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Aerial Construction

Robotic Fabrication of Tensile Structures with Flying Machines

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Abstract

This thesis investigates the architectural potential of aerial construction using flying robots. Because aerial robots are kinematically decoupled from their environment, they offer distinctly new forms of construction as compared to conventional ground-based construction devices. First, the range of aerial robots is not limited by their size, making them capable of operating at full architectural scale. Second, their ability to move autonomously through and around existing structures makes them ideal for intertwining building material. When these abilities are combined with control algorithms that enable the aerial robots to cooperate and perform construction tasks together, entirely new building forms become possible. Ultimately, the three-dimensional freedom of aerial robots enables them to build structures that conventional machines cannot.

This thesis positions aerial robotic construction as a new research topic situated within the traditions of digital fabrication and architecture. The research analyses the specific constraints of aerial robotic construction as a design space, and the specific abilities and constraints of aerial robots as a construction tool that can move freely through the air. The thesis subsequently identifies spatial interweaving of tensile rope structures as an appropriate construction technique for building load-bearing architectural structures, and lays out a methodological framework for designing and constructing airborne tensile structures using quadrocopters. A series of building experiments validate the developed techniques and describe a coherent design and construction process. Ultimately this research brings forward a new perspective on the spatial aggregation of material using robotic processes, and on digitally fabricated architecture as a whole.

Abstract

Im Zentrum der Arbeit steht die Untersuchung des architektonischen Potenzials von Bauprozessen mit fliegenden Robotern. Im Gegensatz zu fest installierten, auf dem Boden stehenden Maschinen, sind Flugroboter nicht an einen statischen Arbeitsbereich beschränkt, sondern können sich frei im Luftraum bewegen. Damit wird eine völlig neue Räumlichkeit der computergesteuerten Fertigung in Aussicht gestellt. Das heisst, der Bauraum von Flugrobotern ist nicht auf die eigene Grösse begrenzt. Vielmehr kann dieser nahezu beliebig ausgedehnt werden – bis hin zum architektonischen Realmassstab. Zudem können Flugroboter digital gesteuert werden; sie können daher autonom operieren, gezielt kooperieren und komplexe Bauaufgaben ausführen. Darüber hinaus führt die erweiterte Erschliessung des Bauraumes zu einer neuartigen konstruktiven Autonomie: Material kann vollkommen frei im Raum platziert werden und gebaute Strukturen können von den Flugrobotern um- und durchflogen werden. Das Bauen mit fliegenden Robotern geht über konventionelle Ansätze der digitalen Fabrikation hinaus und erlaubt dreidimensionale Bauprozesse, die bisher unmöglich waren.

Das Bauen mit fliegenden Robotern stellt einen vollkommen neuen Forschungsansatz in der Architektur dar. Die vorliegende Arbeit positioniert dieses Thema als Teilgebiet der digitalen Fabrikation und untersucht die zugrundeliegenden Entwurfs- und Konstruktionsansätze, die für einen solchen Ansatz notwendig sind. Hierin zeigt die Arbeit auf, dass gerade die Assemblierung von Seilnetzstrukturen einen interessanten, geradezu idealen konstruktiven Ansatz für das Bauen mit Flugrobotern darstellt. Infolgedessen werden experimentelle Methoden und Techniken vorgestellt, um geometrisch komplexe Seilnetzstrukturen mit fliegenden Robotern zu entwerfen und bauen zu können. Dabei steht die wechselseitige Verknüpfung von Entwurf und Fertigung zentral, ebenso wie die Umsetzung im architektonischen Massstab. Dies erlaubt nicht nur eine gänzlich neue räumliche Perspektive auf zukünftige roboterbasierte Bauprozesse, sondern ebenso auf digital fabrizierte Architektur insgesamt.

Acknowledgements

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Contents

Chapter 1

Introduction

This thesis presents a methodology for designing and constructing architecture with flying machines. It investigates the flying robot as a novel construction machine, identifies the fabrication of tensile structures as a suitable construction technique, and develops and experimentally validates appropriate design and fabrication techniques in order to examine the potential of aerial robotic construction.

1.1 Prologue

The digital design space (in which architecture is represented) and the physical building space (in which it is materialised) are converging [1], and as this happens, the traditional relationship between designer and artefact is being called into question. Conventional architectural processes (whereby architects use technical drawings to translate design information into a set of building instructions, which are then passed on to craftspeople who interpret the conceptual design and bring it to material realization) tended to decouple the designer from the final result. Now, the mainstream adoption of digital design and fabrication tools is directly linking the process of design with the process of making. As production is increasingly transferred from mechanically operated devices to computer controlled machines, the skills of the designer become explicitly coupled with the artefact [2, pp. 237-38].

Yet, while popular publications argue that digital fabrication is about to create a "third industrial revolution" [3, 4], the machines that should enable this "revolution" have already existed for half a century. The CNC-machine was developed in the 1950s, six-axis industrial robots have been on the market since the early 1970s, and 3D printers since the early 1980s [5]. And yet computer-aided manufacturing was predominantly regarded as an advanced instrument of production rather than a tool that would also inform architectural design; it is only through a combination of *availability* (of off-the-shelf technology) and *accessibility* (caused by new control interfaces) that these tools have become ubiquitous in architecture [2, 6].

Recent improvements in sensing, computation, and control have led to the development of machines with capabilities that are profoundly different from those of conventional mechanical devices and traditional computer-aided manufacturing tools. The newest generation of autonomous[1] devices can adapt their behaviour to their environment and even learn from their own actions [7], making them significantly more agile, precise, and responsive than earlier tools.

Aerial robotic construction offers a new approach to architecture. [8, p. 267] Today, architectural design and fabrication with robotic systems[2] is predominately associated with industrial robotic arms [9,10], and traditionally, machines assisting in the construction of architecture or the fabrication of building components stand on the ground. A crane requires a solid base to mechanically lift, lower, and move material. The arm of an industrial robot or the linear tracks of a CNC-machine ensure precision through mechanical kinematic connection of their movable parts to a stand. The flying machine, in contrast, is physically decoupled from its working space. It can perform construction tasks that are not limited by the same constraints as ground-based machines [2,8,11,12]. The operating range of a flying robot is not constrained by the size of the machine, enabling it to work at the full scale of architecture. Additionally, digital control enables aerial robots to cooperate and perform complex construction tasks that an individual machine would not be able to accomplish on its own. Critically, flying robots can manoeuvre building material between and around structures, providing a new spatial autonomy for aggregating material in three-dimensional space, and thus allowing them to build architectural artefacts that other construction machines could not. As with industrial robots, aerial robots can be instructed directly by linking them to a digital design blueprint; they are also generic, and can be equipped with different tools to transport and manipulate material in various ways, potentially allowing them to be applied to a variety of construction tasks. While numerous applied and academic studies have investigated the use of industrial robots in architecture, research in architectural fabrication with flying robots is still in its fledgling stages – even though aerial robotic fabrication represents a logical step towards more freedom in robotic fabrication and directly connects to existing digital fabrication techniques. The aim of this thesis is to fill that gap and develop methods and techniques for the design and realisation of tensile architectural structures with flying robots.

1.2 Statement of problem

Building structures with flying robots is a new field of research, both in architecture and in robotics-related disciplines. There are currently few published works on this subject (see Chapter 2.4), and the design and fabrication potential of aerial robots in architecture is largely unexplored. To bring forward the field of aerial robotic construction and to extend it towards a specific application, the research herein develops a construction system that is:

- load bearing;
- robotically constructable and informed by a digital design;
- distinctively buildable only with aerial robots; and
- applicable to an architectural use case.

1.3 Methodology

If robotic aerial construction is to be validated within the fields of architecture and digital fabrication, several fundamental challenges must first be addressed:

- The underlying constraints of aerial construction must be defined before an appropriate aerial construction method can be developed.
- Specific aerial construction techniques and design methods must be developed concurrently, and must be fitted to the chosen aerial construction method.
- The findings of the research must be validated by physical experiments.
- Both the design methods and the physical experiments require competence from multiple disciplines, including architecture, robotics and systems control.

For these reasons, this thesis uses an exemplary case study methodology and an interdisciplinary research team to explore the specifics of whether and how aerial robots can be used in architectural construction.

1.3.1 Aerial construction constraints definition

Flying robots possess a number of specific constraints that distinguish them from other robotic fabrication devices. These constraints shall not be viewed herein as limiting factors [13, pp. 59-62], but rather as a motivation to identify an appropriate construction method in which the unique potential of aerial robots can unfold. Using analytical and empirical processes, this research investigates the constraints of aerial robotic construction within the following categories:

- Machine: related to the specific abilities of the flying machine, for example the degrees of freedom when moving through the air
- Material: related to the material characteristics, such as the relation between weight and strength of the building material
- Construction system: related to the aggregation of material, for example to span space and create structures with a minimum of material
- Design: related to the design method, for example to relate architectural geometry with a coherent construction sequence

Once the constraints were defined and analysed, *construction of tensile structures* was identified as a distinct application area for aerial robots that exploits the unique abilities of these machines.

1.3.2 Construction techniques development

To test the applicability of flying robots for the construction of tensile structures, a series of techniques and tools must first be developed. On the one hand, it is necessary to develop a systematic understanding of the kind of tensile structures that are buildable with the proposed system and to test the underlying building primitives with empirical experiments. On the other hand, the chosen construction method requires the development of computational tools to simulate and support the design process while incorporating construction constraints.

1.3.3 Experimental implementation

The research approach is experimental. Basic building primitives of tensile structures, such as knots and links, are tested in individual experiments. Finally, a full-scale architectural prototype is realised in order to validate the approach.

Interdisciplinary approach

Flying robots have existed for only about a decade. Autonomous Unmanned Aerial Vehicles (UAVs) and their dynamic interaction with the environment are nowadays a prominent research topic in many robotic groups. These machines have been only marginally investigated in architectural production, however. Because integration of architecture and aerial robotics requires competence from different disciplines, the research presented here is based on an interdisciplinary collaboration with Professor Raffaello D'Andrea of the Institute for Dynamic Systems and Control (IDSC) at ETH Zurich. His group has developed the Flying Machine Arena (FMA), a testbed for aerial robotic research. The experimental implementation of this work has been conducted in the FMA in collaboration with IDSC PhD student Federico Augugliaro. His work has focussed on 1) the development of appropriate control strategies for the vehicles to physically interact with the environment; and 2) the development of an actuated rope dispenser (see project credits) [14].

1.4 Outline of chapters

Six chapters form the body of this thesis, while a series of appendices provide further information and document supplementary experiments related to the subject matter.

After this introductory chapter, Chapter 2 contextualises the exploration of flying machines within the discipline of architecture and technology. It reviews previous work and identifies aerial robotic construction as a novel topic of research situated within the tradition of mechanised manufacturing and the field of digital fabrication in architecture.

Chapter 3 investigates the overall fabrication constraints of aerial robotic construction. It draws analogies to other methods of construction and outlines the dependences according to the machinic, material, and structural system. The chapter concludes by identifying the fabrication of tensile structures as an appropriate construction method for flying robots.

Chapter 4 describes the techniques and tools that have been developed in order to implement the aerial robotic construction of tensile structures in physical experiments. It also introduces the basic building primitives needed for their construction. Finally, it discusses the computational components enabling the design of structures in negotiation with the fabrication constraints.

Chapter 5 validates the research by implementing the developed construction method through physical prototypes. A series of basic experiments test the individual building primitives, and conclude with the realisation of a full-scale architectural artefact – a suspension footbridge – that cross-references the research subject.

Chapter 6 summarises the results and provides an outline for future work in this field.

Appendix A explores historic precedents of aerial vehicles in architecture. Appendix B investigates the use of flying vehicles in construction engineering. As a final point, Appendix C investigates the use of flying robots in assembling non-standard space frame structures.

Notes

[1]The differentiating factor between conventional automatic systems and autonomous systems is the ability to make decisions. An automatic system will do exactly as programmed, whereas an autonomous system is able to make decisions on its own after it has been launched. [15]

[2]A robot is a programmable computer-controlled electromechanical machine that can be retooled and reprogrammed to perform a wide variety of tasks. [16, p. 3]

Chapter 2

Context

Aerial robotic construction is a novel area of research and little published work on this topic currently exists. However, as this chapter will show, the exploration of flying robots in architectural production builds on established methods of manufacturing and connects to work in the field of digital fabrication. Furthermore, it shows that the flying machine has influenced 20th century architecture[3] by inspiring experimental architectural expression, and by creating a fundamental shift in the way architecture is produced. The objective of this chapter is therefore to: 1) position the flying robot within the tradition of mechanised production in architecture, and 2) to show its significance to the architectural discourse, both as an epistemological tool for architectural design (see Chapter 6.2.1) and as tool in establishing new methods of production.

The relationship between mechanical machines and architecture has been dynamic over the last century. Early experimental machines inspired designers to speculate about new kinds of architecture. However, the mechanised assembly lines and standardisation in production that followed the conceptual union of architecture and the manufacturing industry were grounded in the separation of design and making [5, p. 38]. In order to increase productivity in manufacturing, the variety of building elements had to be minimised and the building forms standardised. The designing of architecture thus became disconnected with its material realisation. The present shift from mechanical production machines to reprogrammable robots once again transforms the relationship between architect and artefact, as digital design data can both represent an architectural artefact *and* contain the fabrication information to robotically realise it.

Computer-controlled architectural production results in fundamentally different building forms than those created by manual fabrication processes [17]. This difference, however, is mostly based on formal aspects (for example freeform building envelopes). Differentiation in material aggregation and the creation of non-standard architecture rationalises the use of computer aided fabrication. Nowadays this re-engagement of architecture with technology is based mostly on the investigation of material processes with well-established production machines from the automated manufacturing industry, such as CNC-machines and industrial robots. As such, the very tools that are used to realise this new, non-standard architecture in fact stem from the era of the mass production of identical part. The flying robot challenges this development. In contrast to established devices, it is a novel machine that, like the early flying machines of the 20th century, is capable of inspiring experimentation in tectonic form. As such, this chapter argues that the flying machine in general, and the flying robot in particular, acts as a catalyst for architectural conception and material expression.

2.1 Aerial experimentation in architecture

In 1927 in New York, a pioneering architectural exhibition confronted the American public with a new visual image: the aesthetic of the machine. Titled the *Machine-Age Exposition*, the exhibition brought together "architecture, engineering, industrial arts and modern art" [18, 19, p. 70] and featured actual machines, apparatuses, photographs and drawings of machines, alongside architectural drawings, models, paintings and sculptures from avant-garde architecture and art. In so doing, the exhibition positioned the engineer as a creative and aesthetic force in the context of the advanced industrialization that had swept across Europe and America:

> "There is a great new race of men in America: the Engineer. He has created a new mechanical world, he is segregated from men in other activities ... it is inevitable and important to the civilization of today that he make a union with the architect and artist. This affiliation will benefit each in his own domain, it will end the immense waste in each domain and will become a new creative force. [...] The men who hold first rank in the plastic arts today are the men who are organizing and transforming the realities of our age into a dynamic beauty. They do not copy or imitate the Machine, they do not

worship the Machine, they recognize it as one of the realities. In fact it is the Engineer who has been forced, in his creation, to use most of the forms once used by the artist ... the artist must now discover new forms for himself." [20, p. 36]

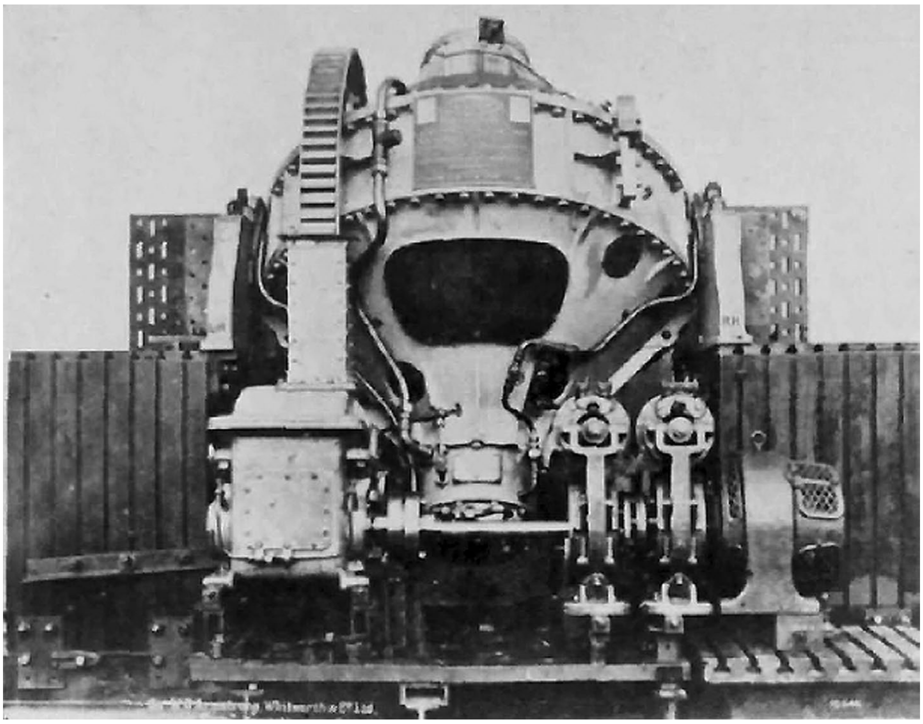


Fig. 2.1: An aesthetic inspiration for architectural design: prototype of a gyroscope stabiliser by E. Sperry, displayed at the *Machine-Age Exposition* [20, p. 38]. Such gyroscopes could weigh several hundred tons and were used to stabilise boats. Today, digital gyroscope modules are used in flying robots (see Chapter 3.1).

The exhibition's curator, Jane Heap of the *Little Review*, argued that machines, ignorant to aesthetic laws, created a new plastic mystery. While focusing on utility, engineers created beauty accidentally. The exhibition therefore proclaimed a "plastic-mechanical analogy" for architectural design [20]. Still, many devices that were displayed at the exhibition (Fig. 2.1) were at that time prototypes or experimental in nature. While most of the devices inspiring architectural design had a clear function, many of them were actually not functional, for example many of the early flying machines (Fig. 2.2). Motivation for inventive technology was not solely based on utilitarian reasoning. It was stimulated by wonder and had to do with human experience and the discovery of the world [21, p.11]. As such, designers in Europe, Russia, and America developed experimental and expressive architectural concepts based on a machinic paradigm. Many of these concepts were never realised (or were speculative in nature and never supposed to be realised). However, the ideas and images they created influenced generations of architects to come. In the early 20th century, in Italy, for example, the *Futurists*[4], created radical architectural concepts based on scientific discoveries, such as the airplane.

2.1.1 The flying machine as aesthetic inspiration

One of the technological outcomes of the industrial era was the possibility for humans to experience speed. The *Futurists*, mainly inspired by the motor car and the airplane, believed in a new world based on acceleration and dynamics. In 1908, Filippo Tommaso Marinetti, poet and founder of the movement, published the influential *Manifesto of Futurism*, stating[5]:

> "We affirm that the world's magnificence has been enriched by a new beauty: the beauty of speed. A racing car whose hood is adorned with great pipes, like serpents of explosive breath - a roaring car that seems to ride on grapeshot is more beautiful than the Victory of Samothrace." [23]

The movement suggested that art should go hand in hand with science, and that it should be violent and reflect the mechanistic dynamism of the world. In 1914, Antonio Sant'Elia presented his vision for a futurist architecture:

> "We must invent and rebuild the Futurist city like an immense and tumultuous shipyard, agile, mobile and dynamic in every detail; and the Futurist house must be like a gigantic machine. The lifts must no longer be hidden away like tapeworms in the niches of stairwells; the stairwells themselves, rendered useless, must be abolished, and the lifts must scale the lengths of the façades like serpents of steel and glass. The house of concrete, glass and steel, stripped of paintings and sculpture, rich only in the innate beauty of its lines and relief, extraordinarily "ugly" in its mechanical simplicity, higher and wider according to need rather than the specifications of municipal laws." [24]

The translation of speed and kinetic movement into something static like architecture was not as uncompromising as the manifesto proclaimed. Reyner Banham later argued [25] that the architecture of the Futurists was not able

Fig. 2.2: Experimental flying machines. Top left, Maurice Léger, helicopter, 1907. Top right, George White, Ornithopter, 1928. Middle, Alexander Graham Bell, Cygnet, 1907. Bottom, flying apparatus of Ellyson, 1932. [22]

to reflect the dynamism of the new machines without mimicking their formal vocabulary [26, p. 27]. Apart from a few exceptions (for example the Fiat Lingotto Factory), the concept of Futurism was not realised by the architectural discourse that followed. Sant'Elia never built a building. However, it presented an alternative perspective in a period of time when everyone was looking for a new direction. It created an architectural perception that was based on the machinic and it introduced the flying machine to architectural conception. The flying machine became a prominent source for stylistic design inspiration and influenced later developments in architecture, such as de Stijl, Constructivism, and the International Style [27, p. 447]. Where *Futurist* architecture predominantly presented an aesthetic representation of the flying machine, the Constructivists shifted the concept of aerial machines in architecture towards a more experiential principle, where flying machines became part of the architectural experience.

2.1.2 The flying machine as experiential generator

Pioneering a new social and political order, constructivist architecture in the Soviet Union in the 1920s combined advancements in technology and engineering with rational design, often incorporating kinetic elements, such as mechanical devices for movable building elements like walls and ceilings. These machine-inspired designs also often used flying machines such as airships and balloons (see Appendix A) to formulate a novel architectural culture that would incorporate and transport the new technological possibilities. Many of the radical concepts remain unbuilt. Developed by exponents like Ivan Leonidov, Georgy Krutikov, Vladimir Shukhov, and Vladimir Tatlin, a new architectural-political language symbolising everyday life in the Soviet Union was adopted by traditional architects in the construction of state buildings and factories. Social realism ended the movement at the beginning of the 1930s. While flying machines and cars have influenced the formulation of constructivist architecture, the group also developed experimental machines themselves. Painter and architect Vladimir Tatlin (designer of the unbuilt kinematic monument for the Third Communist International, a 400 m tall double helix tower containing rotating structures), for example, proposed in one of his last projects, the Letatlin, a muscular powered flying apparatus (Fig. 2.3). The Letatlin ("letat" meaning "to fly") was intended to become an everyday item, similar to a bicycle. This "air bicycle" was supposed to liberate the working class from the confines of gravity and enable them to move freely in space. He stated:

> "The dream is as old as Icarus... I too want to give back to man the feeling of flight. This we have been robbed of by the mechanical flight of the aeroplane. We cannot feel the movement of our body in the air." [28, p. 213]

The Constructivist successfully integrated the flying machine, not just as a visual image, but as a substantial part of the human experience of designed space. As such, different flying machines created different kinds of architectural conditions. The Modernist reconceptualised the the flying machine, too, viewing it as an inspiration for architecture in the way it was *designed and produced* rather than as an aesthetic representation or an integral part of a building.

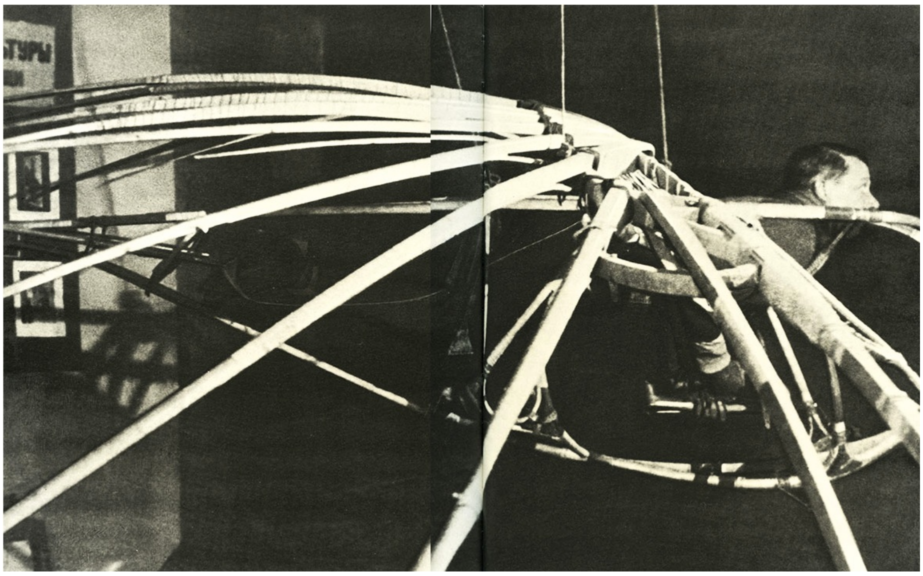


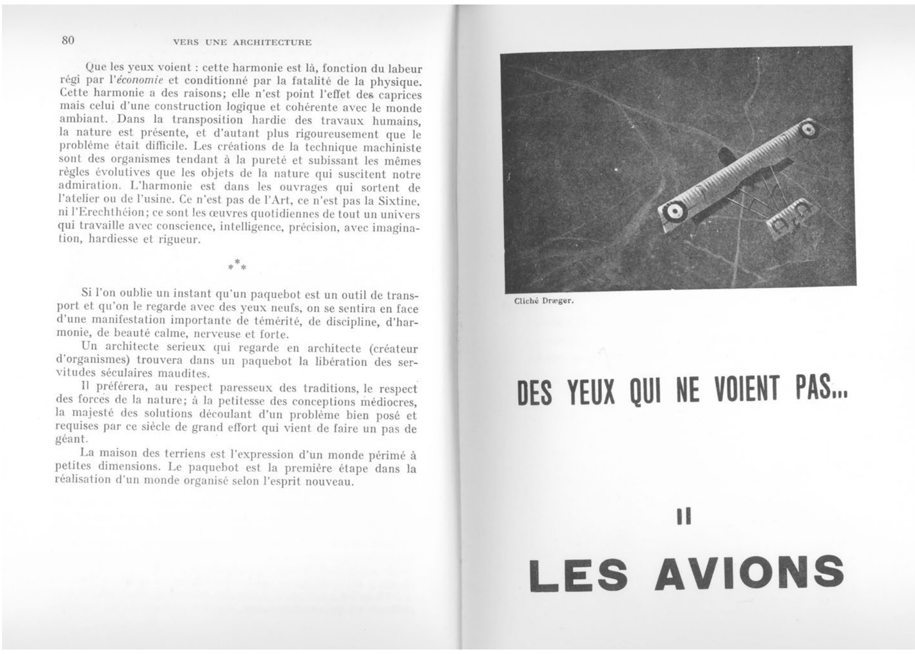
Fig. 2.3: The Letatlin, without its covering fabric, exhibited in the Pushkin Museum of Fine Arts in Moscow, 1932. Tatlin demonstrates the control of the Flying Machine. [28, p. 217]

2.1.3 The flying machine as production symbol

Vers une architecture [29] was Le Corbusier's first book on architecture and one of the most influential architectural texts of the 20th century. Its seven essays formulate and proclaim, in manifesto-like form, a modern architecture. Alongside the illustrations of Roman and Greek classical architecture, the essays display images of mechanical machines, such as turbines and ventilators, and of large-scale industrial buildings, such as grain silos. The book praises mechanisation and suggests that contemporary technology is to be held up as a catalyst for contemporary architecture [25, p. 228].

