*Green Design, Materials and Manufacturing Processes – Bártolo et al. (eds)*
*© 2013 Taylor & Francis Group, London, ISBN 978-1-138-00046-9*

# Architectural fabrication of tensile structures with flying machines

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ABSTRACT: The paper presents a manufacturing process for the erection of tensile structures with flying robots. Analogies are drawn to existing methods of aerial construction and robotic fabrication in architecture. Firstly, we describe a set of aerial building instructions for the vehicles, such as an assembly of a node and the erection of a link. Secondly, we investigate combinations of these instructions as prototypical structural arrangements and identify distinct characteristics for architectural production.

## 1 INTRODUCTION

The manoeuvre of aerial machines in construction is difficult and dangerous (Smith 2010). Today, manually operated flying vehicles are only used in challenging situations where no traditional construction method can be applied. However, new developments in sensing, computation and control allow to create autonomous flying machines that are able to perform complicated maneuvers in unstructured environments. The use of aerial robots opens up new possibilities in architectural production. This paper presents construction methods suitable for erecting tensile structures with flying machines (Fig. 1). It demonstrates the ability of a flying robot in construction to reach distant points in space and the unique skill to fly through and around existing objects while performing building tasks.

Figure 1. Autonomous erection of a tensile structure by a flying robot.

## 2 AERIAL ROBOTIC CONSTRUCTION OF TENSILE STRUCTURES

### 2.1 *Aerial construction*

Speculative architecture with flying machines exists for centuries. As a fantastic novel (Swift 1726), an architectural utopia (Krutikov 1928) or a hypothetical concept (Cook 1969), aerial architecture has always been a research interest.

In architectural fabrication, flying machines are applied on construction sites since the 1950's (Carter et al. 1963). Helicopters in construction are most commonly used to lift building materials and to transport it to remote locations with no access to streets. In highline construction such aerial cranes carry power poles to designated locations where they are assembled by workers on the ground. Helicopters are also applied to lift rotors for the erection of wind wheels or to string cables for the construction of suspension bridges (Cooper 1998). Another method of construction with aerial vehicles is the use of balloons (Gablenz & Spaltmann 2011) using lighter than air technology to generate lift. The balloons filled with helium hoist construction elements similarly to a crane. The position of the balloon and its cargo is controlled by individually adjusting the length of three cables connecting the balloon to the ground. A third technique of aerial construction was presented for the assembly of the Siduhe River Bridge (Wang et al. 2009). The installation of the suspension cables across the 500 m deep valley began with the placement of two pilot cables. The 1300 m long ropes were attached to two rockets and fired over the canyon to erect a link between the two sides.

### 2.2 *Flying robots in architectural research*

Research on robotic construction in architecture dates back to the early 1990s (Andres et al. 1994). Although highly advanced, these developments did not find access to the market since they were not flexible enough to adapt and react in different design situations (Gramazio & Kohler 2008). In the course of the recent shift towards digital technologies in architecture, universities have set up research facilities for construction with industrial robots resulting in adaptable (Helm et al. 2012) and sustainable (Oesterle et al. 2012) construction methods. Such novel technologies motivate new approaches to the design of architectural structures and advanced constructive systems. However, conventional robotic systems have predefined working areas. Stationary robotic arms or CNC-machines have a limited scale of action, constraining the size of the work-piece they act upon. These machines are usually smaller than buildings. This limits their use in architecture to the scale of a small artifact or building component (Kolarevic 2003). Mobile robots like dimRob (Helm et al. 2012), extend the working range of the machine in two dimension but are still constrained in elevation. Flying machines, however, do not have such tight boundaries of movement. The space they act upon is substantially larger than they are themselves making them apt to work at the full scale of architecture. The vehicles are not fixed to a base. This allows them not only to reach points in space otherwise not accessible by conventional machines but also to fly through and around existing objects while performing construction tasks. This unique feature has no other computer controlled construction machine today.

