 30.000 inhabitants (Computer rendering © Gramazio & Kohler).

An object-oriented approach was used for computationally generating the “blueprint” of the Flight Assembled Architecture installation, drawing on Python as programming language for an optimal integration of the original architectural design in Rhino, and the comprehensive math function library

connected with this software. As a first step, the architectural form of the building structure and its single components were abstracted into class models; this was followed by the parameterization of the geometry, such as the individual instantiation and the definition of the geometry's attributes (i.e. the number of modules). While the original architectural design was made in Rhino using NURBS-geometry, the curves defined each individual building layer as particular geometrical articulation. Additionally, this was adapted to particular structural and programmatic parameters.

However, the minimization of overlaps between individual building modules, gravity calculation, and the positioning of evaluators within the building structure, created an infinitely large solution space for the computational optimization (see Figure 9). Thus, a gradient method that defined the position of the single modules in real space was decided upon. The calculation of the gravity center of each module was prioritized and endowed with a particular tolerance factor to ensure a robust yet dynamic assembly.

► Figure 9: Algorithmical optimization of minimal overlaps of individual building modules, including the calculation of the gravity center of each module and the imprecision of the aerial robotic placement.



Against this background, the combination of robotic logics and strong computational and material orientation has become an essential concept of this experiment. Despite the complexity of the task, we purposely chose to examine in depth the specific dynamic characteristics of this combination, in order to unlock a new and interdisciplinary research direction for architecture. Even though the experiment has not proven fidelity or a constructive applicability for full-scale construction, it has successfully demonstrated a new method in architectural research and provided a specific computational design approach that can be transferred to ARC. For this reason, the consequences of this experiment are indeed multiple and intertwined, and cannot be reduced to a simple perspective.

7. CONCLUSION

In conclusion, the vision of ARC in architecture, in which a collective intelligence of flying vehicles is at the center of both the final form of the object and also the process of its construction, radically extends the traditional spectrum of architectural manufacturing methods and therefore creates a new level of robotic use in architecture. Most of all, aerial robotic technology pursues a shift in architectural computation where design decisions orchestrate dynamic manufacturing attributes. Speed is one such attribute, but even more essential for architecture is the attribute of timing. Synchronization (with events and processes like material supply and deposition, or the coordinated action with other vehicles) is essential to leveraging new architectural potentials. Thus, ARC fosters information penetration across the whole process of making, from the transport of single modules to the constructive assembly of highly informed architectural structures, opening up new ways of thinking about architectural design and materialization. On that scope, it is a vision of process, not just a product. However, flying robots of the size and capability that would be required to realize full-scale aerial construction do not yet exist. Further, the system requirements of this approach are task-dependent and thus, as of today, no consensus on what exactly ARC is, or how it can be investigated, has been characterized. As identified in this paper, preserving fidelity is an obscure concept that is being thrust onto architectural robotic as a way to identify effectiveness for this new field of research. Additionally, the amount of available research on this topic is not abundant, and no real experiments have ever been conducted in the field of architectural robotics. And yet this approach is captivating: ARC not only creates a new vision for architectural robotics, but also emphasizes new possibilities for the perception and understanding of it.

ACKNOWLEDGEMENTS

Most of the research presented in this paper results from the current cooperation between the Professorship for Architecture and Digital Fabrication (Prof. Fabio Gramazio, Prof. Matthias Kohler) and the Institute for Dynamic Systems and Control (Prof. Raffaello D'Andrea), both of ETH Zurich. The authors therefore thank their teams for their pioneering efforts on realizing the Flight Assembled Architecture installation, particularly Peter Heckerroth, Andrea Kondziela and Marion Ott (all Professorship for Architecture and Digital Fabrication, ETH Zurich) as well as Mike Hamer, Sergei Lupashin and Cason Male (all Institute for Dynamic Systems and Control, ETH Zurich). The authors are also grateful to the FRAC Centre Orleans (Co-Producer of the Flight Assembled Architecture installation) for both giving the opportunity of realizing such an experiment and its generous support in the overall project. Much of the Flight Assembled

Architecture project would have not been possible without the valuable support of Dr. Lüchinger + Meyer Bauingenieure AG, Amstein + Walthert AG and the Chair of Building Physics (Prof. Jan Carmeliet), ETH Zurich and Empa. The authors are also grateful for the sponsoring by Région Centre, Ministry of Culture and Communication (Direction Régionale des Affaires Culturelles du Centre), Pro Helvetia Swiss Arts Council, Centre Culturel Suisse Paris, Platform Regroupement des Fonds régionaux d'art contemporain, Vicon Motion Systems, ERCO Leuchten GmbH, and JET Schaumstoff - Formteile GmbH. An extra thanks goes to Hallie Siegel for her efforts on the editorial revision of this paper.

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1. This paper is based on a collaboration of the Professorship for Architecture and Digital Fabrication (Prof. Gramazio, Prof. Kohler) and the Institute for Dynamic Systems and Control (Prof. Raffaello D'Andrea), both of ETH Zurich. On that basis, an additional research proposal was submitted, providing substantial parts of writing for this paper. The paper is also settled on an essay by Matthias Kohler with the title "Aerial Architecture" in LOG#25, 2012.
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Jan Willmann, Federico Augugliaro, Thomas Cadalbert, Raffaello D'Andrea, Fabio Gramazio and Matthias Kohler

Institution: ETH Zurich, Professorship for Architecture and Digital Fabrication, Wolfgang-Pauli-Strasse 15, 8093 Zurich, Switzerland, and ETH Zurich, Institute for Dynamic Systems and Control, Sonneggstrasse 3, 8092 Zurich, Switzerland