One section of the book, *Eyes Which Do Not See*, argues that the Machine Age had already produced objects that followed the proclaimed principles, for example, the ocean liner, the automobile, and the aircraft (Fig. 2.4). While architecture lost its way in a debate about different styles, the world around had been transformed by the "reason of the machine". Le Cobusier claimed that there was a lesson to be drawn from the mechanised instruments of modern transportation:

> "The airplane is the product of close selection. The lesson of the airplane lies in the logic which governed the statement of the problem and its realisation. The problem of the house has not yet been stated. Nevertheless there do exist standards for the dwelling-house. Machinery contains in itself the factor of economy, which makes for selection. The house is a machine for living in." [29, p. 107]



80 VERS UNE ARCHITECTURE

Que les yeux voient : cette harmonie est là, fonction du labeur régi par l'*économie* et conditionné par la fatalité de la physique. Cette harmonie a des raisons; elle n'est point l'effet des caprices mais celui d'une construction logique et cohérente avec le monde ambiant. Dans la transposition hardie des travaux humains, la nature est présente, et d'autant plus rigoureusement que le problème était difficile. Les créations de la technique machiniste sont des organismes tendant à la pureté et subissant les mêmes règles évolutives que les objets de la nature qui suscitent notre admiration. L'harmonie est dans les ouvrages qui sortent de l'atelier ou de l'usine. Ce n'est pas de l'Art, ce n'est pas la Sixtine, ni l'Erechthéion; ce sont les œuvres quotidiennes de tout un univers qui travaille avec conscience, intelligence, précision, avec imagination, hardiesse et rigueur.

***

Si l'on oublie un instant qu'un paquebot est un outil de transport et qu'on le regarde avec des yeux neufs, on se sentira en face d'une manifestation importante de témérité, de discipline, d'harmonie, de beauté calme, nerveuse et forte.

Un architecte serieux qui regarde en architecte (créateur d'organismes) trouvera dans un paquebot la libération des servitudes séculaires maudites.

Il préférera, au respect paresseux des traditions, le respect des forces de la nature; à la petitesse des conceptions médiocres, la majesté des solutions découlant d'un problème bien posé et requises par ce siècle de grand effort qui vient de faire un pas de géant.

La maison des terriens est l'expression d'un monde périmé à petites dimensions. Le paquebot est la première étape dans la réalisation d'un monde organisé selon l'esprit nouveau.

Cliché Dræger.

DES YEUX QUI NE VOIENT PAS...

II

LES AVIONS

Fig. 2.4: Title page of the section *Eyes Which Do Not See*. [30, pp. 80-81]

Here, the flying machine is not used as an image, nor as a device that creates an architectural experience. Instead, it is used as a machinic concept that creates a procedural vision of design and production rather than a formal image, and is in this sense analogue to architecture. However, the book does not advocate a pure functionalist architecture. The unification of the architectural with the mechanical also represents an aesthetic and social vision, originating in the modern spirit of the Industrial Age. The book promotes an experimental exploration of a new architecture and closes with a vision of mass-production housing.[6]

2.2 Mechanisation of production

> "Just as functionally interpreted building constitutes a system, so also the construction of this building is a system. The new techniques developed in the last century and the general mechanisation of production facilities led to sub-theories concerned with the achievement of forms (the most important centred around the Bauhaus) and these, in turn, restricted the forms that could be produced." Gordon Pask, *The Architectural Relevance of Cybernetics*, 1969 [31, p. 495]

Mechanised assembly lines had already decreased the flexibility of architectural production, even before system-level thinking was introduced in architecture and production (see Chapter 2.3). While Le Corbusier and other prominent protagonists of modernism like Walter Gropius advertised the machine as a strong metaphor for an all-encompassing architectural reconceptualisation (with the airplane as its symbol)[7], the factual mechanisation of production and emerging industrialised techniques in construction became a new reality for the built environment. In the context of the post-war era of the 1950s, the demand for reconstruction fostered the development of industrialised building techniques. Industrial production methods were supposed to solve the housing problem. The serial mass production of building elements (and other manufactured products) was regarded as a way to reduce fabrication cost and building time, as had been done in other sectors of industry (Fig. 2.6). However, very little actual mechanised manufacturing technology could be applied directly to the construction site [5, p. 37]. While the modernists aimed to implement an aesthetic language originating in manufacturing techniques, the building industry focussed on organisational theories (Fig. 2.5) of the manufacturing industry such as systematisation, standardisation, and prefabrication in order to reduce time, employ lower skilled workers, and reduce the number of steps needed on the construction site. Nick Callicott argues that this development led to a split between conception and realisation, and indicated a paradigm shift for architects:

> "Mass production has become characterised by the production of

> larger numbers of standardised products exhibiting minimum variation. Its function is grounded in a separation of design and production, which is manifested in the technology and architecture of the mechanised assembly line." [5, p. 38]

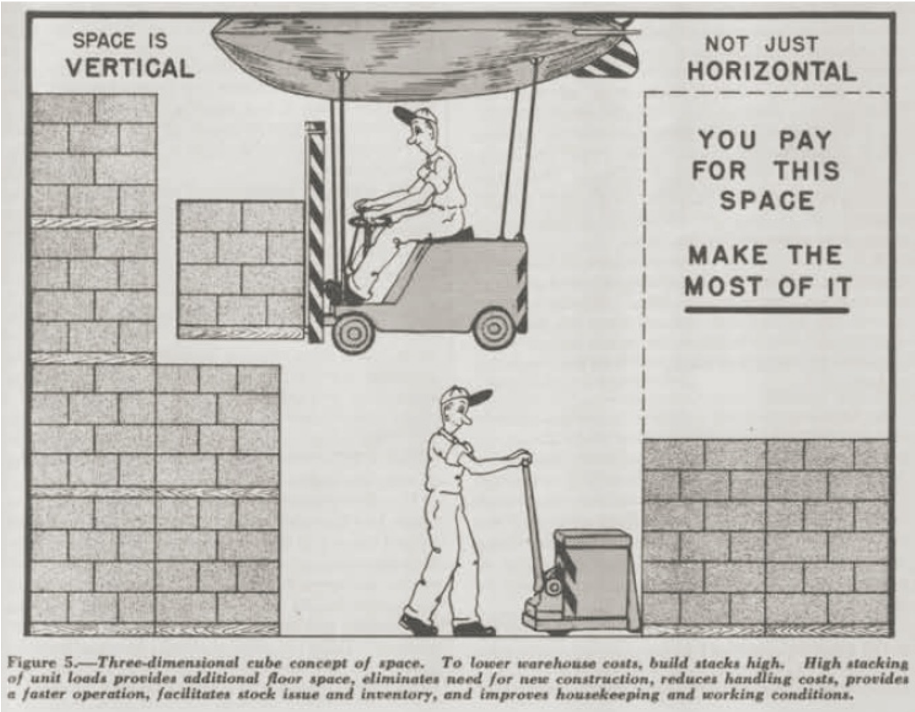


Fig. 2.5: Space is Vertical! Economisation of space (1954). (Federal Supply Service, General Services Administration (Hg.): Warehouse Operations Handbook. Federal Supply Service: Washington DC. via [32, p. 57]

Rather than expanding the architectural scope with the aid of manufacturing technologies, mass production further distanced the influence of the architect on the process of manufacturing itself. Another problem with the introduction of factory-line produced building components was that as the level of standardization in building modules increased, the less flexible the building became. Under the premise of increased productivity and quantity, the building industry reduced variety in construction by standardising building forms. Architectural production, however, has an inherently different objective than mass production of identical parts. A building differs from the factory-line product in its uniqueness. A building is usually the result of a negotiation between a multitude of factors (such as site, function, construction skills, material resources etc.) and hence requires flexibility, which by its very nature, the mechanised production of elements rarely offers.[8]

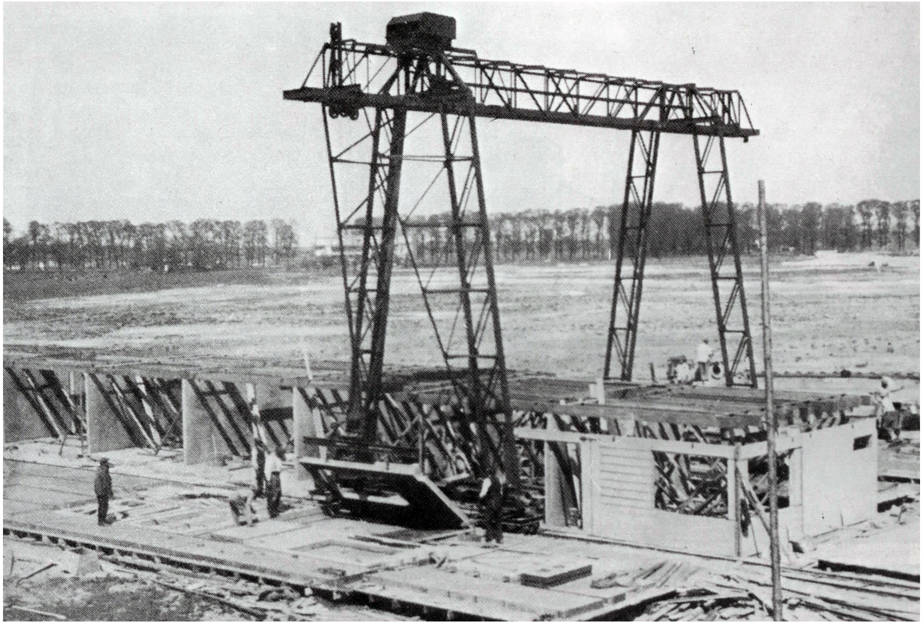


Fig. 2.6: Housing at Watergraafsmeer, Amsterdam, Holland. D Greiner, 1922-24. Early example of mechanised on site assembly of precast concrete slabs. via [33, p. 450]

Technological optimism faded and the attempt to fully industrialise the building process came to a standstill in the U.S. and Europe following the 1973 oil crisis [34]. The mass-housing of the previous decades was increasingly criticised for causing social problems. While the automation of building processes and construction in the West decreased and shifted towards a reformulation of architecture (post-modern architecture), Asia, and in particular Japan, pushed this development further.[9] Despite these case studies in construction automation, machines have not been applied to architectural construction on a large scale. The modernists in the 1920s and 1930s envisioned a union of design and production, resulting from technological developments such as the flying machine. Where the airplane provided a representation through which to rethink architectural design and fabrication processes and eventually lead the building industry to transform towards mass-production, the actual aircraft industry could not rely on mechanised production. In comparison to the built environment, fewer airplanes were required, and therefore mass-production was not feasible. Furthermore, flying machines were (and still are) complex mechanical devices that required high flexibility in production and skilled workers to build them. This motivated the development of computer-controlled manufacturing machines.

2.3 System thinking and computation in production

Today, the separation of design and its realisation [5, p. 38] is challenged by reprogrammable tools [1, p. 174]. In order to contextualise the use of flying robots as reprogrammable tools in architectural production, it is important to situate this practice within the context of evolving computer-controlled design and production technology. This development originates in cybernetics, flexible manufacturing, and digital materiality - an architectural concept that bridges the virtual with the physical.

2.3.1 Cybernetics

The flying machine inspired a new understanding of the relationship between humans and machines, and thus reshaped the notion of machine-inspired architecture. In the context of World War II, improvements in the speed and manoeuvrability of airplanes made it increasingly difficult to shoot down an enemy aircraft. Simply aiming a gun at a target was no longer effective; the gunner had to predict how far ahead of a fast-moving plane he had to aim so that the trajectories of his missiles would intersect with the plane. [35, p. 43]

At the beginning of World War II, mathematician Norbert Wiener participated in a U.S. military research project (D.I.C. 5980, supported by the National Defense Research Committee, 1940) to develop a servomechanism apparatus that would predict where the airplane would be, helping the gunner to shoot down the enemy:

> One feature of the anti-aircraft problem was the cycle involving feedback: information from a radar screen is processed to calculate the adjustments on the gun controls to improve aim; the effectiveness of the adjustment is observed and communicated again via radar, an then this new information is used again to readjust the aim of the gun, and so on. [36, p. 184] via [35, p. 43]

Based on this work, Norbert Wiener introduced the concept of cybernetics [37]. It suggested that animals (and humans) are machines subject to feedback and the fact that they learn from feedback makes them intelligent [38]. His analogy of mechanical devices with biological systems advocated that feedback control, when packaged with the flexibility of electronic circuits, is a tool that does not distinguish between the transmission of information and the transmission of the material, but rather is a methodology that bridges the two.[10]

While Wiener mostly relied on abstract physical systems to demonstrate his ideas, the prevailing development of computers during the 1950s and 1960s shifted the focus towards the writing of code [39, p. 46]. Code and software suggested that a control system can be modified and be flexible. Unlike industrial manufacturing, the designer of such a system does not have to specify information as a deterministic model. Architectural design information and fabrication instructions can be constructed as a system incorporating constraints, variables, and feedback loops. Cybernetician and psychologist Gordon Pask, for example, who collaborated with architects in the 1960s, proclaimed that various computer-assisted (and computer-directed) design procedures would be developed into useful instruments under the influence of cybernetic theory in architecture [31].[11]

Around the same time, Nicholas Negroponte was developing the "Architecture Machine" with his research team, the *Architecture Machine Group*, at the Massachusetts Institute of Technology (MIT). Using the concept of control systems, the group combined engineering and architecture with novel developments in computer science. The architecture machine was envisioned neither as a machine that produces architecture nor as a mechanical building. In the preface of *The Architecture Machine* book Negroponte stated:

> "There are three possible ways in which machines can assist in the design process: (1) current procedures can be automated, thus speeding up and reducing the cost of existing practices; (2) existing methods can be altered to fit within the specifications and constitution of a machine, where only those issues are considered that are supposedly machine-compatible; (3) the design process, considered as evolutionary, can be presented to a machine, also considered as evolutionary, and a mutual training, resilience and, and growth can be developed." [40]

The Architecture Machine Group was only interested in the third option. The machine represented an instrument for architectural design exploration, negotiating between two dissimilar species (man and machine), two dissimilar processes (design and computation), and two intelligent systems (the architect and the architecture machine) [40, Preface]. The group developed various conceptual projects to demonstrate their architectural approach. The *SEEK* project from 1970, for example, was a machine that operated between a model of the world and the real world. Five hundred cubes were positioned in an orthogonal manner by a robotic manipulator while a colony of gerbils (selected for their curiosity) was constantly disrupting the arrangement. The robotic system would discover inconsistencies and realign the askew blocks (Fig. 2.7). The outcome was a constantly changing architecture that reflected the way the animals used the space [41, p. 47]. The Architecture Machine Group criticised contempo-

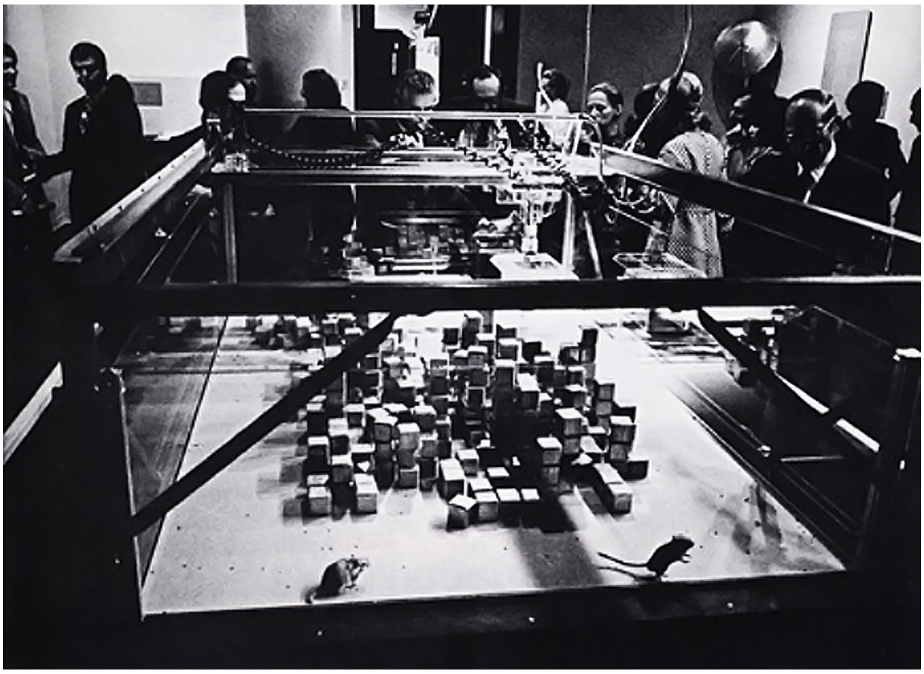


Fig. 2.7: SEEK project, Architecture Machine Group, 1970 [41, p. 47].

rary building technology for continuing to apply methodologies from the industrial revolution and reinforcing sameness through repetition and amortisation through duplication. In turn, they proposed to use computers and information technology for custom-made and personalised architectural production [41, p. 145].

Though Weiner formulated his concept of cybernetics while analysing the problem of how to shoot down fast moving airplanes, his theories led to a new understanding of the relationship between machines and architecture. With the integration of control systems, machines were not only regarded as mechanical production apparatuses, but as tools that inform an architectural design.

2.3.2 Flexible manufacturing

While aircraft may have been used to illustrate mechanised manufacturing in architecture, the reality of the aerospace industry was that it could not rely on modern mass production technology because the quantities of aircraft being produced were too low and the complexity of their production was too high. Many design decisions had to be made during production, which required high flexibility [5, p. 45]. This motivated the development of computer-controlled machine tools in the 1950s. The first numerically-controlled machine tool was invented by John Parsons in 1952, at MIT. Parsons was a subcontractor for the aerospace industry, and the goal of his research was to improve the production of helicopter rotor blades [42, p. 5]. The system used a computer programme for the simultaneous control of the movements of a three-axis cutting tool, which allowed it to machine complex three-dimensional parts (Fig. 2.8). By 1957, the U.S. Air Force used numerically-controlled milling machines in the manufacturing of flying machines. Control systems such as these were designed to enhance not only the level of precision, but also the flexibility of the materialisation process. In the 1960s, the magazine *Architectural Design* (AD) was at the forefront

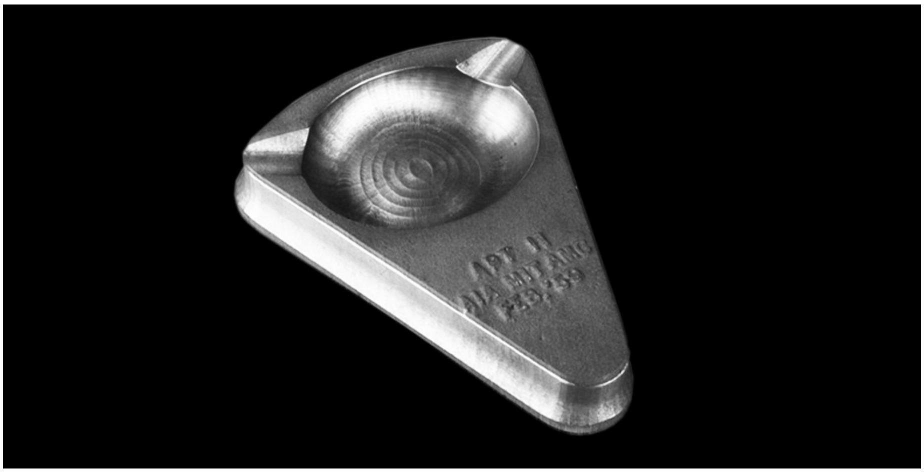


Fig. 2.8: One of the first examples of computer-assisted manufacturing. The Servomechanisms Laboratory at MIT and the U.S. Air Force used a specifically developed language *Automatically Programmed Tools* (ATP) to instruct a milling machine to produce ashtrays for visitors at a public demonstration in 1959 [43].

of the architectural design and technology discourse, and frequently discussed the influence of computer-controlled machines on the manufacturing industry, and hence on architectural design. For example, Fred Scott wrote in his article "How it's made":

> "[. . .] there seem to have been a reluctance for architects to involve themselves in how-things-are-made. This problem is now relevant to factory design, in particular, and to architecture in general because of certain recent developments in the field of batch production – which of course involves most products with an architectural application. These developments stem from the introduction of numerically-controlled machines, the combination of machine tool and computer, into the manufacturing process. The potential of the innovation is a spectacular improvement in communication with the manufacturing process." [44, p. 507]

Fig. 2.9: Cover of the Architectural Design magazine in 1969 shows a GKN Versatran industrial robot with continuous-path control performing arc welding operations on a motor vehicle rear wheel suspension assembly. Photo by Hawker Siddeley Dynamics Ltd, design by Pearce Marchbank.

A year later, an entire issue of AD called "Ditching the Dinosaurs" and edited by Chris Abel was dedicated to this topic (Fig. 2.9). Referring to the GKN Unimate robot, Abel argued that the building industry could be revolutionised by integrating design with responsive production tools ("universal machines") [45].

Even though individuals working in architectural research (such as Nicholas Negroponte, Gordon Pask, and Chris Abel) proclaimed that control systems would force a reconceptualisation of architectural production, both the architectural profession and the building industry failed to recognise developments in Flexible Manufacturing Systems (FMS) that were in use by the aerospace industry at that time.

While computer-aided design techniques have gradually been adopted by engineering, followed by architecture practices in the 1980s and 1990s, the transformation of design information to computer-controlled machine tools is only recently becoming apparent, as will be examined next.

2.3.3 Digital Materiality

In architectural design, the boundary between the intellectual conception and its physical realisation has been dissolving ever since "personal fabrication"[12] [46] industrial robots were introduced to architectural research [47] in 2005. As digital fabrication technologies began to make their way into architecture and the need to study the potential of robots as a design and fabrication tool grew, universities began to incorporate industrial robots [48] into their research facilities, and a number of start-ups were formed to bridge the gap between academic knowledge and industrial building technology [49, pp. 60-75]. Meanwhile, popular publications [3, 4] argue that digital fabrication is about to create a "third industrial revolution", a "revolution on your Desktop" [46]. Following the mechanisation of the textile industry in the 18th century and the introduction of the assembly line and mass production in the 20th century (first machine age), the present revolution is a result of the digitalisation of production, shifting mass manufacturing to individualised production.

The tools that will enable this digital materialisation "revolution" have already existed for half a century; as early as the 1960s, the architectural avant-garde was attempting to position computer-aided manufacturing not just as an advanced instrument of production, but as a programmable design tool. Yet despite a few experimental architectural projects in the 1960s and 1970s [41], and an international conference on robotic fabrication in architecture in 1986 [50], it is only recently that these tools have become accessible enough to be integrated into architectural design and fabrication processes [9, 10].[13]

Today, the six-axis industrial robot is predominately seen as one of the preferred instruments of digital fabrication in architectural research [9]. This tool, however, was created in the age of standardisation. Its generic-ness allowed it to not only function within a standardised production process, but to standardise the production process *itself*. Looking at architectural case studies realised by robots, it becomes apparent that the physicality of robotic architecture represents a principle of the non-standard. Unlike repetitive building systems, it aims to demonstrate difference through variation. This is repeatedly reduced to a formal language of geometric freeform production, which increases the danger of justifying the use of the machine solely for formal purposes, constituting once again a *standardised* architectural approach. Despite different material systems, the architectural prototypes often show a formal resemblance. As such, while the *détournement* of the devices from the First Machine Age finally enables the interplay between digital and material processes in design and construction (ie. the *Digital Material* [47]), it also constitutes the risk of a homogeneous aesthetic.

This thesis argues that the *Second Age of Digital Architecture* [48, p. 4] should likewise exploit devices from the *Second Machine Age* [51]. While recent developments in sensing, computation, and control have helped well-established (automatic) robotic fabrication devices from the *First Machine Age* to become more flexible, they have also led to the creation of (autonomous) machines with capabilities that are profoundly different from those of conventional mechanical devices. These machines from the *Second Machine Age* are more versatile than their predecessors and they could not operate without feedback control. An example of such a machine is the flying robot.

2.4 Aerial robotic construction

> "We haven't pondered enough on the basic causes of the generalized evolution of technology: miniaturization, reducing to nothing or next-to-nothing the size of every machine..." Paul Virilio, *The Aesthetics of Disappearance*, 1980 [52, p. 67]

Contemporary popular culture presents a robotic image from the second industrial age that is based on mechanical complexity. *Transformers* (a popular Hollywood film, video game and comic series), for instance, centres around intelligent autonomous robots from the planet *Cybertron.* These alien humanoid machines can transform into terrestrial mechanical devices, such as cars or trucks. The evolution - from standardised production-line mechanical machine to an alienised machine with intelligent behaviour - is realised by making the mechanical *even more* mechanical. This common representation suggests that progressive technology is based on mechanical complexity. In contrast, *HAL 9000* (the intelligent robotic system from the popular 1968 movie *2001: A Space Odyssey*) presents a completely different image of technological progression:

one where progression happens via the *reduction* of mechanical complexity. Today, these characteristics are evident in novel machinic creations such as flying robots. Miniaturisation of components, such as sensors and actuators, increased computational power, and advanced feedback control systems have led to the creation of machines that are more flexible, can adapt and learn, and at the same time, become mechanically less complex. Autonomous Unmanned Aerial Vehicles (UAVs) and their interaction with the environment are nowadays a research topic in many robotic groups [53, 54]. Research in aerial *construction* with flying robots, however, is still in its infancy.