Research in aerial construction with flying robots is a recent topic. The Flight Assembled Architecture installation (Willmann et al. 2012) demonstrated the ability of quadrocopters to autonomously erect a highly differentiated structure by assembling a 6 meter tall tower out of 1500 foam elements. First steps into aerial construction with quadrocopters were also demonstrated by building cubic structures consisting of bars containing magnets (Lindsey et al. 2013). The ARCAS project (ARCAS 2011) focuses on aerial assembly by helicopters equipped with robotic arms. In parallel, hover-capable Unmanned Aerial Vehicles (UAVs) such as quadrocopters (Michael et al. 2010) and ductedfan vehicles (Marconi at al. 2012), and their interaction with the environment are nowadays a research topic in many groups.

Today, quadrocopters offer an excellent compromise between payload capabilities, agility and robustness (Mahony et al. 2012).

### 2.3 *Tensile elements as constructive material*

Research into construction with flying machines requires on the one hand the development of adequate methods for hovercapable UAVs to physically interact with the environment and on the other hand, the investigation of light material systems and new constructive processes that are both robotically transportable and configurable at heights (Kohler 2012). In this context, this paper explores, with a series of experiments, the building of lightweight tensile structures by quadrocopters. Tensile elements, such as cables, are relatively lightweight, have a high structural strength and can span large distances. Objective of the investigation was the development of a set of building instructions for the vehicles to erect and manipulate tensile building elements. Different combinations of these instructions result in the realisation of different tensile structures. Therefore, we first defined characteristic instructions for the construction and translated them later into trajectories for the quadrocopters. Various configurations of these instructions were then tested to erect distinct prototypical formations of tensile structures. Experimental results validate the feasibility of the approach.

## 3 PARAMETRIC BUILDING INSTRUCTIONS

The flying vehicles lift, place and connect the linear building material to existing objects or already built structural components. The flexible tension elements dynamically react to the behaviour of the quadrocopters they are connected to. The sequencing and trajectory of the vehicle therefore directly influences the construction. In this section we present the basic building primitives we have used during the assembly processes.

### 3.1 *Node*

A node is a point of intersection of the cable with another object (Fig. 2) or with another

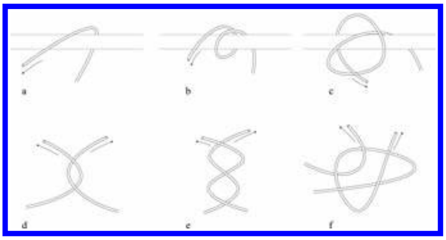

Figure 2. Node building instructions. a) Single turn hitch, b) (Multi-) round turn hitch, c) Knob, d) Elbow, e) Round turn, f) Multiple ropes knob.

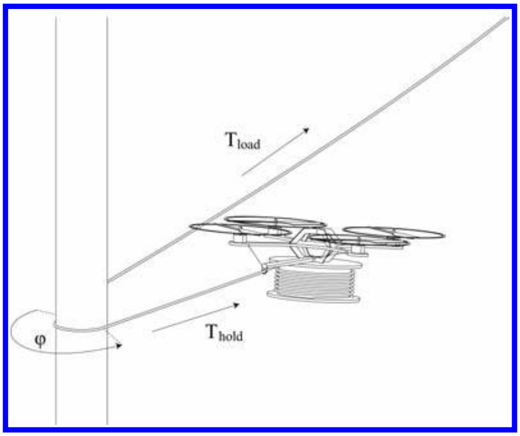

Figure 3. A small holding force on one side can carry a much larger loading force on the other side.

cable element. The material characteristics of the construction elements are used to connect to the support point by tying or weaving around it (Fig. 3). Following the capstan equation (Morten & Hearle 1993), depending on the coefficient of friction (μ) between the cable and a support point, and the amount of turns around the object (angle in radians φ), the loading force ($T_{load}$) can be calculated from the holding force ($T_{hold}$).

$$T_{load} = T_{hold}\, e^{\mu\varphi} \tag{1}$$

This allows to parametrically design the nodes. It can be specified whether it is a gliding connection (Fig. 2a) or a fix node with a large holding force. Because of its exponential nature, a few rotations around an object already prevent the unreeving of the cable and hence generate a knot (Ashley 1944).