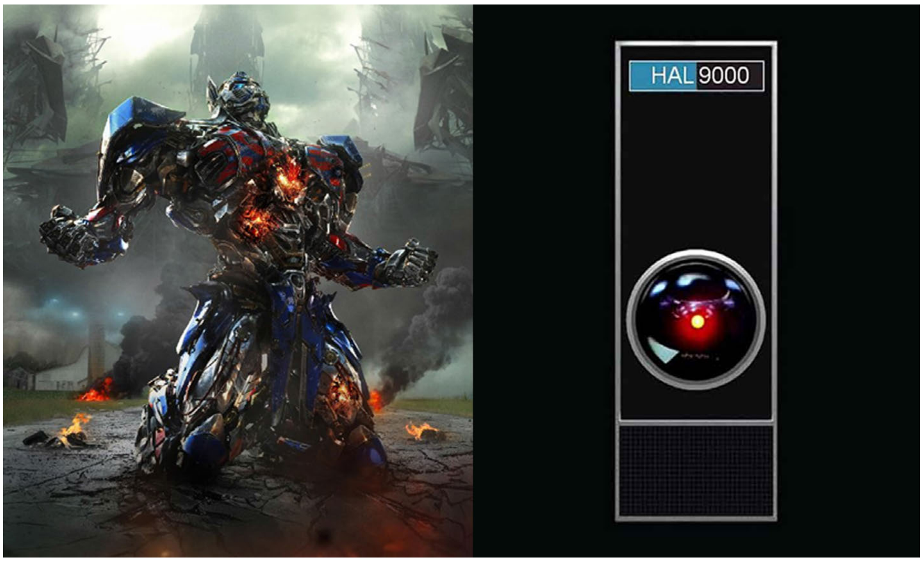


Fig. 2.10: Optimus Prime vs HAL 9000. Contemporary culture presents technical progression based on mechanical complexity. Contemporary technology, however, suggests the reduction of mechanical complexity is instead a result of the integration of advanced feedback processes.

First steps into construction with autonomous flying robots were presented in 2011 [55]. Multiple quadrocopters were equipped with grippers, enabling them to pick up linear truss elements. The building elements were manually prepared with magnetic elements at their ends, which allowed them to be connected to an assembly. Operating in the same building space, teams of quadrocopters would pick up the building material from a pickup station and sequentially place them, eventually aggregating a cubic structure. The magnetic joints effectively compensated the tolerances of the robotic construction system (Fig. 2.11). In the same year, the *Flight Assembled Architecture* installation demonstrated the ability of quadrocopters to autonomously erect a differentiated 6-meter tall tower made out of 1500 foam elements [11, 56, 57]. It demonstrated for the first time the use of aerial robots to create an architectural structure (Fig. 2.12). Four quadrocopters erected the differentiated assembly by picking up the individual building elements from a ground station, where they were prepared with glue. The vehicles would then sequentially place the elements at a designated location in the assembly. The project showcased the ability of the vehicles to create structures on an architectural scale and demonstrated that aerial robotic fabrication can be directly linked to an architectural design. Another project that

Fig. 2.11: On the left, construction of cubic structures using bars with magnetic joints (GRASP Lab, University of Pennsylvania, 2011) [55]. On the right, assembly of a space truss structure using a robotic arm mounted on a robotic helicopter (DLR, 2013) [58].

investigates aerial robotic construction is the *ARCAS* project [59]. It focuses on the assembly of truss structures with autonomous helicopters equipped with robotic arms [58]. A fully-actuated seven Degree of Freedom (DoF) redundant industrial robotic arm mounted on the bottom of the vehicle enabled the vehicles to grasp and orient building elements, and enabled the end-effector to compensate for the movements of the vehicle caused by wind gusts and ground effects when hovering (Fig. 2.11). Furthermore, there have been attempts to use flying robots for three-dimensional printing [60] and for assembling structures with interlocking blocks [61]. While these demonstrations hint towards the potential of aerial robotic construction, most experiments have failed to recognise its design potential. Simply transferring construction methodologies from material processes developed either for the human hand or conventional robotic processes to aerial robotic construction does not take advantage for the vehicle's specific possibilities. This work therefore aims to identify the unique possibilities for design and fabrication of flying machines as tools to autonomously steer material in space. As such, it represents a device that can radically expand the present capacities of digital fabrication technologies and facilitate architectural experimentation that excludes neither the possibility of constructive concretisation nor a possible built reality of the future. It is not a pure technological demonstration that stands in the foreground: above all, it is a matter of pointing out, comprehending, and implementing a new architectural process with all its spatial, aesthetic, and functional consequences. As such, designing and constructing architecture with flying machines opens up a distinct material practice

Fig. 2.12: *Flight Assembled Architecture*, FRAC Centre Orléans, 2011, picture by François Lauginie. [56]

and characterises a novel field of research [2].

This chapter has shown that the abilities of the flying robot, even though it is a radically new device, can be connected to established methods of architectural fabrication. It has also shown the historic importance of the flying machine in the development of 20th century architectural discourse.

Notes

[3]This chapter contextualises the aerial robot in architecture with a retroactive link [62] to historic examples of aerial experimentation in architecture.

[4]Futurism was both an artistic movement and a social movement.

[5]Point four of the *Manifesto of Futurism* [23]

[6]

> "The problem of the house is a problem of the epoch. The equilibrium of society to-day depends upon it. Architecture has for its first duty, in the renewal, that of bringing about a revision of values, a revision of the constituent elements of the house. Mass-production is based on analysis and experiment. Industry on the grand scale must occupy itself with building and establishing the elements of the house on a mass-production basis. We must create the mass-production spirit. The spirit of constructing mass-production houses. The spirit of living in mass-production houses. The spirit of conceiving mass-production houses. If we eliminate from our hearts and minds all dead concepts in regards to the houses and look at the question from a critical and objective point of view, we shall arrive at the "House-Machine", the mass-production house, healthy (and morally so too) and beautiful in the same way that the working tools and instruments which accompany our existence are beautiful." [29, p. 227]

[7]The rise of the manufactured product during the nineteenth century challenged designers from different disciplines to (re)think their methodologies. While social philosopher, writer, and art critic John Ruskin saw a threat to creativity in the mechanisation of production [63], architect Walter Gropius identified radically new means for artistic expression in standardisation and rationalisation. With the Bauhaus school, Gropius created an educational and exploratory framework where students were expected to familiarise themselves with industrial production technologies. The negotiation between designing and manufacturing, however, was not achieved through the rejection of handcraft skills, but rather through their acquisition. Traditional craft was seen as a mediator between conception and realisation [5, p. 36].

[8]While some designers engaged with manufacturing processes and created building systems based on standardised elements, such as the MERO or the USM Haller system, the reality of most of the post-war architectural landscape is largely based on repetitive building typologies originating from mechanised construction processes.

[9]Japan continued to have a demand for large building masses. Simultaneously, the lack of skilled labour led to the promotion of automation in prefabrication and construction, as an alternative to common construction practices [34]. The manufacturing industry grew (allowing higher degrees of automation), and with the introduction of new tools such as the industrial robot, affected most industries. The building industry, however, was still faced with the same problem: the dilemma between flexibility and repetition.

> "Construction is the largest industrial sector and yet it is also the most archaic. Most construction processes are individual and non-repetitive, which does not

> make them suitable for automation. On the other hand, if broken down to their constituent processes, many of them are of a repetitive character. These processes are also labour-intensive with many safety risks. Productivity is usually not sufficiently high and it is difficult to control quality. These features justify attempts at automation and the use of robots. After substantial progress in the use of machines, the construction industry has begun work on the introduction of robots. Robots are being applied to an increasing number of construction processes [...]" [64, p. 180]

[10]

> "Wiener was still only halfway along the line between Descartes to Turing. He wanted machines to imitate the man who acts in the world as well as the man who reasons, to explain muscle action in terms of feedback loops as well as chess in terms of a digital program. He relied on hardware devices for his metaphor of man and demanded a close correspondence between man and machine made to imitate him. Vacuum tubes were meant to be physical substitute for neurons, servo mechanisms for nerves acting upon muscles." [65] via [39, p. 47]

[11]Cedric Price, who worked with Pask and was influenced by his concept of interaction, including observers and users in a system, developed in 1961 the design for the *Fun Palace*. The project was a proposal for a new typology of entertainment centre. It was conceived as a dynamic spatial environment that would adapt to and be shaped by its users. The building embodied a mechanised structure and was drawn by Price as a mechanical apparatus. In 1963, Pask joined the design team of the project as an advisor and designer of a cybernetic theatre of the *Fun Palace*. Following his conversation theory, he wanted to allow interaction between the observers of a play and the performers, and proposed to wire the audience into a feedback loop connected to the performers via computers [66].

[12]Personal fabrication (PF) is in many ways analogous to the personal computer (PC).

[13]Computers (and the machines they control) used to be expensive, and only large companies with significant funding (such as those in aerospace industry) could afford them. With off-the-shelf technology, the prices of computers and computer-controlled machines has dropped drastically. And yet such machines can still only be used by skilled operators with knowledge of specialised processes. The availability of more computational power and the development of easy-to-use control interfaces are currently hastening the uptake of computer-controlled production machines by non-specialised workers, and will likely soon lead to their everyday use in architecture.

Chapter 3

Construction constraints

Flying robots[14] have features that differentiate them from other kinds of machines. In the context of aerial robotic fabrication, some of the attributes are beneficial, while others are disadvantageous. This chapter investigates these opposing attributes to develop a design space for aerial robotic construction. As such, it provides the necessary knowledge about the fabrication limitations of flying robots. By identifying the generic constraints of aerial robotic fabrication, the thesis is able to define an appropriate fabrication and design methodology for flying robots and examine their architectural potential. Experimental exploration and prototypical results from the following chapters provided the necessary data to formulate the constraints and the subject matter of this chapter.

3.1 Machine constraints

Since the early 2000s [67], various platforms of computer controlled Unmanned Aerial Vehicles (UAVs) have been the subject of robotic research.[15] In this thesis, the vehicles of choice are quadrocopters[16]. These flying robots are agile, have the ability to hover, and their mechanical simplicity makes them a robust platform for aerial robotic research. Additionally, they offer higher safety due to the four separate propellers, which store less kinetic energy than a comparable conventional helicopter's main rotor. Qudrocopters have demonstrated their dynamic capabilities in various experiments [68–70]. Today, they offer a useful compromise between payload capabilities and dexterity [71]. A quadrocopter can be equipped with additional sensors (for example a camera or a Global

Positioning System (GPS) unit) or actuators, depending on the application. This makes it a generic machine that can be adapted, for example with a specific end-effector, to perform a variety of tasks.

3.1.1 Flight dynamics

A quadrocopter has four rotors attached to a frame. The frame usually has the shape of a cross and is fabricated from rigid, lightweight material such as carbon fibre rods (*AR.Drone* [72]) or a carbon fibre sandwich panel (*AscTec Hummingbird* [73]). At the four ends of the cross sit four motors with rotors attached to them (Fig. 3.1). The machine further consists of a flight controller (a microcontroller), motor controllers, a wireless communication unit, a battery and various sensors, and a Inertial Measurment Unit (IMU) to determine the vehicle orientation, heading, and velocity. A quadrocopter generates lift by cre-

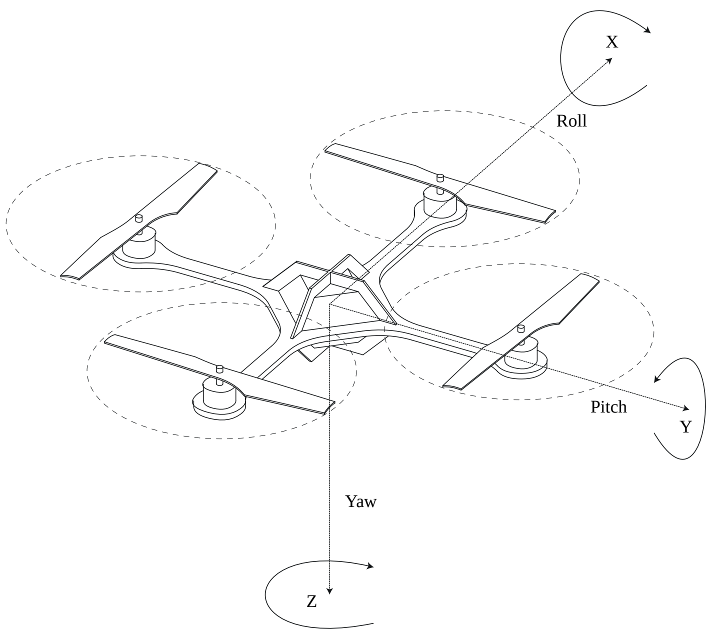


Fig. 3.1: Typical quadrocopter body frame.

ating thrust with its four propellers. Two rotors turn counterclockwise (aligned on the X-axis on the frame) and the other two rotate clockwise (aligned on the Y-axis on the frame). The yawing moments generated by the rotors, rotating at the same speed, cancel each other out [74]. The machine can move along the Z-axis by simultaneously increasing or decreasing of the force of all motors. Furthermore, the vehicle can navigate in three-dimensional space by changing the rotational speed between individual motors, hence changing the moment around a specific axis (Fig. 3.2). A rotation around the Z-axis (yaw) can be obtained by speeding up one pair of propellers (rotating in the same direction) and slowing down the other by the same amount. A pitching moment (resulting in a movement along the X-axis) can be obtained by speeding up one of the motors aligned on the X-axis and slowing down the other by the same amount. Similarly, a rolling moment (resulting in a translation along the Y-axis) can be generated by speeding up one of the motors aligned on the Y-axis and slowing down the other by the same amount. [71] A quadrocopter can therefore reach

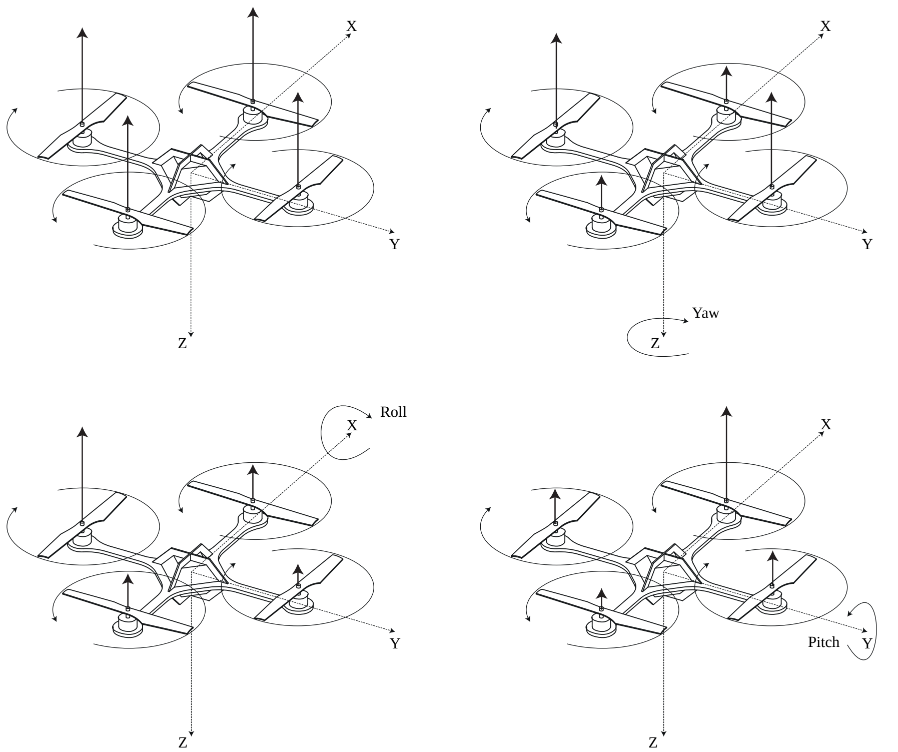


Fig. 3.2: Translation in three-dimensional space by changing the rotational speed between motors: Top left shows a movement along the Z-axis, top right shows a rotation around the Z-axis, bottom left shows a movement along the Y-axis, and bottom right shows a pitching moment, which results in a movement along the X-axis.

any three-dimensional position in space. However, the vehicle cannot hover in space at any given orientation. As described, changing the rotation angles (pitch and roll) of the vehicle results in acceleration (Fig. 3.3). Hence, the vehicle has a rotational limitation in a quasi-static position. This constraint does not effect yawing rotations (rotations around the Z-axis).

This limitation differentiates the quadrocopter from, for example, a six-axis industrial robot. A six-axis industrial robot comprises three axis for positioning and three axis for orienting and therefore is able to reach any point at any given orientation within its workspace in a dynamic or static manner. In comparison, the flying quadrocopter has limited degrees of freedom.[17] Theoretically, it would be possible to position a building element at any given orientation, if the module were to be placed dynamically, rather than statically. In this situation, the acceleration of the vehicle at the point of placement resembles the required orientation around the X- and Y-axis. In order to position a building element at a given orientation in a quasi-static manner, an additional actuator would be required to compensate for the roll and pitch orientation.

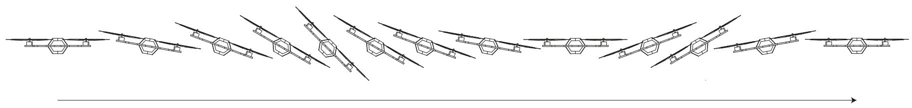


Fig. 3.3: Quadrocopter dynamics during a translation on the X- or Y-axis over time.

3.1.2 Localisation and precision

A flying construction robot, in contrast to a ground-based robot, is physically decoupled from its working space and is therefore dependent on real-time information about its pose in the environment. Through the processing of sensory information, the system is aware of its spatial situation and it is these feedback processes that couple their physical presence with the environment. The flying robot, not being physically connected to solid matter, is inherently unstable and must constantly adapt the rotational speed of the individual rotors in order to gain stability. The precision and accuracy of the machine is related to the quality of the received sensory data and the ability of control algorithms to process it, as well as the frequency in which these corrections can be processed.

A GPS sensor allows precision to be measured within meters [75], whereas a differential GPS (DGPS) [76], a Real Time Kinematic (RTK) system [77], or a Ultra-Wideband Communication system [78] brings the precision to centimetres, and a motion capture system sharpens the precision to millimetres. The quadrocopter, however, even one with the most accurate and precise tracking system, is still always moving and oscillating between target and actual performance. The setup used for most experiments in this work [79] allows accuracy and precision below 20 mm [80]. In addition to these global tracking methods, a flying robot can also be equipped with active on-board sensors allowing local positioning. This can be obtained with a laser system, such as light detection and ranging (Lidar) [81], or with cameras [82], for example, with a PTAM system (Parallel Tracking and Mapping) [83].

In the context of aerial robotic construction, the construction method must be able accommodate for the tolerances of the system used. Unless millimetre-precision is not required, or an actuator or a constructive detail can compensate for the movements of a vehicle, high precision fabrication operations (like space frame assembly – see Appendix C) are not suitable for aerial robotic fabrication. As with any construction process, the tolerances of the machine must somehow be taken into account when developing a construction methodology for aerial robots. Here, flexible form-active structures offer an advantage, since they self-compensate for fabrication tolerances (see Chapter 3.5).

Depending on the environment, each estimation method for determining the pose of a vehicle (its position and orientation) also has constraints that limit its usage. A global position system such as GPS or RTK only works outdoors and when in the line of sight of satellites. Camera-based navigation requires good lighting to identify physical features, and state estimation tends to drift over time. The global sensing motion capture system used in the experiments of this thesis requires a line of sight between its external infrared cameras and the vehicles. The machines have three retroreflective markers attached to their frames (three points are required to define the pose of a rigid body object), while at least two cameras must have a clear line of sight to each vehicle at any time to determine its pose. The more cameras that see the markers, the stronger is the state estimation [80].

The requirement of a line of sight is not problematic when operating in empty space, but it becomes evident in situations where the vehicles move between and under obstacles that block cameras' views of the scene. Depending on the tracking system, the construction method must consider the visibility conditions. While a layer-based construction typology (from the bottom to the top, with downwards looking external cameras) might not cause problems, a construction that operates in between existing and already constructed members requires a porous structural aggregation that facilitates visibility, rather than a typology based on large surfaces that generate line-of-sight obstructions.

3.1.3 Force and battery life

The ability to carry a payload is a *de facto* requirement for flying robots used in aerial robotic construction, as the robot must be able to transport building elements and manipulate material. Building materials are transported and manipulated through the distribution of force – or thrust – generated by the propellers. The robot's ability to generate thrust and manoeuvre are greatly influenced by the load it is carrying; hence the maximum possible thrust and the maximum possible payload are connected. As mentioned above, a quadrocopter generates lift by creating thrust with its propellers, and navigates in three-dimensional space by varying the rotational speed of the rotors and the force applied on the motors. Acceleration along the X-axis, for example, requires the reduction of the rotational speed on one of the motors, which in turn reduces the force that can be applied along the transformation axis. In contrast to ground-based robots, the maximum achievable forces of a flying robot are related to the acceleration and body rates: the higher the pitching and rolling momentum, the higher the respective forces applied. A regular quadrocopter can apply the maximum possible force along the positive Z-axis, because it can generate full thrust on all four propellers; and it can apply the least possible force in negative Z-axis, because the rotors only fulfil the function of stabilising the machine's gravitational force (the self-weight of the vehicle).[18]

A variety of flying machines can be used in aerial construction, depending on the weight of the building elements and the force and time required to complete the construction tasks. Regardless of the specific vehicle type that is chosen, however, trade-offs in vehicle weight, size, and thrust must be carefully managed to account for limited battery power. The flight time of a vehicle (and hence the maximum construction time for a construction task) relates to the required force, the payload, and the aggressiveness of manoeuvres [19]; a battery with low capacity decreases the flight time but increases the lifting capacity of the vehicle since it is usually lighter than one with a high battery capacity. Lighter batteries are not the only means of scaling a quadrocopter's payload capacity, capacity [20]. Another method is to scale the vehicle's size, as large vehicles (with larger blades and stronger motors) have greater lifting capacity than smaller vehicles. Larger vehicles often come with a safety trade-off, however: their rigid blades (often made of carbon fibre) make them dangerous to operate near humans [84].

3.1.4 Multivehicle cooperation

One method of scaling payload without increasing vehicle size is to have multiple machines collaborating on a lifting or manipulation task [53]. Digital control of the vehicles enables the robots to communicate and synchronise their actions among themselves [85]. Two forms of cooperation can occur. Firstly, quadrocopters can work in parallel in the same building space to speed up a construction process. Secondly, they can interact with each other on the same building task, to perform manoeuvres that a single vehicle could not accomplish on its own. However, having multiple vehicles operating in the same space poses additional challenges. The machines require a gap between each other that is larger than their physical envelope: the flight boundary of a vehicle is defined by the airflow circulation around the rotors, and the air stream of one vehicle can effect the other one, making them both unstable. Since the propeller wash is mainly directed downwards, machines can fly closely alongside one another, but require greater spacing when flying on top of one another. Aerial robotic construction must therefore consider the varied spatial requirements of multiple machines operating in the same space.

3.1.5 Ground effect and aerodynamics

Just as airflow circulation can destabilise an aerial robot, so can the ground effect. The performance of a rotorcraft is affected by its closeness to the ground or any other boundary that might alter or constrain the flow of air into the rotor or constrain the development of the rotor wake [86, p. 275]. Indeed, any object that blocks airflow has the potential to make a quadrocopter crash if it gets too close when flying or hovering. A quadrocopter must therefore maintain a minimum distance from such objects, whether these are objects that the vehicle is flying near, or ones it might be carrying. Closed-surface objects require greater distance, whereas objects with porous surface structures absorb the wash generated by the propellers and thus allow closer proximity. Also, payloads with large surface areas are less aerodynamic (and thus more difficult to transport) than those with smaller surface areas – this is particularly important when flying outdoors, as wind turbulence can impact the stability and manoeuvrability of the vehicle.

3.2 Material constraints

Because the payload capacities of aerial robots are limited, the materials used in robotic aerial construction must be light enough to be lifted, transported, and placed.[21] Since this thesis focuses on the fabrication of structural systems, it excludes light-weight building materials that are not load-bearing (such as Styrofoam). Building material suitable for aerial robotic construction is therefore distinguished by a low specific weight in relation to its structural load case. Any investigation into lightweight construction systems must consider the critical relationship between structural performance and weight [22], and connections should reflect the lightweight nature and performance capacity of the material. In aerial construction, the material's ability to be joined and manipulated by an aerial vehicle (within the constraints discussed above) must also be considered.

3.3 Construction system constraints

Lightweight construction systems are characterised not just by the building material and connection types, but also by how the building elements are aggregated into a structural system [87]. To be able to create an artefact with a low weight, the volume of a single building element must be low in comparison to the overall volume of the erected artefact. Lightweight construction systems are concerned with the amount and the arrangement of building elements, in order to define structural assemblies with a minimal weight. [88] The characterisation of structures that are classified according to usefulness and efficiency was prominently defined in 1998 by Frei Otto as the "lightweight principle".[23] While the predominant concern in typical lightweight structural systems is to reduce mass by optimising structural form, the demands of aerial robotic construction ask such systems to consider an additional aim: to achieve maximum structural and spatial performance with a minimum of material. Today, lightweight construction methods are often used to economically span large distances or in the construction of temporary buildings.[24] The most common systems are space frame structures and tensile structures.

3.3.1 Space frame structures

Space frame structures are three-dimensional, modular structures that are light, strong and often comprise of discrete, linear elements. First examples of such

Fig. 3.4: Lightweight construction systems, presented by Bernard Rudofsky in 1964 at the MoMA exhibition *Architecture without Architects.* Principles of lightweight construction have been applied for centuries by nomadic people and by "non-pedigreed architecture" [89].

structures were developed by Alexander Graham Bell (Fig. 3.5). He experimented with space trusses composed of octahedral and tetrahedral modules to build flying machines such as kites and gliders.[25] In the 1940s, three-dimensional space truss systems became commercially available with the introduction of the *MERO* system [90]. The system consists of mass-produced tubular elements that are joined at a ball-shaped node. This construction system became popular in the 1960s and presented a new aesthetic for a systemic, modular architecture [92].

Space frame structures have demonstrated their potential in creating large spanning artefacts that are robust (space grids are structures with a high redundancy) and, most importantly, lightweight. In the context of aerial construction, space frame structures offer an interesting topology. Rather than planar or massive building modules (walls, ceilings or beams) that span and enclose space, space frame typologies encourage spatial thinking about the three-dimensional organisation of the building members. Further, space frame structures are statically indeterminate. The system is based on an additive process, through which singular elements are assembled to form a stable unit and individual members can be accumulated where needed. In order to be efficient and to ease erection for human builders, space truss systems are largely based on repetitive grid arrangements. Systems that allow for more flexibility are usually more complicated, requiring custom solutions for joints and complex assembly instructions for the builders. Robotic construction challenges this dependency on regularity and repetition. With the integration of digital fabrication technologies, struc-

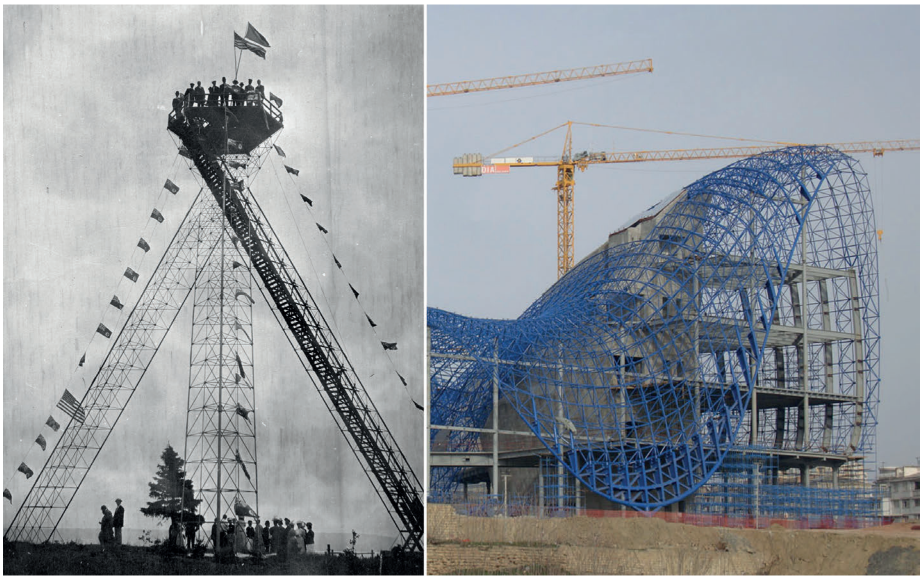


Fig. 3.5: Tetrahedral tower by Alexander Graham Bell unveiled in 1907 in Cape Breton Island, Nova Scotia, Canada. Free-form *MERO* [90] construction system at the Heydar Aliyev Centre in Baku, Azerbaijan by Zaha Hadid Architects, during construction in 2011 [91].

tures can be designed to be specific to a particular design project [93].

In aerial robotic construction, flying robots must be able to attach a building element, transport it to its designated target point in space, and place it with a given orientation. More details and initial robotic experiments are discussed in Appendix C.

3.3.2 Tensile structures

A tensile structure is a construction that is comprised of structural members in tension (no bending and no compression). Furthermore, tensile structures are form-active systems: they are non-rigid, flexible assemblies whose shape is a materialisation of both the connectivity diagram of its parts and the geometric form it settles into once force equilibrium is reached.

A form-active suspension structure changes its form when the loading is changed or the support conditions are altered in order to find a new structural equilibrium. Because of their non-rigid matter and their dependence on loading conditions, tensile structures reflect the natural flow of forces. Because they are loaded in tension only, form-active structures are the most economical system for spanning space in terms of the weight/span ratio [94, pp. 58]. A tensile

Fig. 3.6: On the left, a view of the Tensile Steel Diagrid Shell of the Oval Pavilion by Vladimir Shukhov during construction in 1895. On the right, a villager constructs a new bridge over the Apurimac River in Huinchiri (Peru) in 2012.

structure can be a one-dimensional object[26], such as: a wire, a rope, a thread, a cable, a chain or another flexible member, suspended from two support points. A flexible linear member connecting two anchor points creates a catenary curve, reflecting the flow of forces under its own weight. Multiple, interlinked members can form a two-dimensional structure[27], or a three-dimensional structure[28]. Two-dimensional objects may be closed-surface structures, such as a textile fabric, or porous surface structures, such as cable-nets. Similarly, three-dimensional tensile structures can form a volumetric object, or be composed as a structure with openings, for example, a three-dimensional cable-net structure.

Unlike space frame structures that resist gravity and can stand, for example, on the floor, tensile structures require elevated support points that generate space for the tensile structure to find its equilibrium hanging form. Aerial robotic fabrication of tensile structures, similarly to space frame structures, require the flying robots to pick up tensile material, fly it to a designated location, and fasten it to existing structural members. Contrary to the assembly of space frames, the absolute orientation of the tensile member is less important during construction, since the loading will determine its orientation and "self-assemble" through the flow of forces and the topology of erection. While a material aggregation with rigid elements can be conceptualised geometrically, the designing of form-active structures requires knowledge about the redistribution of forces. Form-finding methods can support the design of tensile structures and simulate the behaviour of flexible material.

Simple flying devices have been used to fabricate tensile structures since the industrial revolution. In 1733, John Kay invented the flying shuttle (Fig. 3.7), a ballistic device that helped to improve looms, greatly accelerated weaving processes, and initiated automated textile fabrication. With the flying shuttle, larger textiles could be produced since the weft (the weaving term for the crossways yarn) could be shot from one side of the warp (the weaving term for the series of yarns that extended lengthways in a loom) to the other side [95], rather than passing it through by hand. Whereas the Jacquard loom (invented by Joseph Marie Jacquard, and first demonstrated in 1801) provided a mechanical control method for the manufacturing of textiles with complex patterns by allowing the arrangement of the raised and lowered warp yarns to be controlled by a sequence of punched cards [35, p. 159], the passing of the weft is still regulated by a simple rectilinear motion. As such, the making of textiles is usually limited to the fabrication of two-dimensional fabrics with interlaced yarns at right angles. Flying robots have the potential to increase the design scope by combining the ability to transport rope through space (a variation on John Kay's flying shuttle) with the ability to manipulate the warp space (a variation on the Jacquard loom). As a result, the hierarchical division between two distinct sets - the weft and the warp - becomes obsolete, providing a new autonomy to guide and intertwine material in three dimensions.

Fig. 3.7: A typical flying shuttle, invented by John Kay in 1733. The shuttle contains a spool, onto which the weft yarn is wound.

3.4 Computational design constraints

Flying robots are digitally controlled machines that can be linked to a digital design to perform fabrication tasks.[29] A digital design (or code), however, must consist of geometric information about the artefact. And yet – by incorporating the behaviour of the machine [2] and the specific material/construction constraints – it might also take into account the characteristics of the fabrication process. This aspect can be particularly crucial in the design and fabrication of structures using flying robots. When deploying building material for example, a vehicle might apply a variable amount of force when manipulating it in a particular manner. Computational design enables operation within design space that integrates different aspects of a specific robotic construction system: it enables the spatial definition of the form of a structure, the simulation of the behaviour of material, and the definition of an assembly order, while at the same checking on its buildability. Aerial robotic construction benefits from a computational design system that enables architectural geometry data to be defined in relation to the construction system, in order to exploit its architectural potential and inform its physical realisation.

Following the definition of the constraints in Chapter 3.1-3.3, the challenge of the design system is to integrate the requirements of the quadrocotpers (for example the fabrication space to avoid collisions or the tolerances) with the characteristics of the material (for example the behaviour of form-active material) and the conditions of the construction system (for example to determine the assembly order). As a result, the computational components not only describe a design geometrically (as spatial information), but also specify a spatio-temporal performance of material interaction. The design benefits if it reflects the generative process of making and enables the architect to intervene and therefore design this process.

3.5 Conclusion: Aerial robotic construction of tensile structures

Aerial robotic construction offers an interesting platform for an investigation into the "dissensus"[30] between designing and making.[31] With aerial construction, this divergence becomes vast, and in consequence, the design space becomes narrow. The development of a construction methodology for flying robots to cooperate and place building elements is inherently difficult. Yet while there exists no universal principle for such a system [11], the multitude of constraints (inherent to the machine, the material, and the construction system) define a solution space that can be explored with the help of computational design techniques.

This chapter describes key challenges in using quadrocopters to build architectural structures. The vehicles are inherently unstable, they are difficult to control, they have limited payload capacity, and they offer specific degrees of freedom. On the other hand, the machines are physically decoupled from their workspace. This unique ability motivates the investigation into a congruent approach to building large-scale structures that differs from existing digital fabrication methods.

An appropriate construction method involving flying robots must leverage the potential of the machine while coping with its handicaps. It must integrate the material, the construction, the design, and the machine into a system. Subsequently, the physical requirements of aerial robotic construction encourage the exploration of lightweight construction techniques. The fabrication of tensile structures with one-dimensional members, such as ropes or cables, distinguishes itself as a construction system that is, conceptually speaking, particularly appropriate. Building tensile structures with flying robots offers the following advantages:

- Machine: The orientation limitations (roll and pitch) of the vehicle in a quasi static condition do not constrain the configuration of building members since the form-active building material orients itself as a result of the distribution of loads and not according to the placing orientation. The flexible nature of the material also has advantages regarding the accuracy and precision constraints of the robotic system. When placing rope, for example, the material can slide into place and thus compensate for the tight tolerances and inherent instability of the machine. Furthermore, the unidirectional limitation in applying force becomes dispensable up to a point (for example, when tying a rope around an existing structural member), since the fabrication of a knot is defined by the topology rather than the vehicle's flight angle during assembly. This allows the machine to be optimally orientated in relation to the applied force. If the spatial situation allows for it, the vehicle can optimally orient itself when applying force on a node. Using centrifugal forces, the machines can even apply tension that is larger than the maximal thrust forces generated by the motors [96]. Additionally, the small surface area of the building material offers minimal contact area for wind effects and minimal visual occlusion for the machine's location system.

- Material: Rope has a beneficial ratio between weight and strength, enabling it to efficiently span large spaces. Furthermore, tensile material can be produced at varying lengths and cross sections and is therefore a highly scalable building material for tension-only constructions. Hence, a building member is described by only two parameters (length and diameter). Depending on the design, the loading case, the span, and the vehicles' lifting capacities and size, the material can be selected accordingly.

- Construction system: Rope is a generic building material that can be arranged in various ways, allowing for an optimal architectural and structural performance. Individual rope segments can be laid sequentially onto one another. Regardless of the complexity a tensile structure will eventually have, building it always begins with the construction of a simple link connecting two supports. Connecting various other members to this link transforms the one-dimensional structure into a two-dimensional or three-dimensional structure. The flexible nature of the building material is advantageous for aerial transportation, since it can be wound up. Also, it offers only minimal surface contact, and as a result, does not obstruct the airflow of the propellers during the flight. Finally, it allows the vehicles to fly between already built members and thus create interworked structures.

Computational tools facilitate the design of tensile structures by simulating the behaviour of the tensile material, which is crucial for the finding the tensile form. Fabrication constraints and build-up logistics can be implemented at the earliest steps in the design phase, allowing the creation of complex geometries that converge between digital data and physical materialisation. With the exception of an initial space frame experiment (Appendix C), this thesis therefore focusses on methods and techniques of aerial robotic fabrication of tensile structures. This delimitation is based both on analytical choice (originating in an understanding of the constraints outlined in this chapter) and on the physical experiments (explored in Chapter 4, 5 and Appendix C) that have validated it.

To build tensile structures with flying robots and to experimentally validate the approach, a series of specific techniques and tools were developed. The following chapter will examine the basic building primitives of aerial tensile fabrication and introduce computational components that enable the design of aerially buildable tensile structures.

Notes

[14]A flying robot is reprogrammable, multifunctional flying machine that can perform a variety of tasks through programmed motions. A flying robot can be a fixed-wing aircraft, a helicopter, a ducted-fan vehicle or an airship, and so on. For the rest of this thesis, a flying robot refers to a specific kind of flying machine: the quadrocopter.

[15]Fixed-wing UAVs refer to flying machines with wings, such as airplanes, usually requiring a runway for take-off and landing. Rotary-wing UAVs or rotorcraft UAVs, such as helicopters, ducted fan vehicles or multi-rotors, are capable of Vertical Take-Off and Landing (VTOL), hovering, and complex manoeuvres. Airship-based UAVs, like blimps and balloons, use lighter-than-air technology to generate lift. They are large and slow, but have the ability to carry big payloads. Finally, flapping-wing UAVs, inspired by birds and flying insects, generate thrust and horizontal velocity by wing flapping [97, pp. 10-13]. The size of UAVs ranges from fixed-wing vehicles in the size of manned airplanes (for example the *Northrop Grumman RQ-4 Global Hawk*, weighing over 12 tons [98]) to micro aerial vehicles (MAV) with dimensions smaller than 15cm (for example the *Crazyflie Nano Quadcopter*, weighing just 19 grams [99]).

[16]The robotic setup is further described in Chapter 5.1.

[17]In contrast again to the industrial robot, the velocity of the quadrocopter influences the physical configuration of the machine. Moving an element attached to the machine through a tight opening might be possible only at a specific velocity, reflecting the translational dynamics [100].

[18]Mechanically more complex flying robots, such as multi-rotors with variable roll and pitch propellers, would principally allow more flexibility in applying force in all directions. These machines are subject to on-going robotic research [101], but are currently less robust.

[19]The quadrocopters used in Chapter 5 have a flight time of approximately 15 minutes. The flight time could vary between 10 and 20 minutes, depending on the task.

[20]The quadrocopters used in this research have a payload capacity of approximately 250g. However, multi-rotors are commercially available with payload capacities of up to 10kg. Of course, machines with higher lifting capacities can carry larger and heavier building elements. However, it also is dangerous for humans to be near such machines. Furthermore, an increase in vehicle size can limit a structure's density (see Chapter 4.1.3)

[21]Lightweight materials like aluminium or fiber-reinforced plastics are today used for special applications in architecture. With the continuous cost reduction in polymer production, high-efficiency components with high strength-to-weight ratios, such as carbon-fibre-reinforced plastic, aramid or ultra-high-molecular-weight polyethylene (used for the the experiments in Chapter 5) become increasingly available and are being applied in construction [102].

[22]The specific strength of a material, for instance, describes the ratio between strength of substance (force per unit area at failure) divided by its density. This strength factor, however, depends on the specific load case. A material might have advantageous specific tensile strength properties, but a weak stiffness-to-weight ratio. Werner Sobek argues that a lightweight material cannot simply be selected because of a certain ratio describing material plasticity deformation limitations. Rather, it must be situated within a multitude of constraints that

are specific to a load case and hence to an architectural design [88]. As early as the late 1920s, Buckminster Fuller promoted to use of lightweight building materials:

> "In 1927 I gave myself a theoretical problem which turned out to be feasible in high performance to per pound engineering. I gave myself the problem of delivering large structures by air." [103]

Fuller designed lightweight buildings, such as the *Dymaxion House* in 1929, using airplane manufacturing techniques and airplane production materials. He famously asked: "How much does your building weigh?", challenging his contemporaries to use building material efficiently. It is no surprise that Fuller was inspired by the materiality of the aircraft. It was the aerospace industry that was most involved in the investigation of lightweight materials and many of its material developments have since been introduced to the building industry.

[23]

> "The forms of relatively lightweight constructions are rarely coincidental. Usually, they are the result of development and optimisation processes which, for whatever reason, follow the principle of the reduction of mass. We call this principle the light-weight construction principle." [104, p. 11] via [105]

[24]With settled forms of living, it became possible to construct heavy buildings that were designed for durability. Monumental buildings such as castles and palaces represented a step backwards from lightweight construction [105, p. 41]. Heavy building materials such as stone represented wealth and power. More intelligent construction methods and more efficient methods of using material shifted the demand for colossal buildings to a lighter, Gothic architecture. Following the Gothic period, architects and structural engineers developed a variety of construction systems using lightweight principles. At the beginning of the 20th century, Antoni Gaudi used upside down scale models, made out of strings and small bags with weight attached to them, to create a form-optimised representation of his designs [106, 107]. Also around the turn of the 20th century, Vladimir Shukhov designed and built lightweight steel structures such as radio towers and large distance spanning exhibition halls using tensile gridshells, membranes, diagrid arrangements (Fig. 3.6), and hyperboloid structures [108]. Buckminster Fuller (Fig. 3.5) [109,110], Konrad Wachsmann [111], and Max Mengeringhausen [90] developed lightweight space frame (or space grid) structures [112], and in the 1960s, Frei Otto created large spanning tensile structures [113].

[25]In an article published in 1903, he expanded the structural principle to the construction of buildings:

> "Of course, the use of a tetrahedral cell is not limited to the construction of a framework for kites and flying-machines. It is applicable to any kind of structure whatever in which it is desirable to combine the qualities of strength and lightness. Just as we can build houses of all kinds out of bricks, so we can build structures of all sorts out of tetrahedral frames and the structures can be so formed as to possess the same qualities of strength and lightness which are characteristic of the individual cells." [114] via [112]

[26]Large in one of the three dimensions and small in the remaining two.

[27]Large in two and small in the third dimension.

[28]An artefact that is relatively large in all three dimensions.

[29]The digital design representation, whether it is a modelled surface, or a line of code, is simultaneously a design and a machine protocol. Thus the maker of the drawing enters a territory that has so far been the exclusive realm of a builder or a manufacturing expert, forming judgement on the basis of fabrication feasibility [115]. A craftsman does not merely interpret a drawing and translate it blindly into a physical object, but has knowledge about the specific materialisation process. This allows for adaptation during the making, required especially if the designer oversees a fabrication constraint.

[30]Felix Guattari argues in *The Three Ecologies* in 1989: "Rather than looking for a stupefying and infantilising consensus, it will be a question in the future of cultivating a dissensus and the singular production of existence." [116, p. 33]

[31]In the context of architectural production, robotic fabrication in general – and aerial robotic fabrication specifically – is always a negotiation between intellectual conception and physical materialisation. Architectural design data cannot literally be translated into a material realisation. Design data can only represent or inform the material; but it cannot *be* the material. The relationship between design and fabrication is thus based on a convergence and not on equality or harmony. A designer, using robotic tools, should mediate between the virtual and the physical, cultivating and understanding their differences.

Chapter 4

Techniques for design and construction

The discussion about the specific characteristics and constraints of architectural construction processes with flying robots in Chapter 3 motivates the in-depth investigation of tensile structures as a lightweight construction system of choice for aerial robotic construction. However, to actually build architectural scale tensile structures with flying robots, the process had to be analysed and dissected into its basic primitives. This chapter characterises these primitives and introduces the techniques that were developed to control them. This chapter first introduces the building primitives that constitute a tensile structure, and then describes the computational tools that support the design of a structure before it is built.

4.1 Building primitives

As described in Chapter 3.2.2, tensile structures are form-active: i.e. formed by the flow of forces. This flow of forces, as well as the resulting form, can be steered by the design. The way linear tensile members are arranged, connected, and supported defines the physical outcome. A form-active, tensile structure redirects the forces along the geometry.[32] As such, a tensile structure acts as if it were materially continuous. Interacting individual tensile members self-link through the flow of forces into a connected structure. Aerial robotic construction, however, requires that the tensile structure be broken down into a construction sequence. This allows the payload to be reduced, since a vehicle must transport only a single building member rather than an entire pre-assembled structure, such as a cable-net surface structure. Furthermore, the breaking down of a tensile structure into basic construction steps increases the flexibility of the design. The buildability can be generalised since basic construction manoeuvres can be experimentally tested and individually validated. Afterwards, they can be combined flexibly to create different structures, offering a general construction framework. The vehicles can adapt to changes when building and interacting with each other *in situ* to create assemblies that could not be pre-assembled. This chapter, therefore, presents the fabrication of linear tensile structures with flying robots as a sequence of discrete building primitives connected to one another. It distinguishes between three basic primitives: knots, links, and braids. These three primitives are considered the variables that determine a tensile structure through their concatenation, whereas the interlacing presents a fourth type, a special case of such a concatenation.

4.1.1 Knot

Since the Stone Age, knots have been used as a method to connect objects. Gottfried Semper argues that the knot is the oldest construction technique and symbol of architecture, and represents the origin of (textile) tectonics [117, p. 180]. In the context of this thesis, knots are understood as a building primitive that constitutes the connection member of a tensile structure. In practice, tensile members are often fastened to objects through a special connector, such as a screw bolt or a clamp [118, pp. 100-109]. Such connectors can be generic, for example with a rotating element that provides additional degrees of freedom, allowing the same connector to be used for various configurations and enabling a high degree of flexibility on the construction site. Furthermore, they usually do not weaken the tensile material, since the rope fibres are only minimally bent. However, most connectors are designed to be installed by humans. Tightening a screw bolt, for example, is a multisensory operation created for the human hand and is difficult to automate with a robotic system. Robotic fabrication processes, conversely, have the ability to apply connection methods that are difficult to perform for the human hand. [93] For example, because it is physically detached, a flying robot can manoeuvre around and in-between structural supports to steer rope material around objects and tie knots. A knot-based connection technique for aerial robotic construction has the advantage of being self-compacting; it can thus take into consideration the abilities of the machine and inform the construction methodology accordingly. This work therefore leverages the connective nature of rope – and the friction caused by winding it around structural supports – to knot together three-dimensional structures.

Definition

A knot is a point of intersection, where a tensile construction member such as a rope or a cable intersects with another object or with itself. The stability of a knot is determined by its topology and material resistance, which is based on the friction of the material. A knot can be a solid fastening, or it can be a sliding connection [119].

Knot-tying is probably the first construction method used by humans to connect objects. Because this archaic technique has a long history of use across many disciplines, a number of distinct, application-specific knots have been developed. Indeed, special encyclopaedias provide overviews about the diversity of knots: *The Ashley Book of Knots* [120], for example, lists over 3800 different knots with written explanations and illustrations. Furthermore, a knot can be specified with *modifiers* [121, p. 43] that describe its properties, such as its material characteristics (i.e. color, size, shape, and flexibility) or its structural properties (i.e. tension). Whatever their various distinguishing characteristics, however, all knots have one thing in common: they are constructed by passing tensile material over and under itself or other members, creating friction with the crossings. This abstraction is used to deal with the complexity and the manifold aspects of knots, by defining a generalised framework that mathematically describes them. This method results in both a representation of the knot itself, and fabrication instructions for the flying vehicles [122]. The framework is based on a topological description of how a knot is tied sequentially, and consists of three parts:

Topology Knot theory is an existing branch of topology that studies mathematical knots[33] and offers various ways of describing them. Common representation methods are knot diagrams that use knot projections, whereby a knot is projected on a plane (Fig. 4.1) [123]. Material characteristics (such as thickness) and spatial information (such as position and orientation) are ignored, and the knot is simply represented by a curve in two-dimensional space. A break indicates a crossing, where the broken line marks the part that lies underneath. The two-dimensional diagrams allow any knot to be drawn, whereas different representations might represent the same knot (Fig. 4.1) [124]. The fundamental question of whether or not two knot projections are equivalent has concerned mathematicians for centuries [125, p. 197]. For the fabrication of knots, however, the question about the equivalence is irrelevant: if two knots have different planar representations but are in fact equivalent, the continuous deformation, once the knots are taught, transforms them into the same knot. Beyond simply providing a means of visual representation, another advantage

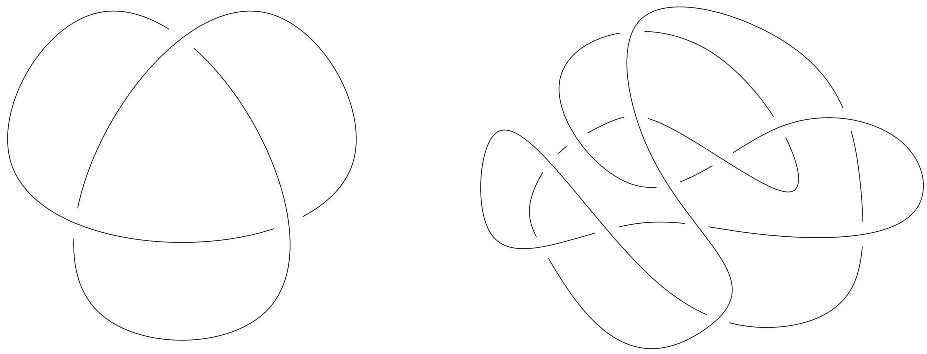
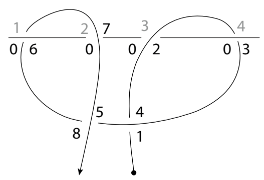


Fig. 4.1: Knot projections of the *trefoil* knot. The two different diagrams represent the same knot since the knot on the right can be deformed with continuous movements into the knot on the left.

of knot projections is that they can describe a knot numerically, using notations. Knot theory offers various ways of creating such notations. The goal of each method is to encode a diagram, so that it can later be reconstructed from the code. Today, computational tools allow diagrams to be automatically transformed into codes and vice versa [126]. The work presented here uses a derivation of the Dowker-Thistlethwaite Notation (DT-Notation) [127], where the crossings of a given knot diagram are labelled according to a set of rules, and are transferred into a matrix with three rows, where each column defines one crossing.

Mathematical knots have joined ends, with no beginning and no end. Even though it is inspired by knot theory, the knot description in this work requires that the beginnings and the ends of knots be implemented as a segment of the linear building material. A knot is therefore represented with two terminals, one representing the beginning and one representing the end (Fig. 4.2). Furthermore, when building tensile structures, knots are usually connected to other supports rather than to just themselves. This support is projected as a horizontal line onto the diagram. This line can represent either a rigid support element, a bar, or an already constructed tensile member. To create the notation, one must follow the start terminal of the rope that builds the knot and label the first crossing with a 1. Continuing the path, the second crossing is labelled with a 2, and so forth. When intersecting a crossing that has already been labelled, a second label is assigned. These increasing numbers build the first row of the matrix. If the path crosses the horizontal support line, a 0 is assigned to the crossing. The second row of the matrix states the crossing number, which is either positive (if the path is crossing the rope) or a 0 (if the path is crossing the support). While most knot representations do not require the orientation of a crossing to be specified, some knots might not be well defined without the orientation. For a left-handed rope-to-rope crossing, a 1 is inserted, and for a right-handed rope-to-rope crossing, a 2 is inserted. For a rope-to-support crossing, the support numbers are inserted (grey numbers in Fig. 4.2). The horizontal line crossings are additionally marked with increasing numbers from left to right, helping to construct the third row of the matrix. This matrix notation encodes the knot numerically and describes the path of a rope crossing above and under the support element and itself.



1	2	3	4	5	6	7	8
4	0	0	1	8	0	0	5
-1	3	-4	2	-1	-1	2	2

Fig. 4.2: Planar knot diagram and matrix notation of the Munter knot.