### 3.2 *Link*

A cable spanned between two structural support points generates a link. During the fabrication process we distinguish between static and dynamic supports. Already existing structural elements are static supports. The flying vehicles manipulating and guiding the cables from one static support to another are dynamic supports. The flying vehicles are controlled by appropriate methods that enables them to track desired trajectories and apply a desired force to the cable (Augugliaro & D'Andrea 2013). Furthermore, the vehicles automatically orient themselves along the cable direction, allowing for a smooth cable deployment. The tension of each link can be defined parametrically (Fig. 4).

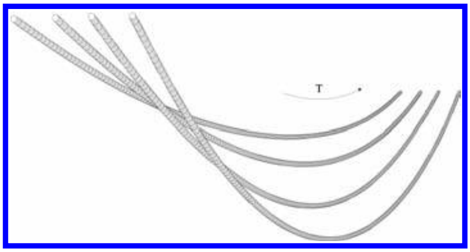

Figure 4. Control algorithms allow to apply a desired force (T) on the cable when spanning a link.

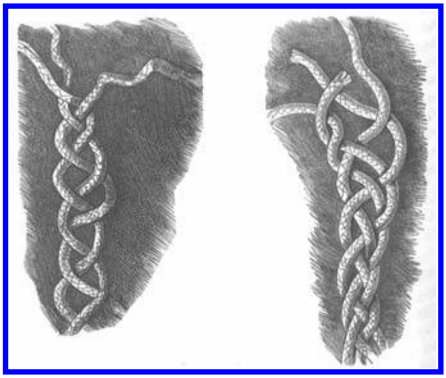

Figure 5. A braiding (Semper 1860) could not be constructed by a single UAV. However, the cooperative sequencing of three vehicles would allow to assembly the braid on the left. Four machines could produce the braid on the right.

### 3.3 *Multivehicle cooperation*

Digital control of the robots enables the vehicles to communicate and synchronize their actions among themselves. The machines can collaborate to lift particularly heavy loads (Micheal 2010). In addition, cooperation can be exploited during the assembly process. The vehicles don't merely distribute the workload among themselves but perform building tasks an individual machine could not accomplish alone, independently of the payload capacity. The flying robots can have complementary abilities with different skills. During the manufacturing of a node, for example, where the working end of a cable has to be carried through a loop (Fig. 2f), one vehicle could guide the working end while another forms the loop for the first one to fly through. However, working with multiple vehicles poses additional challenges. For example, the wash generated by the propellers of one vehicle could affect the performance of the others. Despite these difficulties, the cooperative performance of multiple flying machines widens the spectrum of possibilities in architectural production (Fig. 5).

### 3.4 *Experimental setup*

The experiments are performed in the Flying Machine Arena (www.FlyingMachineArena.org), a 10 × 10 × 10 meter indoor space for aerial robotic research. The space is equipped with a motion capture system that provide vehicle position and attitude measurements. This information is sent to a PC, which runs algorithms and control strategies and sends commands to the quadrocopters. The vehicle of choice are quadrocopters. These flying robots have demonstrated their dynamic capabilities performing flips (Lupashin et al. 2012), balancing poles (Hehn et al. 2011), learning fast maneuvers (Schoellig et al. 2012) and juggling balls (Muller et al. 2011).