Sequence The knot representation described above reformulates knot theory's infinite knot with no ends by breaking it up and adding a beginning and an end to the diagram and thus describing it in its final configuration. To translate the knot design information into fabrication instructions, the notations must also take into account the sequence in which members pass over and under other members. This is crucial, since, when constructing a knot, the only relevant crossings are those that result from the sequential build-up (Fig. 4.3).

From left to right, each column defines one crossing step of the fabrication sequence. The resulting matrix provides all the instruction needed to fabricate the knot.

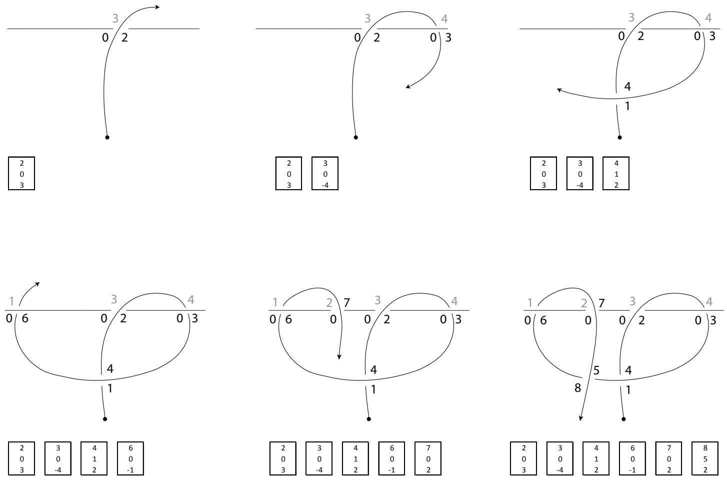


Fig. 4.3: Adaptation of the knot diagram required for the actual fabrication of the knot. The matrix on the bottom right constitutes the complete instructions for the Munter knot.

Spatiality The topological notation does not incorporate a knot's spatial information (such as scale, position, and orientation), which is required to generate the trajectory for the flying machines. Therefore, in the last step, the spatial parameters are integrated into the model to make it three-dimensional. To describe a knot in three-dimensional space, the centre point (3D-point) of the knot on the support element is required. Further, the orientation of the support element must be specified (3D-vector) in order to define the spatial orientation of the knot and avoid collisions with the support structure. Finally, the last parameter needed is the approach direction of the flying machine (3D-vector), usually a derivation from the location of the previous knot and the centre point of the knot in question. These three parameters define a plane in three-dimensional space and add the required spatial information to the knot. A flying vehicle is able to tie the knot by flying circular movements around the centre point following the crossing sequence of the knot notation.

The generalised method presented herein allows knots to be described and translated into fabrication instructions. However, not all knots are buildable by flying machines. Depending on the orientation of the support element and the available building space, a knot might not be realisable. Also, a vehicle may require different strategies to build different kinds of knots. Knots that are fabricated

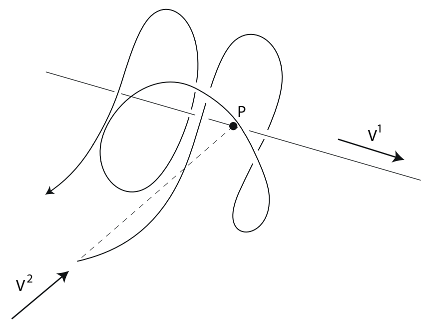


Fig. 4.4: Three-dimensional trajectory of the Munter knot with the centre point of the node (P), the orientation of the bar (V^1) and the approach direction (V^2).

with a constant tension (winding knots) are less difficult to fly than knots with loops, where the vehicle must pass the working end of the rope through a loop (overhand knots), as the following sub-chapter will show.

Exemplary knot constructions

A knot notation is an abstraction that reduces the material complexity (ignoring friction and gravity) of the knot and provides a description for its construction. When tying a knot, additional parameters might affect its realisability. The force the vehicle applies on the rope when tying a knot can effect how the rope hangs in space. A rope might slide on the support structure and the buildabilty might be constrained by a small building space, or an unfavourable support orientation or approach direction. And yet the actual manoeuvres required to tie even complex knots are often repetitive, as these are often a concatenation of basic primitives (i.e. of crossings around either the support element or the standing part of the rope (Fig. 4.5)). This chapter proves the concatenation principle by examining four exemplary knots that attach a rope to a linear support element, and which were realised by quadrocopters. These knots constitute the basic crossing primitives mentioned above, enabling them to be concatenated to more complex knots. A *turn* and a *munter* can be executed by a continuous movement around the support structure with a constant tension, while a *half-hitch* and a *clove-hitch* require the terminal (the working end of the rope) to be passed through a loop.

The following knots have been autonomously realised by a quadrocopter, using a visual localisation method for way-point navigation (different from the experimental facility described in Chapter 5).[34] In order to examine the limi-

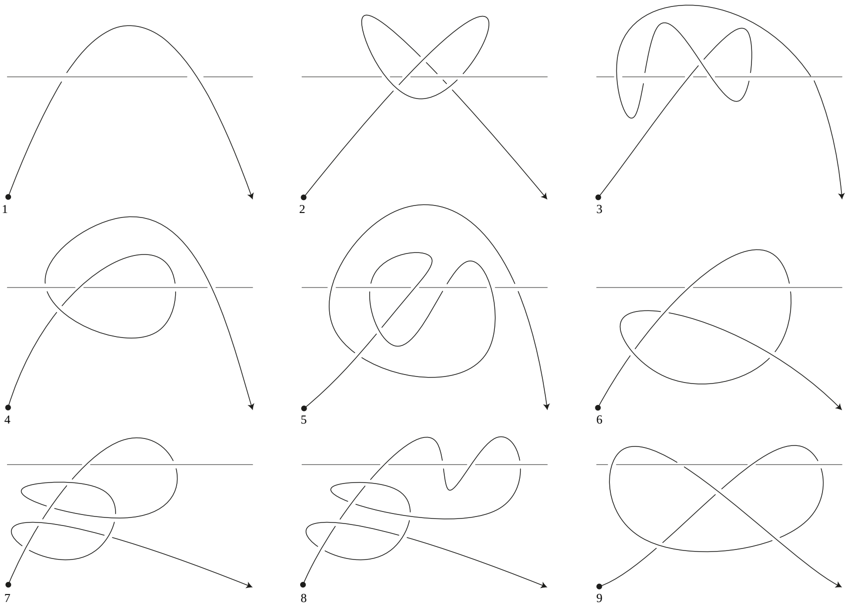


Fig. 4.5: Planar projection of examples of knots. The different knots constitute repeatable basic crossing primitives around the support bar and the standing part of the rope: (1) *turn*, (2) *round-turn*, (3) *two-round-turn*, (4) *munter*, (5) *double-munter*, (6) *half-hitch*, (7) *two-half-hitc*h, (8) *two-half-hitch-round-turn* and (9) *clove-hitch*. In this chapter, the *turn*, the *munter*, the *half-hitch*, and the *clove-hitch* are further examined.

tations arising from different spatial orientations of the support, each knot has been tested at a horizontal, vertical, and 45-degree inclined support element.

Turn A *turn* can be constructed by creating a round (or multiple rounds etc.) (Fig. 4.5.1-2) by pulling the working end of the rope around an object [120, p. 12]. A *turn* is the most elemental knot, and is used to build the primitive on which most other knot fabrications are based. It is robotically realised by having the quadrocopter fly around a support element as it deploys tensile rope from an attached dispenser (Fig. 4.6). The knot can be tied independently of the support bar orientation. In a non-horizontal arrangement, the tensile rope must be kept under constant tension to prevent the rope from sliding on the support element. The minimal building space the manoeuvre requires relates to the orientation of the support and the acceleration (see Chapter 3.1.1) of the machine. For example, because the height of the machine is small in comparison to its length and width, flying the knot on the horizontal bar requires less space than flying the same manoeuvre on the vertical bar. While the knot can be fabricated from different approach directions, the ideal orientation of the bar is within approximately 60 degrees of the approach orientation so that the vehicle does not collide with the support structure when performing the manoeuvre

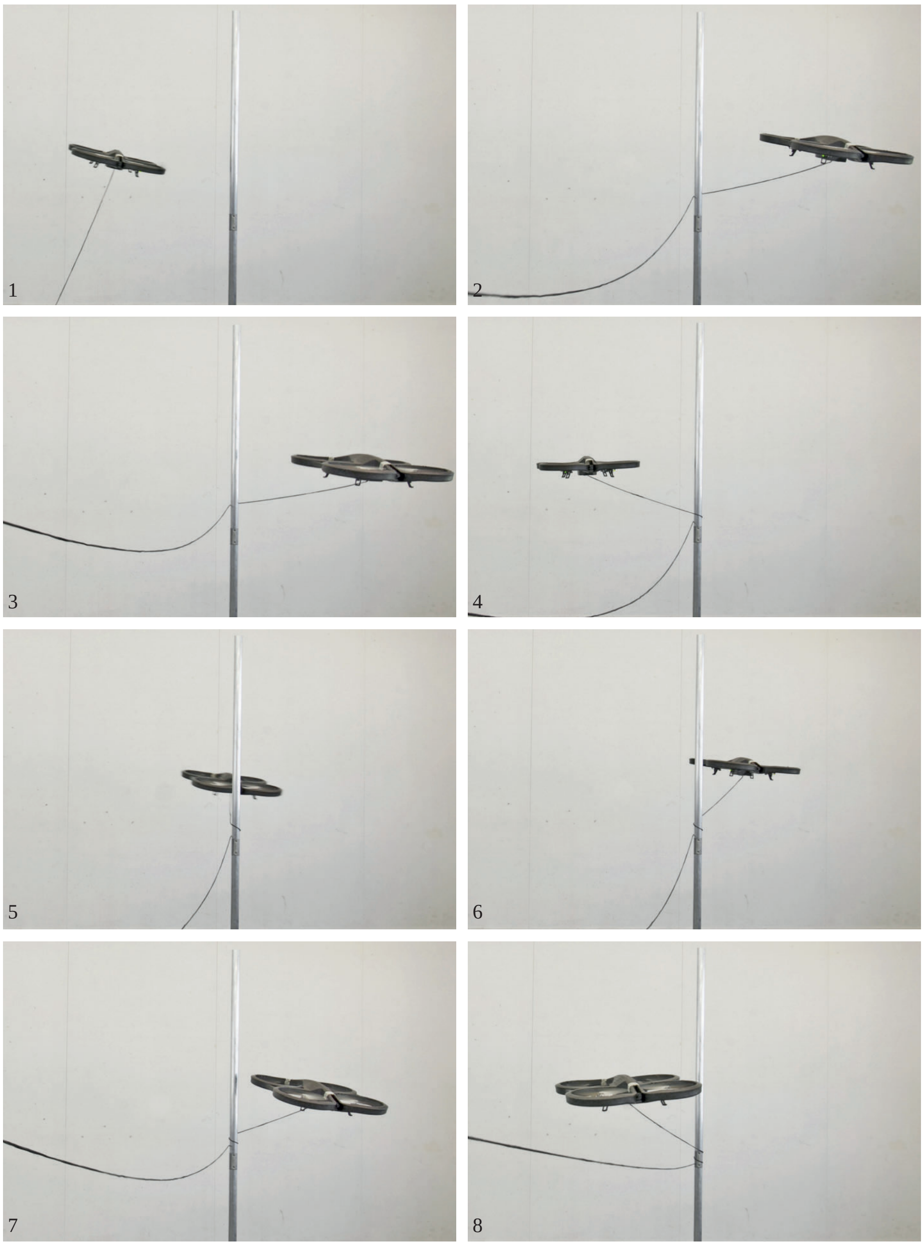


Fig. 4.6: A *two-round-turn* performed around a vertical support element. The knot is created by flying twice around the bar (1-8). [128]

(see grey area in upper drawing of Fig. 4.10). As soon at the machine interacts with the support structure, tractive forces act upon it. The control system must adapt for these forces so that the machine can follow the programmed trajectory. The strength of the knot can be increased by multiplying the number of turns around the bar. The required holding force can be calculated using the capstan equation (see Experiment 1 in Chapter 5.2).

Munter The *munter*, or *Crossing Hitch* [120, p. 40], is a useful knot for aerial construction (Fig. 4.5.4). It is a simple knot that is often used by mountaineers to damp the rope in the event of a sudden fall. The *munter* is realised by making a *single-turn* around the support bar, followed by a *turn* around the deployed rope, before making another *turn* around the support bar, but in the opposite direction (Fig. 4.7).

The knot can be fabricated independently of the support orientation. Just like in a *turn*, in a *munter* with a non-horizontal arrangement, the rope must be kept under tension. Flying a *munter* knot requires more space than flying a simple *turn* (in addition to going around the bar, the vehicle must also fly around the rope). Structurally, the *munter* performs better than the *turn*. It distinguishes itself by creating a more stable connection due to stronger friction, as the connection point rubs not only on the support object, but on the rope itself. The alternating rotations around the bar equally distribute the forces when the knot is loaded from the rope to the support element. The *munter* can also be multiplied to create an even more solid fastening to an object.

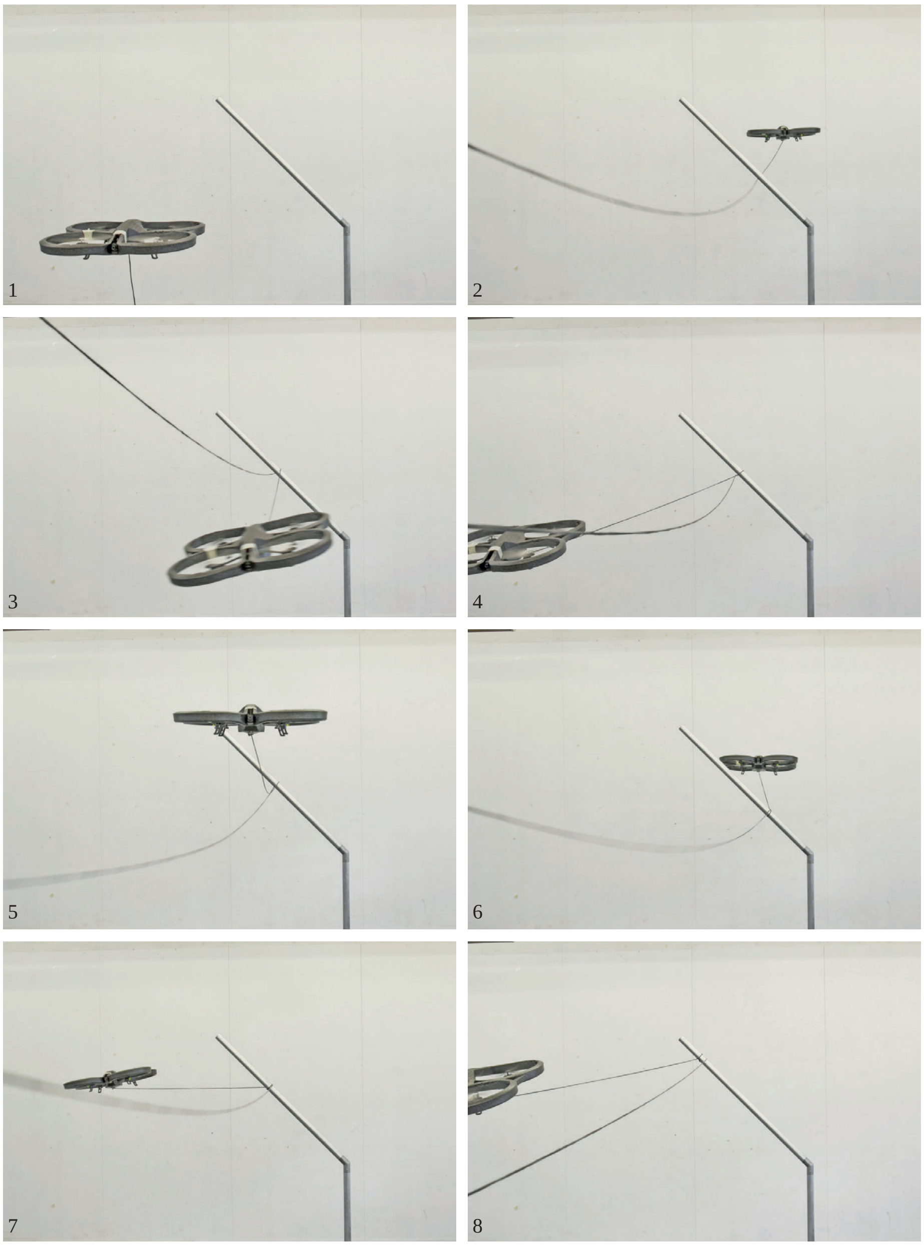


Fig. 4.7: The *munter* knot fabricated at an inclined support bar. The knot is created by flying a *turn* around the bar (1-2), followed by a *turn* around the standing part of the rope (3-5) and again a *turn* around the support element but in the opposite direction (6-8). [128]

Half-hitch The *half-hitch* is a basic overhand knot, where the working end is pushed through a loop (Fig. 4.11). It is fabricated by making a *turn* around the support object, before guiding the working end of the rope over and under the standing part and pulling it through the loop [120, p. 14]. *Half-hitches* build a fundamental primitive for a wide variety of stable knots. When loads act on an overhand knot, the loop that crosses itself tightens and causes the assembly to jam, creating a secure fastening. The construction of an overhand knot

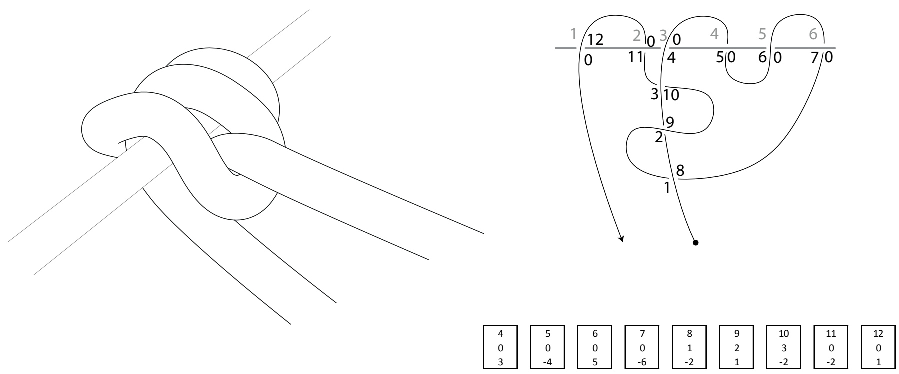


Fig. 4.8: Exemplary drawing and notation of one of the four knots: *Half-hitch* with an additional *round-turn*. The knot starts with a *round-turn* on the bar (1). Then a hanging segment is created on the standing part of the rope (2-4) through which the vehicle pulls the rope through (5). Afterwards, the overhand knot is tightened by creating another *turn* around the support element (6-8).

using flying machines is challenging, since it cannot be realised with constant tension. Using the gravitational force, the vehicle must create a catenary that is large enough to fly through. It is only possible to create such an arrangement if the following conditions are fulfilled: First, the knot works best with a horizontal support bar, because this is the only case where the rope does not slide down along the support as soon as the vehicle releases the tension to create the catenary. Furthermore, a *half-turn* on the support bar does not create enough friction to create a stable support condition on the standing part of the rope. To stop it from sliding away once the tension is released, an additional turn around the bar is required (Fig. 4.8). The sliding is also a problem when creating the catenary. The working end might slide on the standing part of the rope (Fig. 4.9). The rope's coefficient of friction defines the angle at which the rope will start sliding. With Dyneema, the material used to test the fabrication of the knot, the rope starts to slide on itself at approximately 4 degrees (Dyneema has a very small coefficient of friction). The possible approach direction is therefore limited by the sliding of the rope. However, at approach directions from below the knot centre point, the machine can compensate for the sliding by pulling the rope (Fig. 4.9). The larger the constructed catenary, the more reliable is the performing of the manoeuvre, but also the larger is the required building space. Furthermore, the size of the catenary relates to the approach direction and become infinitely large. Hence, an approach direction up to -60 degrees of the center point of the knot is feasible (see grey area at the bottom drawing in Fig. 4.10). The successful realisation of the knot creates a solid fastening to an object. The solution space, however, is largely constrained by the angle of approach, which causes the rope to slide on itself.

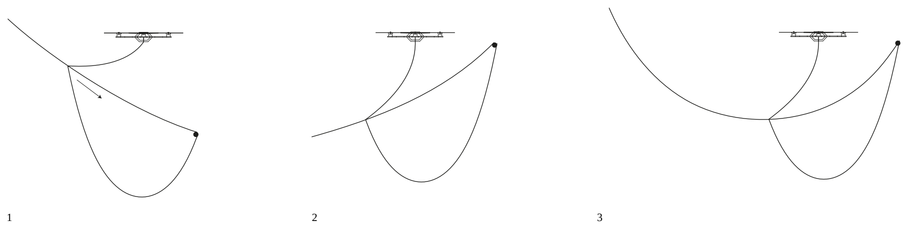


Fig. 4.9: Realisability limitations of the *half-hitch* at different approach directions around a horizontal bar. (1) is not buildable, but (2) and (3) are.

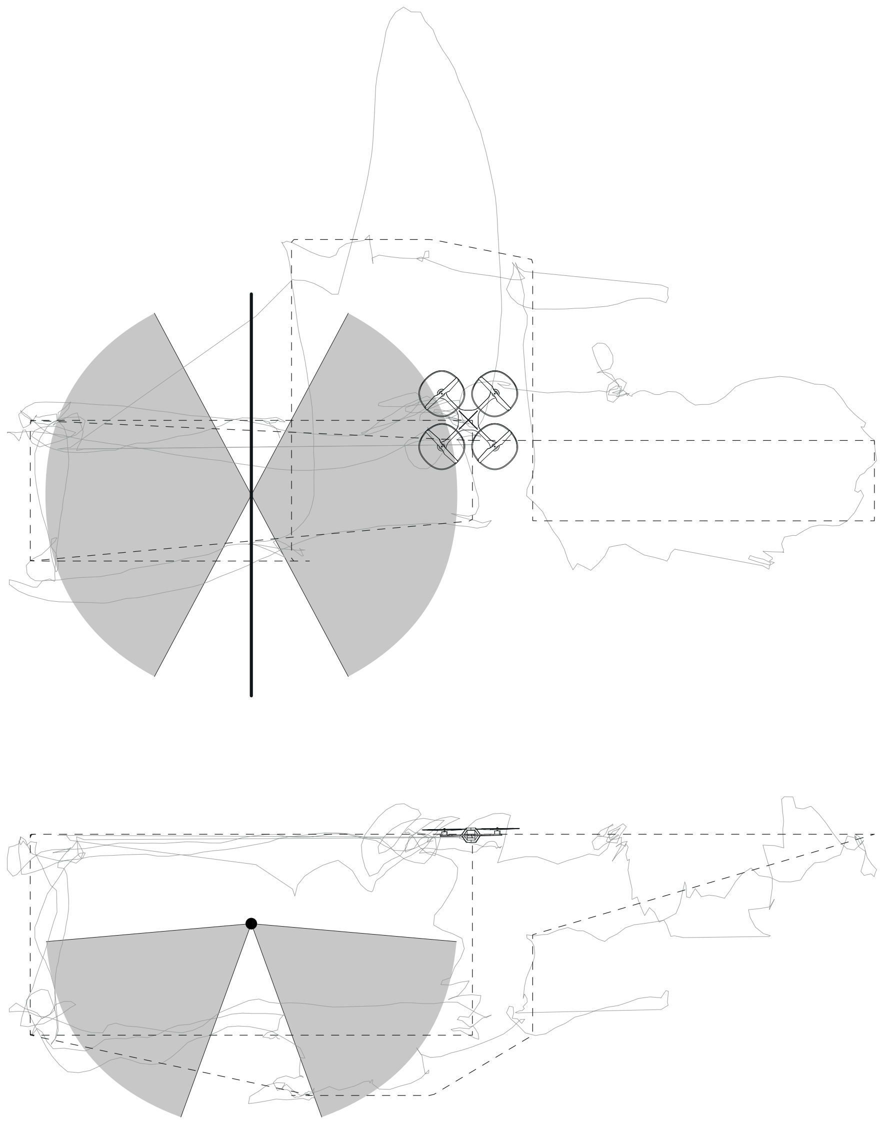


Fig. 4.10: Visualisation of the log-file data from a *half-hitch*, executed on a horizontal bar, in plan (top) and elevation (bottom). The dashed line represents the programmed trajectory and the solid line shows the path of the vehicle. The upper drawing shows how the machine goes astray before following the programmed path again. This is caused by the forces acting on the vehicle as soon as the rope interacts with the bar, pulling on the machine. The grey area around the support bar indicates the range of feasible directions of approach for this knot.

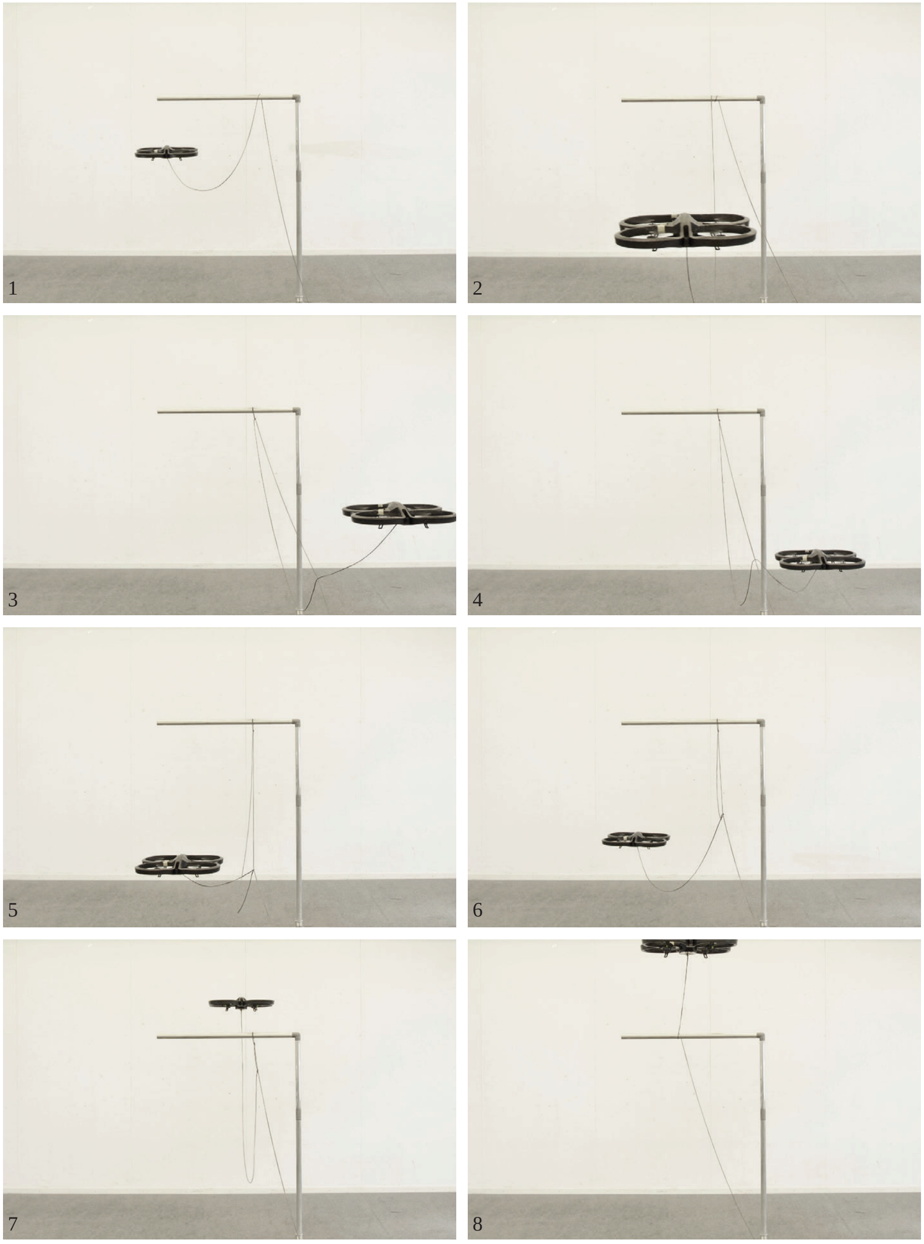


Fig. 4.11: The *half-hitch* constructed on a horizontal support bar. It is tied by first creating a *round-turn* on the support element (1), followed by a sagging rope segment on the horizontal bar (2-5), through which the vehicle pulls the rope (6-7) and tightens the knot (8). [128]

Clove-hitch The *clove-hitch* is an important knot that allows existing objects to be connected [120, p. 14]. It consists of two successive *half-hitches* (Fig. 4.12). When it is loaded, the knot slips and rotates towards the applied force, while tightening and jamming the rope, thus creating a solid fastening. Unlike the *half-hitch*, the *clove-hitch* is constructed around the support bar, rather than around the standing part of the rope, making it easier to untie.

The *clove-hitch* is also an overhand knot that, like the *half-hitch*, requires the construction of a catenary through which the working end can be pulled. The knot also requires a horizontal support (to prevent sliding), and is best started with a *round-turn*, which builds a stable point from which the next segment can freely hang. To make this manoeuvre possible, the catenary is suspended from the horizontal bar rather than from the standing part of the rope; for this reason, the knot can be realised from approach directions that are higher than the knot centre point. The start and end point of the catenary lay horizontally on the support bar. This keeps the length of the catenary constant and the building space unaltered and fixed. In contrast to the *half-hitch*, the *clove-hitch* requires a large horizontal support element to realise the knot (Fig. 4.12).

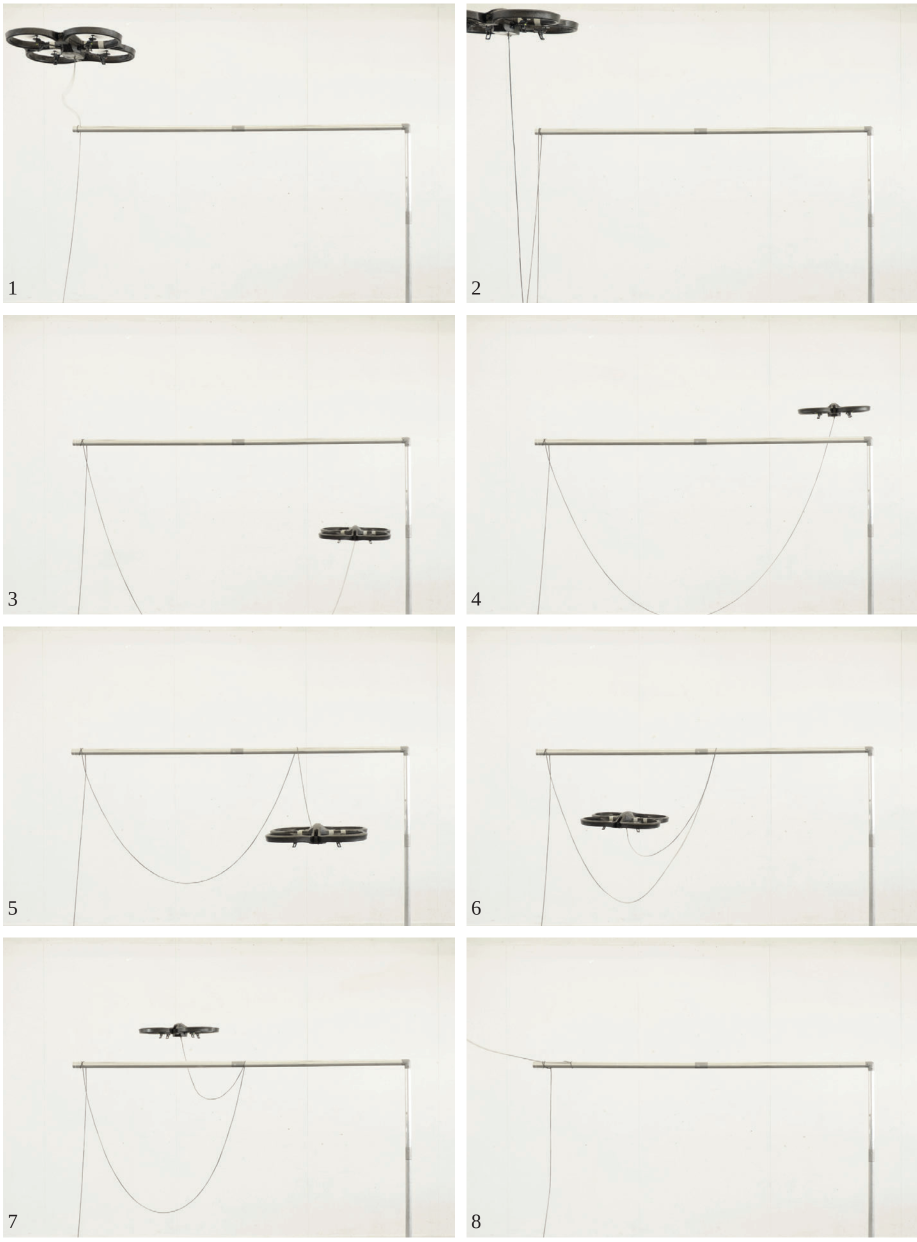


Fig. 4.12: Tying of a *clove-hitch* on a horizontal support bar. After flying a *round-turn* on the support element (1), the vehicle creates a sagging rope segment on the support (2-5), before flying through it (6-7) to create an overhand knot when tightening the rope (8). [128]

Discussion

After assessing the feasibility of a large spectrum of knots for their potential to be realisable with quadrocopters, the four knots described above were selected and experimentally validated. There exist a multitude of other knots, but their realisation is often a combination of the basic movements shown above. The construction of overhand knots (knots that pull the rope through a loop) allows complex and strong connections to be created. Still, their fabrication is challenging, since the tension on the rope must be varied during the deployment and is limited to certain approach orientations. Preliminary tests conducted within the scope of this thesis showed that it is possible to increase the solution space for overhand knots by using a second vehicle as a temporary, dynamic support point (Fig. 4.13). This would solve the sliding problem and the vehicle could be positioned dynamically without obstructing the building space. However, as a generalised method of tying knots with one vehicle, winding knots (like the *turn* or the *munter*), provide a repeatable method for tying knots with flying robots. Firstly, they can be flown with a constant tension, which allows the support element to have any given orientation. Secondly, they can be realised independently of the approach direction (provided the angle between the approach vector and the support vector is large enough). And finally, the building space needed for construction is smaller, because no hanging rope segment must be constructed. Therefore, for the experiments in Chapter 5, the *munter* and the *turn* were chosen as building primitives to connect the tensile members.

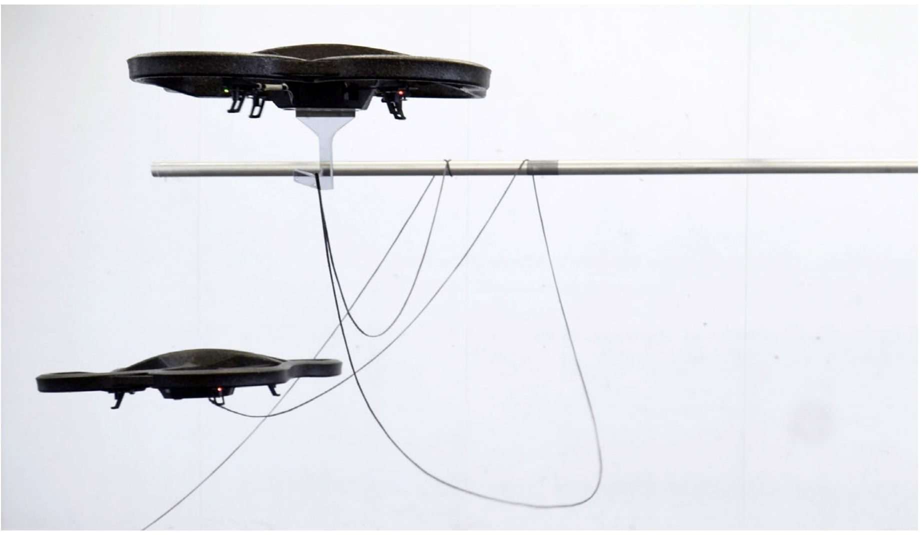


Fig. 4.13: Multi-vehicle cooperation while creating an overhand knot.

4.1.2 Link

Whereas the knot is the primitive defining an attachment point in space, the link is the primitive that spans space by connecting two knots. While rope can transfer tensile loads aligned with its centre line, its flexible nature means that it always takes on the form of a catenary curve whenever it is not under tension.

Definition

A rope spanned between two knots creates a link. The geometry of a link might change over time, such as over the course of the construction of a tensile structure, when intersecting with another link or redistributing the forces, or when creating a new equilibrium state, for example if a structure is dynamically loaded by people walking over it.

A link is defined by: 1) the location of its two supports points; and 2) the length (or tension) of the tensile material. It is only supported at its ends, and thus forms a hanging curve under its own weight. The shape of the link can be derived using the catenary equation, which resembles a graph of the hyperbolic cosine function [129, p. 121]. Any link can be drawn when the rope length and its start and end points are known, but not all links are realizable. The buildability of a link is constrained by the lifting capacity of the vehicle, which is itself determined by the weight of the building material (length of the rope) and the horizontal tension applied. When the sag of a link from the catenary equation and as well as the linear density of a specific tensile material are known, the horizontal force (link tension) can be calculated (4.1 [130]), where (h) is the sag, (w) is the weight per unit length and (S) is the length of the link. To create a high-tension link, the respective weight of the link (and hence the length of the rope) must be reduced, so that the limited force carrying capacity of the vehicle can be shifted to increase the tension force instead (Fig. 4.14).

$$F_h = \frac{w}{8h}(S^2 - 4h^2) \tag{4.1}$$

Examples

Building a tensile link is mainly dependent on the support conditions and the tension applied when fixing it (Fig. 4.15). The support structure can either be

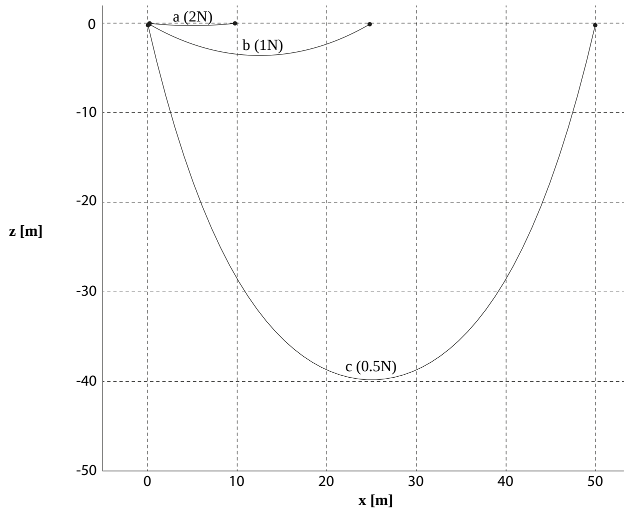


Fig. 4.14: Calculated relationship between the horizontal force and the span that can be supported with the limited force capacity of the vehicle. Decreasing the tension on a link allows larger distances to be bridged, and shifts the direction of force from horizontal to carrying payload. The graph shows the computed links with the linear density of a 3 mm Dyneema rope.

a solid object (for instance a bar) or a flexible structural member (for example an already constructed tensile link). The construction of a link with stable support conditions is less difficult to realise, since its form does not change when forces act upon it (Fig. 4.15; 1,4,7). When building a link onto another tensile link, however, the form of the support structure is modified by the force acting on it. This modification must be considered when building tensile links, since it influences the physical outcome of the structure. A relevant parameter is therefore the tension on the links. If a support link is taut, it acts almost like a solid support point (Fig. 4.15; 2, 3, 4, 6). On the other hand, if the same support link is sagging, it acts as a flexible link; the more considerable the sagging, the more the structure will be transformed when new links are attached (Fig. 4.15; 8, 9, 10). Links with quasi taut tension can be fabricated on fixed support points and on taut links. When flying the knot, the approach direction of the link must be considered in order to minimise the sliding of the rope on the support. The fabrication of links with controlled, variable tension adds complexity to the fabrication process. This can either be obtained by an actuated rope deployment system [131] or by adjusting the length of the rope before flying a connection. For the latter, the vehicle flies a defined distance while deploying rope material, relating to the rope length of the link to be constructed, at a constant tension, before fixing it at the designated support point. The same method was used to construct the overhand knots (Fig. 4.11

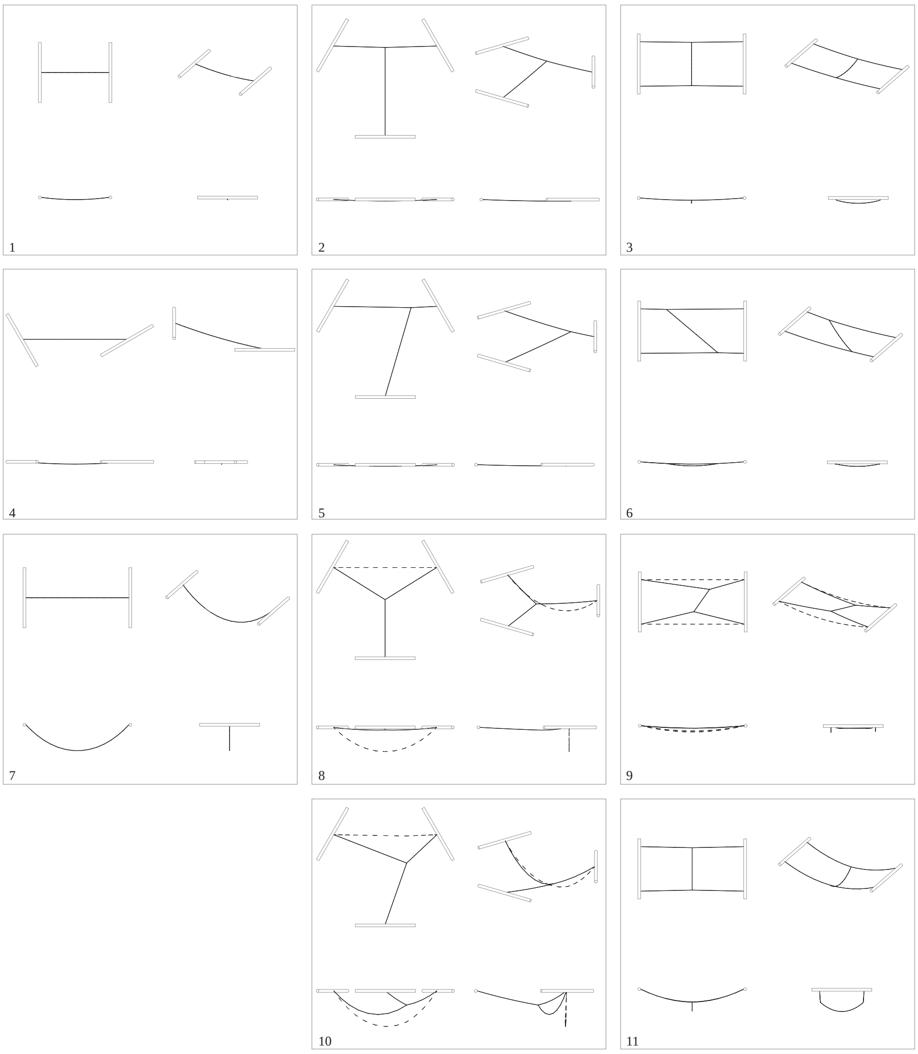


Fig. 4.15: Catalogue of links in plan, elevation and perspective view. The dashed line indicates a change of form of a structure over time: (1) taut link at a rectangular solid support structure with a variable distance between the support points, (2) taut link between a rectangular solid support structure and a taut support link with a variable distance between the support points, (3) taut rectangular link at two taut support links with a variable distance between the support points, (4) taut link at two solid support structures with variable support orientation, (5) taut link between a solid and a taut support link with variable support orientation, (6) taut link and two taut support links with variable support orientation, (7) non-taut link between two solid support points with variable tension, (8) taut link between a solid support and a non-taut link with a variable distance relating to the length of the support catenary, (9) taut link at two non-taut support links at variable angles, (10) non-taut link between a solid support and a non-taut link support at variable angles, and (11) a non-taut link at two non-taut support links with variable tension.

and 4.12). Additionally, the robotic system must be capable of tying knots at flexible support points that might swing and thus perform in an unstable manner. And finally, the design system must incorporate the dynamic behaviour of flexible links that interact with each other (Fig. 4.16).

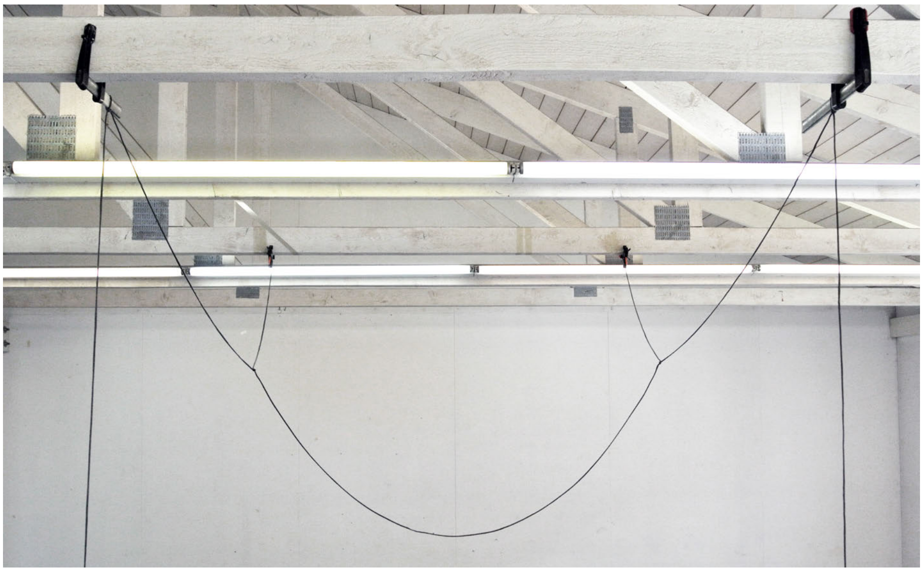


Fig. 4.16: Rope-to-rope link with sagging members.

Discussion

The machinic payload constraints limit the solution space of buildable links according to the weight of the rope and the tension applied (the flying machines used in Chapter 5 can apply approximately 2N-3N of force while still being controllable). The shorter the rope length, the smaller is the payload and hence the higher the tension that can be applied and vice versa. Integrating the rope tension parameter into the system increases the design freedom, but increases the difficulty for the flying robots to actually construct these links. In order to reduce the fabrication complexity, only *turn* knots are further considered as connection points between non-taut (sagging) ropes. These sliding connections are less difficult to realise since the vehicle has only minimal interaction with the support structure, and the link slides in place, depending on the tension applied during deployment. In turn, this reduction in construction difficulty challenges the way such structures are designed. Interacting links cannot merely be considered as individual links with solid connections to one another; rather, they require a distinction between fixed and sliding connections (this is further described in Chapter 4.2.2). The relationship between knot type and link is further characterised by the load acting on the structure. A link connected at a defined length to a support bar and holding its own weight might change when a force is applied to it, resulting in the knot tightening and making the link sag (see Chapter 5.5.6).

4.1.3 Braid

Tensile structures can be realised by concatenating knots and links. Depending on the support points, the types of knots, and the spatial arrangement, a variety of tensile structures, such as simple linear suspension structures, surface-like cable grid structures, or complex three-dimensional assemblies, can be defined. There are, however, tensile members that can be parametrised similarly to the knots and links but which cannot be clearly characterised as either being a knot or a link. They are situated in between, often with attributes of both building primitives. One example of this special type of building primitive is the braid.

Definition

A braid is a building primitive where multiple strands share a single starting point and the loose ends are interworked so that they overlap and cross over each other [121, p. 41]. A braid enables individual links to branch together to create a collective link, and then flexibly split apart again. Due to the relatively dense interworking of the strands, a braid is at the same time a (linear) knot and a link.

Example

The building primitives discussed so far can in principle be constructed with one vehicle, since different links can be placed sequentially. A braid, in contrast, in most cases requires multiple vehicles cooperating for its fabrication, since the order of interworking the rope members cannot be sequenced and executed by one vehicle. The number of strands in a braid determines the number of machines required for its realisation (Fig. 4.17). For example, if performed by a single vehicle, the machine is only able to fly a helix trajectory around an already built link, creating a twist with non-uniform tension (Fig. 4.17.1). Two vehicles increase the design space, enabling either the construction of a twist-braid with two strands and uniform tension (Fig. 4.17.2) or a braid with three stands (one already constructed beforehand) with non-uniform tension

(Fig. 4.17.3). To create a uniform braid with three strands, three vehicles are required (Fig. 4.17.4), a braid with four single strands requires four (Fig. 4.18), and so forth. The density of a braid is defined by the slope at which the

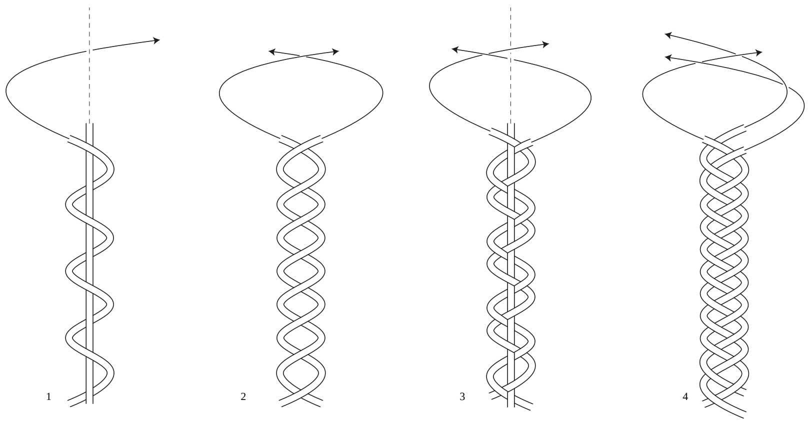


Fig. 4.17: Different braids according to the minimum number of vehicles needed for their realisation: Non-uniform two strand twist with one vehicle (1), uniform two strand twist with two vehicles (2), non-uniform three strand braid with two vehicles (3), and uniform three strand braid with three vehicles (4).

material is placed. This slope is determined by the angle between the axis of the braid and the position of the vehicle with respect to the braid building point (Fig. 4.17). The larger the angle, the denser is the braid, the more vehicles are involved in building, and the greater is the required distance between the vehicles and the braid building point. The building space required to create a braid correlates with the number of vehicles involved in the construction. The density, or the slope, of a braid need not be constant, but can vary from strand to strand and can change over time.

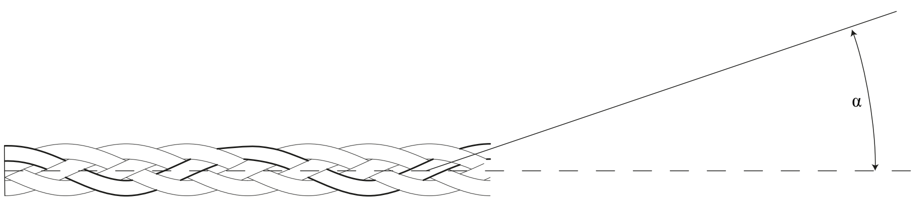


Fig. 4.18: The angle between the braid axis and the position of the vehicle relative to the braid building point defines the density of the braid.

4.1.4 Interlacing

Within the scope of this thesis, the knot, the link, and the braid constitute the primary building primitives, and their concatenation define a tensile structure. Interlacing is a special case of such a concatenation, and is a combination of knots and links that can be parametrised similarly to the braid to define a pattern of interworked tensile members.

Definition

An interlacing denotes interworked rope that passes over and under members crossing their path at variable directions and densities, constituting a pattern from which a tensile structure is configured.

Examples

Two such primitives – the mesh and the weave – were investigated in this thesis.