The vehicles are equipped with a cable dispenser and a roller on which the tension elements are wound up. The friction of the roller can be adjusted and thus influencing the tension of the cable during its deployment. For the experiments described in this paper we worked with Ultrahigh-molecular-weight polyethylene rope (Dyneema). The material stands out due to a low weight-to-strength ratio, making it suitable for aerial manipulation. A 100 m long rope with a diameter of 4 mm weighs 1.1 kg and supports 1400 kg. The method allows to install different kinds of tensile elements such as cables, ropes or wires. The further description refers to the tensile elements as cables.

## 4 STRUCTURAL TYPOLOGY

Following the definition of a set of building instructions, we present in this section distinctive combinations of them, forming characteristic structural elements.

### 4.1 *Linear structure*

The linear structure is a tensile element spanning between two support points. It arranges a node, fastening the cable to an existing structural element and establishes a link, arranging an additional node at a second support point (Fig. 6).

With this basic building element, we demonstrate the ability of a flying machine to reach any point in space in order to erect a structure. Whether it is a link between two skyscrapers or a connection over 500m deep valley, the vehicle performs this task independently of the conditions on the ground. The tensile strength of the structure can be increased by adding additional links between the two supports.

### 4.2 *Surface structure*

The two-dimensional intersection of linear structures constitute a surface structure (Fig. 7). The vehicles establish nodes and link the tensile elements to a structural entity. The loads and stresses of the intersecting members interact to find a structural equilibrium. The form of the structure adapts to the loads applied to it and hence dynamically changes during the deployment of additional nodes.

Figure 6. Linear structure. The vehicle autonomously fastens the cable at the existing structure before spanning the link.

Figure 7. Surface structure. The vehicle constructs a planar structure by flying through and around built components.

The surface structure experiment demonstrates the ability of the flying machines to fly through and around already constructed members of the structure while manipulating it. This is a unique feature of aerial machines. Conventional robotic arms in contrast would intersect with the structure while performing this manoeuvre.

### 4.3 *Volumetric structure*

The three-dimensional intersection of linear structures establishes a volumetric structure. Similarly to the surface structure described above, the volumetric structure members seek a tension equilibrium. Varying the tension on individual links

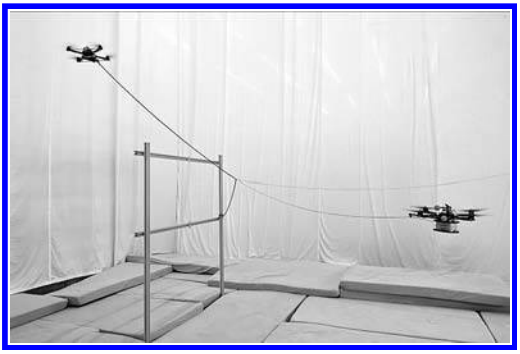

Figure 8. Volumetric structure. Two vehicles cooperate in order to accurately position a node in three-dimensional space.

allows to shift the position of a single turn node in space. Additional degrees of freedom can be added by having two vehicles cooperating. The vehicles can freely place a connection in space by performing a synchronised node manoeuvre at the designated position (Fig. 8). The controlled situating of a node within the design space could not have been done manually and demonstrates the possibility for new forms of architectural materialisation.

## 5 CONCLUSION

Architectural fabrication with digitally controlled flying machines is a new research direction, still in its fledgling stages. The construction method introduced in this paper, addresses the ability of flying machines in architectural production. It takes advantage of the capability of the vehicles to reach any point in space, allowing robots to erect suspending structure at locations otherwise not accessible by conventional construction machines. Further on, it makes use of the unique skill of aerial machines to manoeuvre in and around existing objects to fasten construction elements, and to fly in and around already built structural elements to manipulate them. Finally, it shows the knack to add degrees of freedom by multivehicle cooperation during the fabrication process, allowing to position nodes freely within the three-dimensional space.

From the architectural as well as from the robotic perspective, various aspects of the approach seek further exploration. The fabrication process is less constrained by traditional assembly and build up parameters, such as the need to build from the ground up. This profound difference calls for new design strategies incorporating nonlinear fabrication sequencing to materialise architecture that could not have been built before.

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