Mesh A mesh is an interlacing that is openly worked, making it transparent and porous [121, p. 38]. The tensile members are crossed at different orientations. The crossings follow a defined rhythm of over- and under-crossings (Fig. 4.19). Meshes are effective in creating two-dimensional and three-dimensional structures that adapt when loaded by distributing the forces over the multiple interworked members. When building a mesh with flying machines, two factors

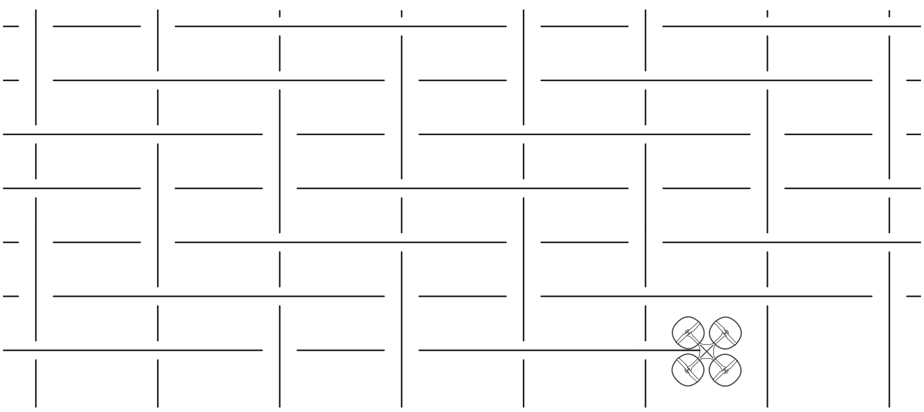


Fig. 4.19: Conceptual abstraction of a planar mesh interlacing in plan.

must be considered. First, the size of the vehicle defines the minimal density of a mesh, since the vehicle must be able to manoeuvre between the structure during the fabrication (Fig. 4.19). Fig. 4.21.1 shows the fabrication of a zigzag mesh structure by flying a figure eight trajectory around the support elements (see Chapter 5.3). The density of the assembly, relating to the *turn* angles at the corner and the distance between the support links, is limited by the size of the machine. (In principal, flying machines of different sizes could fabricate a mesh collaboratively, where thicker and longer links are built by large vehicles and the interlacing is performed by smaller vehicles that can navigate between the already constructed structural members.) Second, the sequence in which the members pass over can determine what kind of structures are buildable. While certain assemblies may only be realisable with multiple interacting machines, considering the order of interlacing can influence the number of machines required (Fig. 4.20).

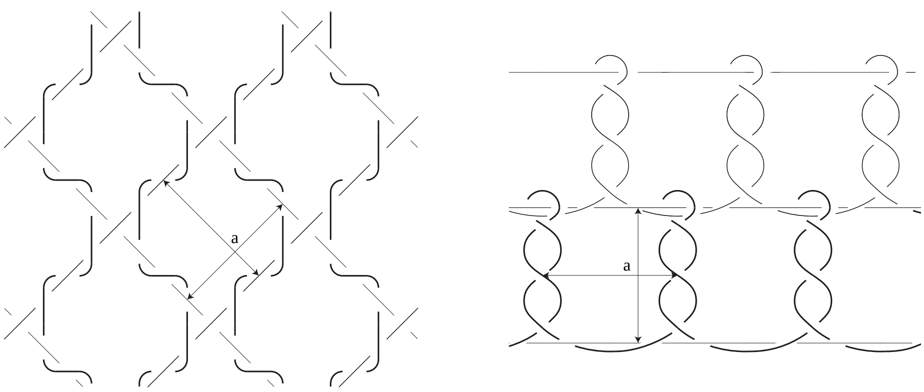


Fig. 4.20: Two examples of mesh that could be built by a single vehicle. The line thickness indicates the construction sequence from thin to thick (after [117, p. 186]). The fabrication sequence is indicated by different line-weights. The density of the mesh is limited by the size of the machine, which must safely navigate between already built structural members (a).

Weave A weave has interworked tensile members that create a closed assembly. Similarly to the mesh, a woven structure can be assembled by crossing linear tensile members with different orientations according to a defined pattern. The non-transparent nature of the primitive can be used to create partitions and to spatially enclose a structure.

Different aerial weaving strategies can be applied to fabricate closed tensile structures. One is to use the ability of the material to slide on the support links (Fig. 4.21.2). With enough distance to the structure, a series of *turns* can be performed on the support link, followed by a pull movement that merges the

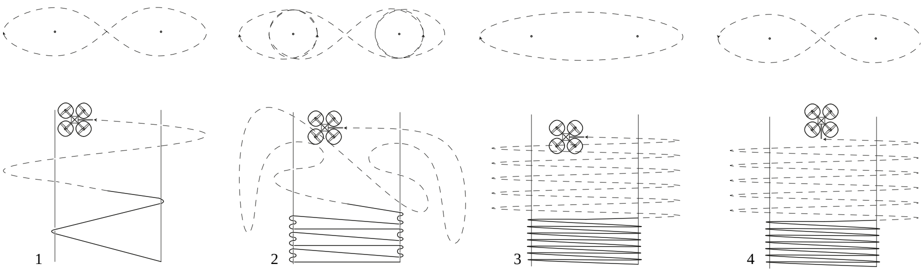


Fig. 4.21: Zigzag-mesh (1), pull-back-weave (2), winding-weave (3) and nozzle-weave (4). The dashed curve indicates the trajectory of the vehicle.

weave and creates a dense aggregation. The *round-turns* stabilises the pulled link and prevents it from sliding during the creation of the next link. The number of *turns* on the supports can be varied to specify the density and the pattern of the structure (Fig. 4.23). Another way of creating a weave structure is to wind around the support members (Fig. 4.21.3). This can be achieved by flying around the support structure in a circular motion, and deploying the tensile material as a series of links, next to one another. Though it has not been experimentally verified in this thesis, a potential third method is to deploy the material with a figure-eight movement around the support elements using a dedicated dispenser nozzle at the vehicle (Fig. 4.21.4). The function of the dispenser is to guide the rope away from the vehicle with a tube or a nozzle, creating enough distance between the already fabricated members and the vehicle to prevent collisions. When performing such a fabrication manoeuvre, the yawing orientation of the vehicle must be kept constant. In contrast to the mesh interlacing, a weave is less dependent on the size of the vehicle. The fabrication of a weave requires a lot of building material. To increase the efficiency while creating a closed structure, the cross section of the tensile rope could be changed from round to flat.

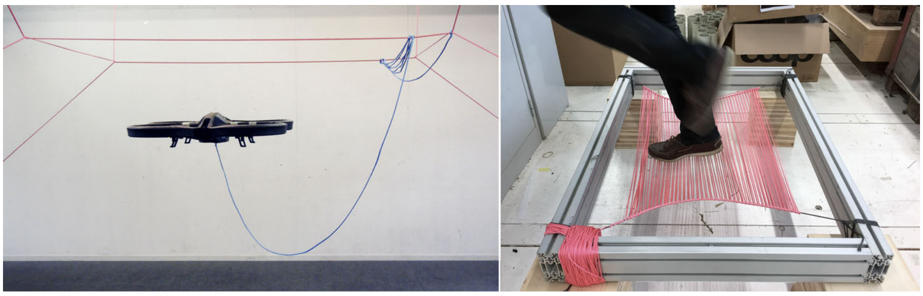


Fig. 4.22: Pull-back-weave experiment (left), and loading and usability test of a manually built pull-back-weave as a surface structure to walk on (right).

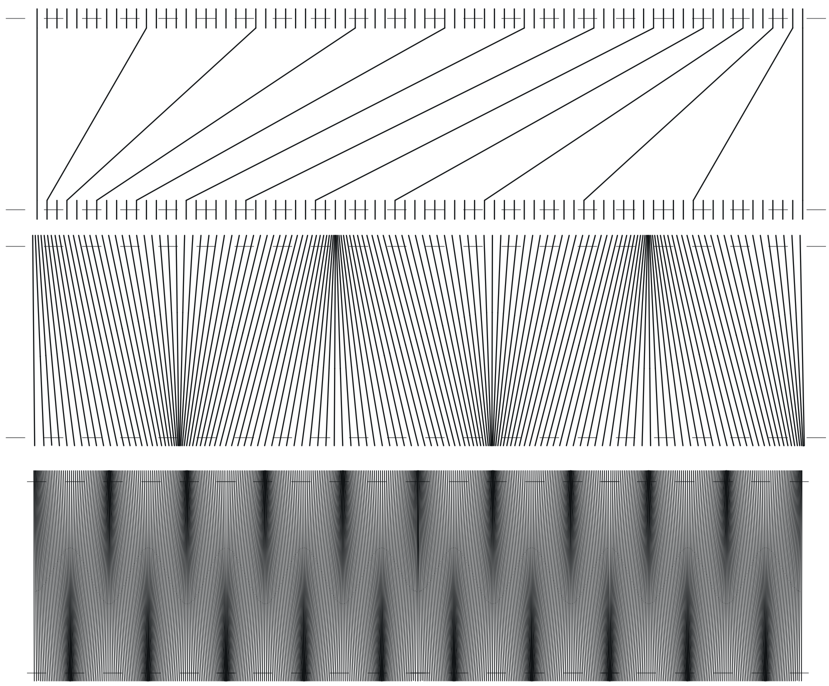


Fig. 4.23: Conceptual representation of a differentiated pull-back weave, where the number of *turns* on the support links define the density and the orientation of the structure. The vertical strokes in the upper drawing indicate the number of *turns* on the support elements. The middle and the lower drawing show the method at two different intensities (different rope diameters).

4.1.5 Discussion

Within the scope of this thesis, the building primitives of the knot, the link, and the braid (as well as the interlacings, a special case of combining knot a link primitives) constitute the framework of the basic construction primitives in aerial robotic tensile fabrication (Fig. 4.24). The proposed notation for the description of knots represents a generalised method to describe a knot and generate its fabrication information. The previous analysis of links and interlacing

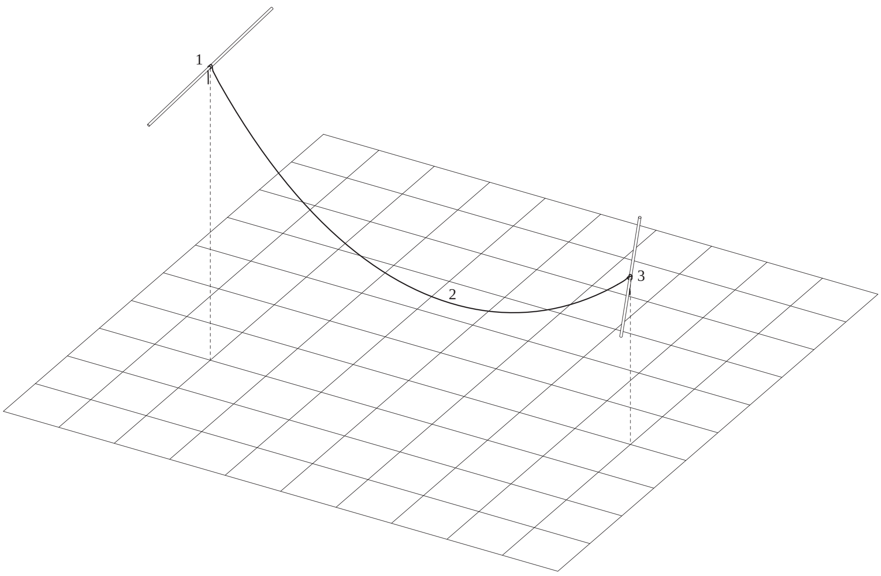


Fig. 4.24: Example of a definition of a basic tensile structure. (1) the first knot primitive is defined by the knot (for example the notation of a *round-turn*), the support location, the support orientation, and the approach direction of the vehicle. (2) the second knot primitive is also defined by the specific knot (for example the notation of a *munter*), the location of the knot, the support orientation, and the approach direction (in this case the vector from the first support point to the second support point). (3) the link primitive is defined by the link length and the two knot primitives.

reveals two key factors that challenge the design of tensile structures, however. First, modelling the behaviour of interacting links is challenging: though an individual link with fixed supports can be defined mathematically, sliding links acting together are more difficult to define, and strategies to simulate their behavior must be found before their final form can be designed. Second, the sequence of how the links are connected to each other defines what kind of structures are buildable, and as such, defines the design space. This requires the development of a strategy to logically sequence the deployment of the material. The following sub-chapter investigates the respective necessary tools and techniques.

4.2 Design tool

As the previous chapter has shown, designing tensile structures is challenging. In order to design tensile structures that are buildable with flying robots, a series of computational strategies have been developed and tested to specifically address challenges of the proposed aerial building method. These strategies have been implemented into a design tool that aims to determine feasible construction sequences through simulation techniques, and evaluate the structure before building. The computational tool provides a visual representation of the tensile structure and evaluates the realisability by examining the machinic constraints (for example collisions) of each building primitive according to the assembly sequence, creating an error message if a problem occurs.

4.2.1 Polygonal chain design approach

This thesis proposes to design a tensile structure with flying machines using a sequential design approach. In order to do so, a computational model of a structure must be defined by the designer. The designer defines each individual link as a geometrical member, according to the construction sequence, whereas each geometrical member represents a single construction step. The resulting model represents a time-based model of the construction, rather than a final artefact. The approach could be described by analogy to the geometrical model of a polygonal chain (Fig. 4.25). A design starts with a single point, representing a knot on a support structure, followed by a link to another support point, and so on. The resulting geometry is simulated and evaluated sequentially, step by step. The designer of the structure comprehends the assembly following the fabricational logic and adjusts the design accordingly (Fig. 4.26).

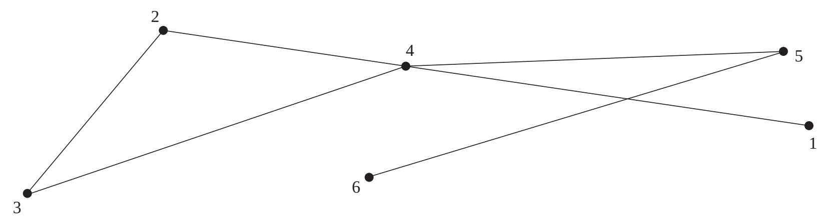


Fig. 4.25: The design system follows the logic of a polygonal chain. The order in which the geometry is generated resembles the fabrication sequence. For example: generate fixed knot (type a) at support point (1), generate link at length x with fixed knot (type b) at support point (2), generate fixed knot (type c) at support point (3), generate link with tension y with sliding knot (type d) on support point (4), etc.

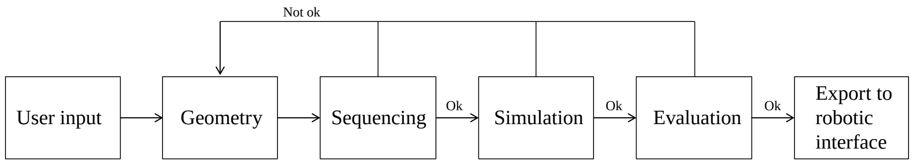


Fig. 4.26: The designer of the structure obtains feedback about design decisions sequentially. The order in which geometry is defined (for example a link) also determines the assembly order. The simulation provides form-finding feedback and the evaluation verifies the buildability of the building primitive.

4.2.2 Simulation of tensile members

Objective

Designing a form-active structure that consists of multiple interacting tensile links is challenging since its specific shape is not known in advance. Generating a form with linear tensile members such as ropes or cables requires the aid of form finding techniques in order to statically determine the structure acting in pure tension under self-weight [107]. Furthermore, a tensile structure might contain knots that are not fixed (a simple *turn* node) and that slide on structural members. Computational simulation techniques (such as physics engines [132]) allow the behaviour of tensile members to be simulated while providing visual representation that validates a design based on its simulated form. The simulation data is also required to evaluate the realisability of a structure (see Chapter 4.2.4).

Method

A strategy was developed for the physical simulation of tensile members, and the way they act under gravity and collisions. The computational architectural design environment that was used within the scope of this thesis (the CAD program Rhinoceros 3D) does not have a built-in physics engine that allows the simultaneous simulation of collisions and geometric tensile behaviour. As a result, a connection[35] from the computational CAD environment to an external physics engine (Maya nucleus [133]) was developed. The strength of the nucleus solver in Maya is in unifying different dynamics solvers with a generalised approach (using triangle meshes that also include points and curves). The behaviour of tensile material can be simulated, including collision dynamics with other objects and itself.

The geometrical information of a structure, such as the support points or the length of a link, is solely defined in the Rhinoceros 3D environment and the physics engine works only in the background. A custom component (within Rhino-Grasshopper) acts as the interface to the physics simulation. Once a tensile link is geometrically defined within this component and the simulation parameters (collision accuracy, bend, and stretch resistance) are allocated, the geometrical data and the simulation settings can be sent to the external engine. After the physics engine has calculated the behaviour of a link, the geometrical output-data from the simulation is automatically transmitted back to Rhinoceros 3D and rebuilt as geometry (Fig. 4.27). This simulation strategy was used to design the load-bearing structure in Chapter 5.6.

Discussion

A computational simulation, in this case, can only be an approximation of its physical realisation. However, it allows digital designs to be evaluated for their physical performance. Since the goal of the physical simulation here is not only to visually represent, but also to provide information about the feasibility of the structures, it should be as accurate as possible. A simulated model might deviate from its physical realisation, but this deviation can be reduced by tuning the parameters of the simulation. For example, the resolution of a curve can be increased to simulate its behaviour more accurately when colliding with other objects. A more accurate simulation is slower to compute, however, and yet timely feedback on design decisions is essential if the design process is to be intuitive. The friction at which the members slide on each other, or the tension a rope applies to another link, are parameters that can be adjusted in the physics engine. To test and tune the accuracy of the simulation model, interacting tensile links have been physically constructed and measured (Fig. 4.28). This allowed the discrepancy between the physical simulation and the physical building process to be minimised.

The physics engine enables form finding of tensile links interacting with each other (including collisions), and allows the user to evaluate the shape of a structure within an architectural CAD environment. This strategy also has drawback, however. It does not offer real-time interaction because the large quantity of interacting members and the required accuracy of the simulation parameters make the simulation slow. Furthermore, since there is more than one simulation parameter, the multiple interrelated variables of the physics engine make it difficult to precisely tune the simulation according to a physical model.[36]

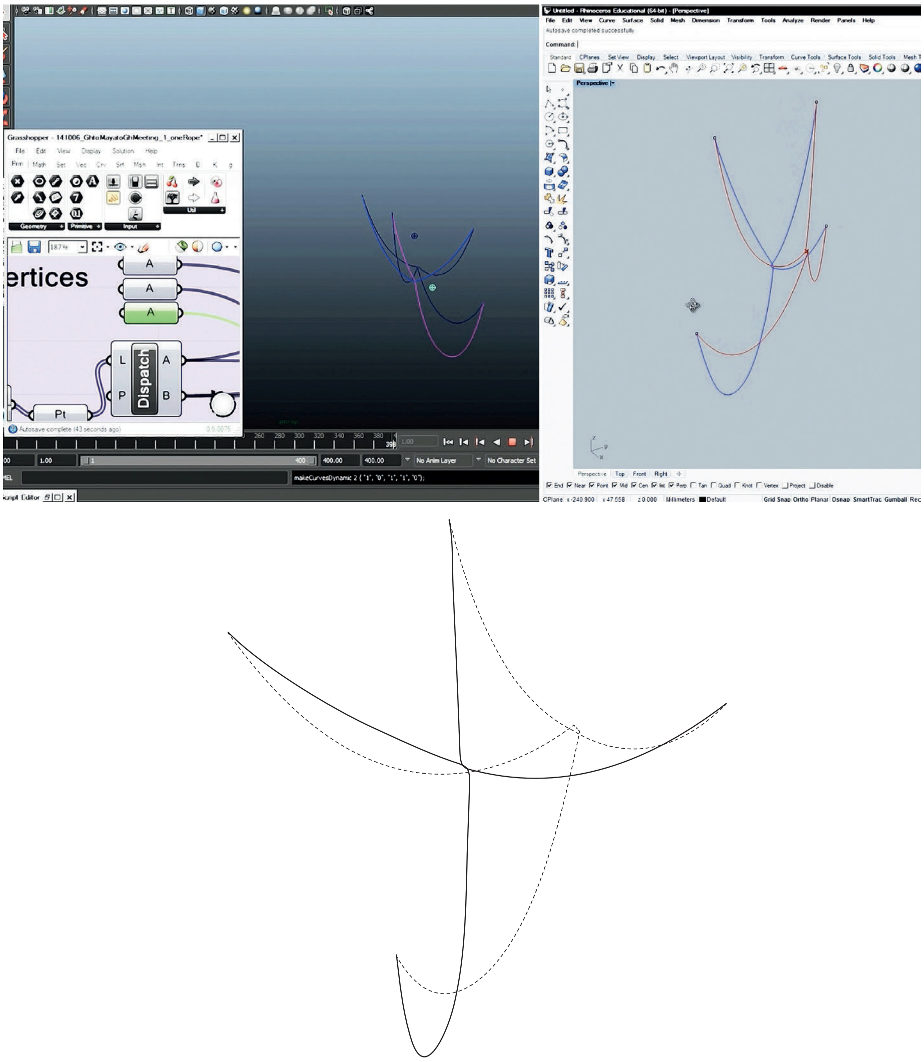


Fig. 4.27: Simulation of two interacting tensile links that are connected with a sliding *half-turn* knot. Top: screenshot of the simulation design environment. A Grasshopper component links the CAD environment in McNeel Rhinoceros 3D to the physics simulation in Autodesk Maya. Bottom: visualisation simulation input and output data. The dashed curves show the simulation input from Rhinoceros 3D and the solid curves show the rebuilt simulation output, calculated by the physics engine. The links created a new force equilibrium that considers sliding and collisions.

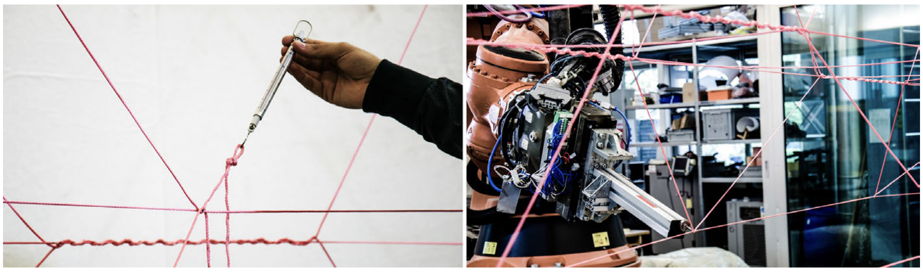


Fig. 4.28: A tensile structure has been constructed to validate the simulation component from 3 mm Dyneema rope, with a force of 2 N. The physical model was then measured with the help of an industrial robot, measuring key points of the achieved structure in space.

4.2.3 Sequencing

Objective

Aerial robotic construction must take into account the order in which tensile members are built. Therefore, in addition to the simulation, a sequencing component was developed and integrated into the design tool. This thesis proposes a sequential design approach, similar to the definition of a polygonal chain. This approach is based on the following assumptions: First, flying robots do not require building from the ground up. The robots, loaded with material, move independently of the structure they are building, until they temporarily interact with it and deposit material [12, p. 25]. Because of this freedom of movement, the order of material interaction does not always have to be spatially linear, and does not have to follow a certain direction (bottom-up, left-right etc.). A vehicle, for example, might fly between and through already built structural members and manipulate them three-dimensionally and over time. This, however, adds complexity when conceptualising a structure, since the non-linear placing order must be taken into consideration. The second reason for the sequential design approach derives from the flexible nature of the building material. The form-active structure changes its shape with every newly built interacting link. The geometry changes over time, constraining the path the vehicle can take. The digital model must describe this spatio-temporal performance of the structure.

Method

Taking this sequential approach into account, the sequence is defined by the order in which the designer defines the links. These links are simulated at every step. When a new link is defined, it is simulated by the physics engine into the

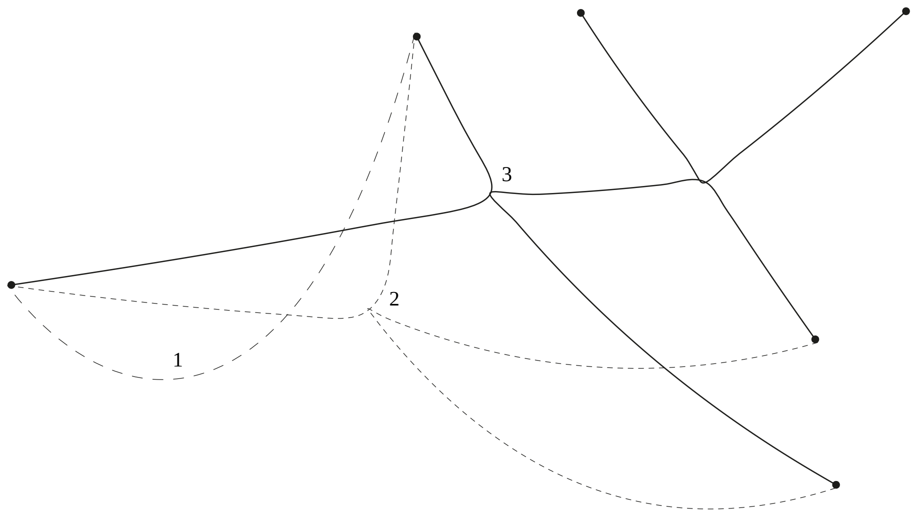


Fig. 4.29: A sequential model of a tensile structure with three links and two sliding *half-turns*. The model is simulated at every step: first with one link, then with two, and finally with three links. The numbers indicate how a point on the first link is moving over time. To prevent collisions when flying, the system must be aware of the spatial situation before and after the material is deployed.

already simulated geometry. The custom component developed in Rhinoceros 3D iteratively records all the simulation input and output data, creating a digital model with a timeline, where each frame represents one fabrication step (Fig. 4.29).

Discussion

The sequencing component records the simulated states according to the construction sequence and makes it possible to jump back to a specific step in the design sequence and implement changes. It considers the order of how a structure is built as the designer defines the structure. The component has been used to design the final experiment in Chapter 5.6. One disadvantage of it is that, in turn, when adding a link in between an already defined and simulated sequence, the preceding links must be redefined; since the order has changed, the design has changed. If the order of the structure is not effected and, for example, only the length of a link is changed, the proceeding links do not have to be redefined in the digital model, but must be re-simulated and re-evaluated. Once a model is complete and the sequence is defined, the simulation can be run, for instance, with varying link lengths that represent possible tolerances in the construction of the links by the vehicles, allowing the structure to be verified before it is built.

4.2.4 Evaluation

Objective

As described in Chapter 3, the fabrication constraints are an important aspect of aerial robotic construction. Subsequently, the evaluation of a structure's buildability must be incorporated into the design process, according to obstacle, physical, and machinic constraints. These constraints directly influence the design of the structure and must be integrated in the design process, requiring an evaluation component to be implemented into the design tool.

Method

Each knot type has a specific solution space in relation to the orientation of the support element and to the approach direction. Alongside the sequencing and the simulation of the structure, each knot is evaluated first regarding its orientation, and second regarding the possible collisions with the elements of the environment (for example the ground or a wall), and with the already fabricated structural members. The vehicle size and manoeuvrability influence the solution space (4.29). An offset to existing structural members creates a geometrical volume that represents a no-fly zone for the vehicles. Every newly defined link is run through the evaluation process to check its realisability (in respect to all already built members). As mentioned previously, if a design change is introduced at an earlier step in the sequential digital model, all succeeding steps must be re-evaluated.

Discussion

The evaluation enables the realisability of links and knots to be checked as part of the design process. It considers the constraints of the vehicle and the construction system, and informs the user (via text messages) on which building members are not possible to construct and why they must be changed. In this case, the developed component uses only geometrical data, such as the physical envelope of a vehicle or the position and the orientation of the support, to determine the construction feasibility of a building primitive.[37]

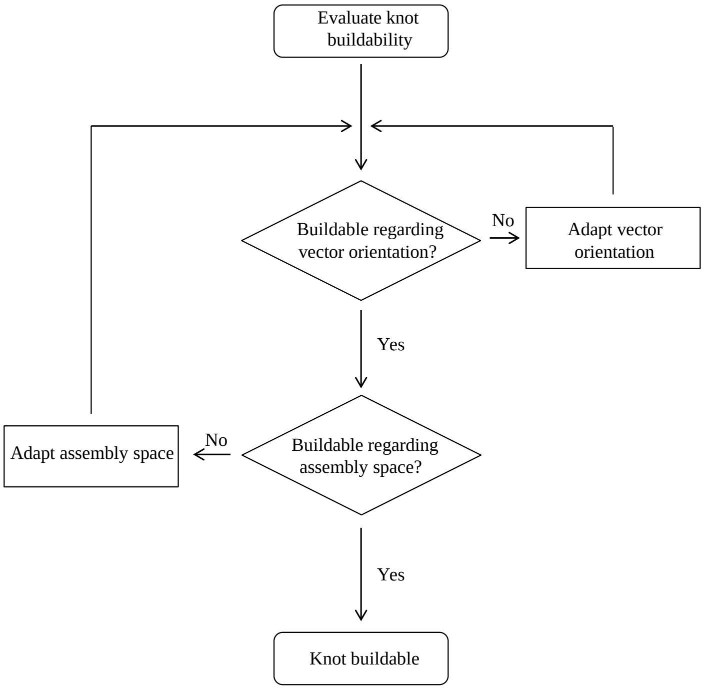


Fig. 4.30: Workflow diagram of the developed computational evaluation component: Each newly defined knot is evaluated on its buildabilty with respect to already constructed members.

4.3 Summary

Rope is a generic building material. It can be assembled in a number of ways, resulting in specific configurations. Although the length and cross section of a rope is clearly defined, its form and assembly logic is not [48, p. 185]. Consequently, this chapter defines a tensile structure as a concatenation of basic primitives (Fig. 4.31). Breaking down the building members into their fundamental primitives allows them to be flexibly combined and offers a high degree of flexibility in construction. Additionally, this creates a notation that makes the building of tensile members possible for the vehicles, allowing them to construct tensile structures by teaching them simple manoeuvres that constitute a structure of multiple members by their concatenation. The challenge of this "generic" and thereby versatile fabrication approach is that the design system must reflect it. Rather then prefabricating a tensile structure on the ground and lifting it like an aerial crane to its designated location, the act of breaking down tensile structures into a concatenation of knots and links increases the difficulty of conceptualising and planing such structures. The behaviour of ropes interacting with each other must be taken into account, and the assembly logic and fabrication constraints must be considered. The research proposes a

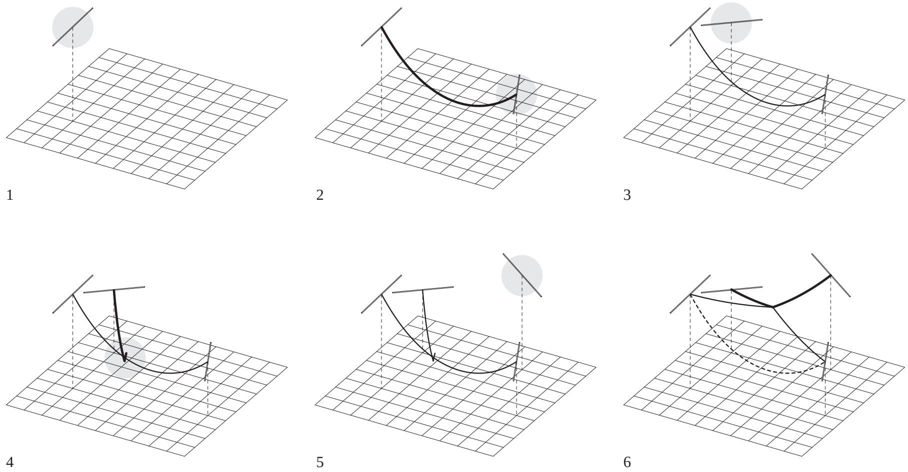


Fig. 4.31: Design process example of a tensile structure that consists of two interacting rope members: (1) the design starts with the selection of the first support point (parameters: location and orientation of the support, as well as approach direction of the vehicle) and the definition of the respective knot primitive (for example a *munter*). The knot primitive is then evaluated (indicated by the grey area) on its realiseability in relation to the support. (2) a link primitive, along with the respective next knot primitive, is defined by choosing the next support point (parameters: link length, knot notation, support location, support orientation, approach direction). The support is again evaluated based on the definition of the knot primitive and the link is simulated with the physics engine. (3) the third knot primitive for the second rope member is defined and evaluated. (4) the second rope member goes around the first one. To do so, a knot primitive (a *turn*) and a link are defined with the support point on the first link. The knot primitive is again evaluated and the links (not interacting at this point) are simulated. (5) finally, the last knot primitive and the last link primitive are defined. The knot is evaluated and the link simulation parameters are defined. (6) the final structure. The second rope member has interacted with the first one with a sliding knot, creating a new structural equilibrium. The dashed catenary curve indicates the spatial arrangement of the first rope member before the interaction.

sequential design approach with computational components that integrate the challenges of defining tensile structures that are buildable by quadrocopters, by integrating simulation, sequencing, and evaluation.[38]

To further develop the techniques of aerial robotic construction, the specific tools and methods described herein were empirically tested and validated. Thus, the next chapter describes the physical experiments used to evaluate the proposed design tool.

Notes

[32]Traditional structural systems often comprise discrete buildings elements, such as columns, beams, or walls that rely on the stiffness of the material and which are dimensioned linearly.

[33]A mathematical knot has joined ends and ignores physical properties, such as friction. [123]

[34]A lightweight off-the-shelf quadrocopter with integrated camera that can be controlled with a laptop was used to perform the knot experiments [134]. Using visual navigation Parallel Tracking And Mapping (PTAM), the vehicle can be programmed to follow a specific path that consists of way-points exported from the design environment. The camera images and the sensory information were processed on a laptop, using the Robot Operating System (ROS), and several open source software packages [135]. PTAM assumes a static-world and does not work well with objects moving in the scene [83]. The vision system allows a map of the environment to be created, however this map cannot be scaled from vision alone, and requires additional metric sensors, such as an air pressure sensor, to scale it [136]. In good conditions, after calibration, the method provides decimetre accuracy. The system, however, is less accurate and less robust than the indoor system used in Chapter 5.

[35]The UDP protocol was used to link the CAD environment to the physics engine in Autodesk Maya.

[36]To generalise the simulation approach, further testing and development are required. The integration of a feedback process and measuring the assembly during the fabrication would offer advantages in both simulation and fabrication processes. An inaccurate digital model could be adapted and the tolerances during the build-up could be compensated.

[37]The evaluation component could be improved by integrating the dynamic constraints of the vehicle, such as the generated propeller wash or the forces during rope deployment. Another constraint that has not been implemented yet is multi-vehicle cooperation, for example, when fabricating a braid.

[38]The techniques for building primitives and the computational design tool examined in this chapter are by no means exhaustive. There are surely other ways to describe tensile structures and other methods to build them. This also applies to the design technique. The computational tool developed herein attempts to provide a method that connects the designing and the making of tensile structures with flying robots. Of course, these tools require further development and there are surely other methods that could help the designer when developing a structure. One approach that is contrary to the described polygonal chain method, for example, would be to start with a global description of a complete structure, further post-process it with an optimisation routine, evaluate it, and then define its assembly logic.

Chapter 5

Experiments

5.1 Introduction

Following the definition and development of the fundamental elements of the design and construction methodology, this chapter shows experimental results to validate the method and techniques. Experiments involving the basic physical prototypes, a linear structure, a surface structure, and a three-dimensional structure examine the realisability of tensile rope structures with flying robots. The first three experiments validate key building primitives described in Chapter 4.1. The experiments conclude with the realisation of a 1:1 scale load-bearing suspension footbridge.

Testing facility

The experiments were conducted in the Flying Machine Arena [79], a 10 x 10 x 10 metre indoor space developed for aerial robotic research. The room is equipped with a net on three sides, to enclose the space, and mattresses on the ground, to soften the occasional crashes. The space is equipped with a global sensing motion capture system that provides vehicle position and attitude measurements. This information is sent to a PC, which evaluates this data based on a specific control strategy and sends commands to the quadrocopters. An example of a control strategy is, for instance, an algorithm that prevents vehicles from colliding when operating in the same space [57]. In addition to the temporal aspects of defining a trajectory, the path of a vehicle can be spatially defined with a series of waypoints that the vehicles pass, which can be drawn in a CAD program [12, p. 27]. By combining the spatial and temporal aspects of a given flight task, a trajectory can be generated along the waypoints. The interface between the design environment and the robotic system in this particular work comprises waypoint information combined with additional data in text file format, such as link tension, knot type, and support orientation.[39] The encoding of design information and its transmission to the robotic setup was iteratively refined throughout the different experiments. Experiments 1-3 were conducted prior to the implementation of an connecting interface between design and fabrication. Here, design information was communicated with drawings as well as with the manual measurements of the support structures installed within the building space (see Chapter 5.2.3). This information was then encoded into the robotic platform and manually adapted over the course of the experiments in an iterative manner. For example, if a vehicle would always crash at the same crossing, the radius to fly around was increased and the parameter adjusted. The numeric interface linking design information and robotic fabrication was developed (see Chapter 4) for the realisation of the final experiment (Experiment 4). Here, however, the digital model, the simulation, and the construction instructions (for example the parameter for the tension on a link) required adjustment over the course of the experiment (see Chapter 5.5.6). The Flying Machine Arena testing platform has been developed over multiple years by the Institute for Dynamic System and Control at ETH Zurich [137]. Today, it serves as a research environment, as well as a demonstration platform. General information about the set-up can be found in [80].

Flying machines

In this work, the vehicles of choice are quadrocopters (see Chapter 3.1). These flying robots are based on the Ascending Technologies Hummingbird frames [138] equipped with custom electronics [80]. For the experiments, the vehicles were equipped with custom rope dispensers mounted in the centre. The dispenser has the form of a spool on which the rope is wound up. The required length of rope could be rolled on the spool on the ground before building, with about 1 m of the beginning of the rope hanging from the dispenser (Fig. 5.1). This hanging segment is required to construct the first knot of a link. Before a vehicle starts tying this first knot at the designated location, it can move freely in three-dimensional space with the attached dispenser. While in Experiments 1-3 the friction of the roller and hence the tension of the rope during deployment were constant and could only be adjusted manually with a screw, for Experiment

4 an actuated motorised spool allowed the tension to be adjusted dynamically while flying [131].

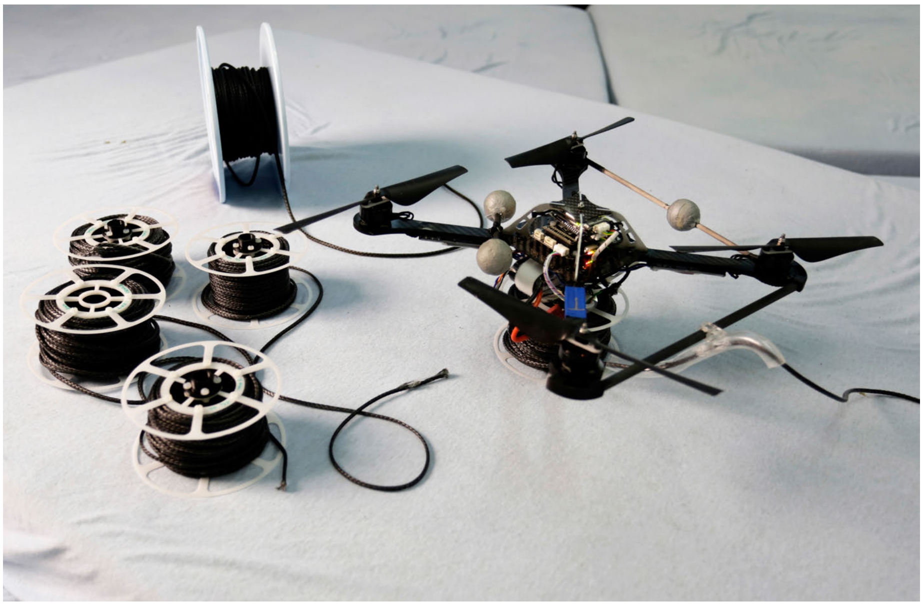


Fig. 5.1: Quadrocopter and wound spools with different lengths of 4 mm Dyneema rope.

Building material

The linear tensile material used in the experiments is Ultra-high-molecular weight polyethylene rope (Dyneema), with 3 mm and 4 mm diameters. The material distinguishes itself for aerial construction due to its high strength and low weight. Its weight-to-strength ratio is around 8-15 times lower (better) than that of steel [139]. For example, a 100 m long rope with a diameter of 4 mm weighs only 700 g and can support up to 1300 kg. Its low stretch and positive durability properties (water, chemical, and UV-resistance) make it suitable for 1:1 building experiments. Dyneema has also proven to be a fitting material for helicopter transport ropes [140]. The product used in the experiments (Liros D-Pro [141]) is 12 times plaited and heat set. It is available with round cross sections from 1 to 16 mm. Furthermore, Dyneema has a low coefficient of friction, making the rope slide easily. This is beneficial when the rope must slide under a load to find a structural equilibrium, but it is challenging during the fabrication of a knot, when minimal sliding is desired.

5.2 Experiment 1: Linear structure

5.2.1 Objective

This experiment aims to test the ability of a vehicle to construct a basic one-dimensional suspension structure, by establishing a taut link between two distant support elements (Fig. 5.2). The experiment validates the combination of two primary building primitives: the turn knot and the taut link [142].

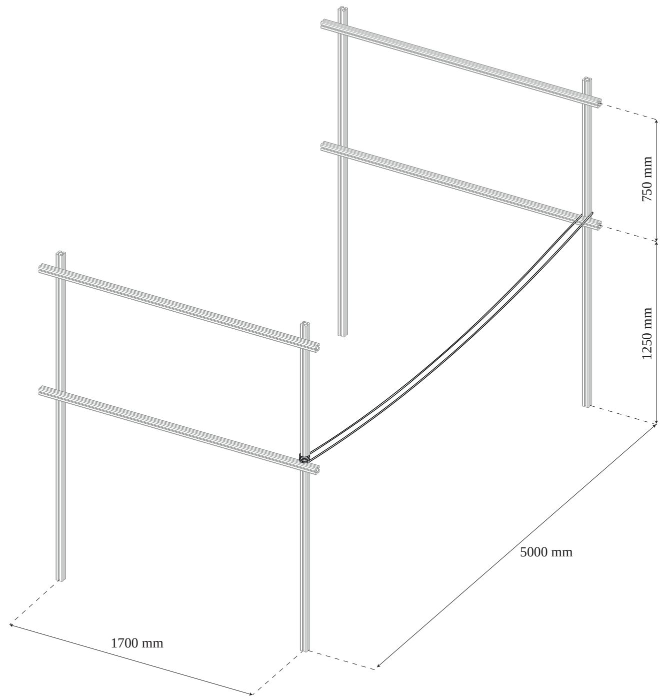


Fig. 5.2: One-dimensional suspension structure built between two distant support structures.

5.2.2 Methodology

Two primary building primitives – the knot and the link – are required to build the structure in this experiment. At one of the support elements, the vehicle must first create a knot strong enough to support the weight of the rope. It must then tie another knot at the second support element to create a link between them. The parameters of the structure are: the distance between the supports, and the holding force of the knot.

Despite its simplicity, the turn knot building primitive used in this experiment presents itself as a valuable method for fastening a rope to a support bar. The flexible nature of the rope allows it to be wound around the support, creating enough friction to grip. The strength of the connection can be dimensioned using the capstans equation (5.1) [143]. Depending on the coefficient of friction (μ) between the tensile material and the support material, and the number of turns around the support (angle in radians φ), the loading force (T_{load}) can be calculated from the holding force (T_{hold}) (Fig. 5.3). A small loading force can carry a much larger holding force because of the interaction of forces at the support.

$$T_{load} = T_{hold} e^{\mu\varphi} \tag{5.1}$$

This allows the turn to be specified either as a sliding joint (with only a single turn), or as a fixed connection with a large holding force (with multiple turns). Because of the exponential nature of the capstan equation, only a few turns around the bar are needed to prevent the unravelling of the rope from the support structure.

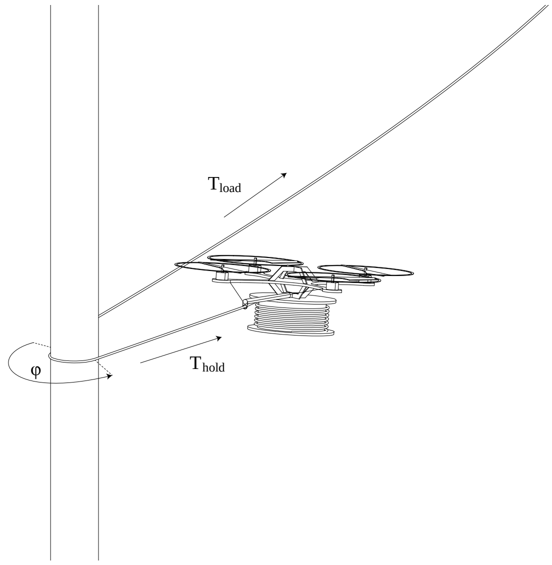


Fig. 5.3: A relatively small holding force on one side can carry a large loading force on the other side.

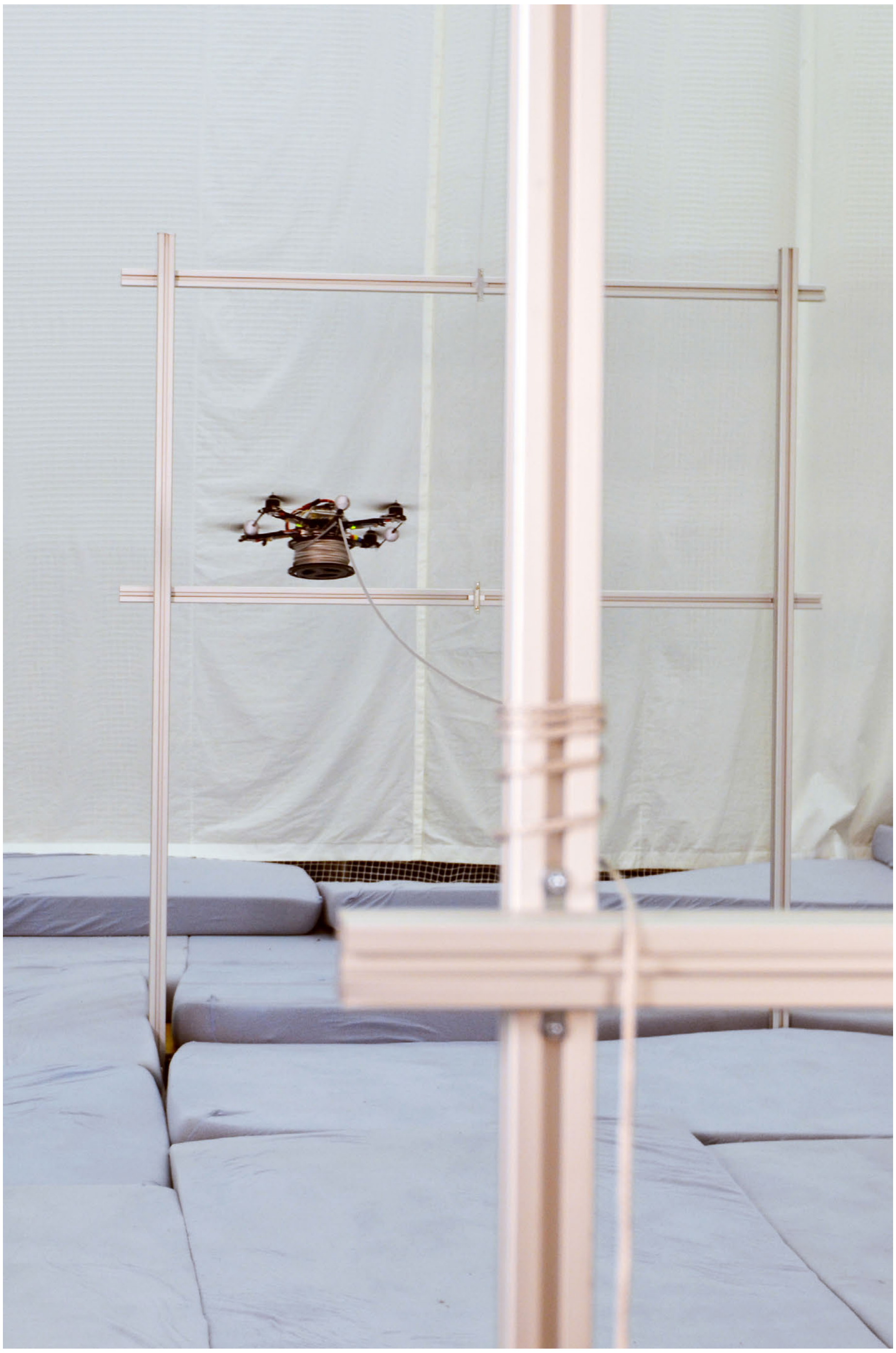


Fig. 5.4: The construction of a link.

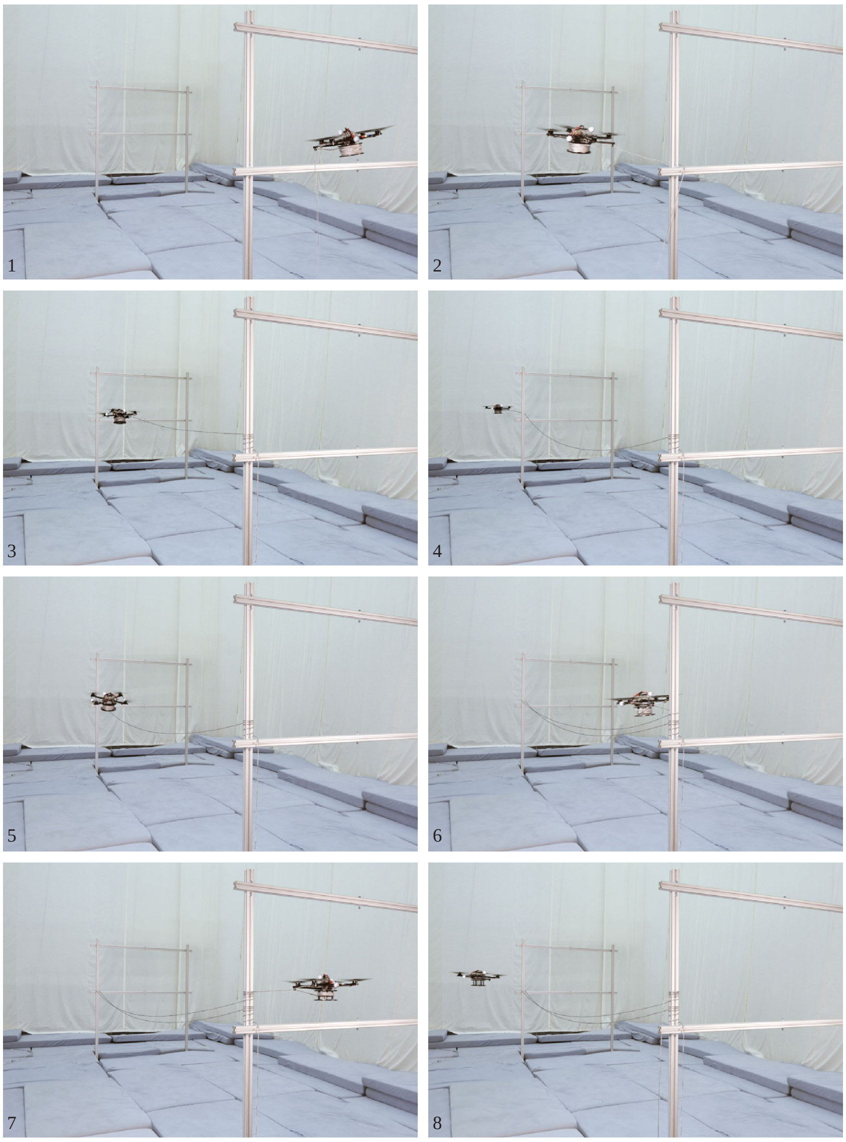


Fig. 5.5: Concatenation of a multiple-turn knot (1-2), a link with a single turn (3-5), and a link followed by another multiple-turn knot (6-7) [142].

5.2.3 Realisation

The minimum distance between the poles[40] is defined by the space required for the vehicles to manoeuvre around the poles (in this case approximately 1 m), and the maximum distance is delimited by the payload capacity of the vehicle transporting the rope (in this case approximately 20 m). In this experiment (Fig. 5.4) the distance between the poles was 5 m. The exact position of the supports is measured with the aid of the motion capture system, by positioning retroreflective markers on the supports.[41] The spool is equipped with the amount of rope required to construct both the knots and the links.

The structure is realised (Fig. 5.5), firstly, by flying multiple turns around one support element. The vehicle takes off with a rope segment of around 1 m hanging from the spool, which is attached to the support by the circular motions of the turns.[42] Once the knot is strong enough to hold the weight of the rope (after a few turns), a link can be constructed by flying to the distant support element, where a single turn is performed, followed by another link to the starting point, fixing the rope again with multiple turns. As soon as all 14 m of rope is unwound and the rope drops off the spool on its own, the vehicle is again physically decoupled from the structure it has built.

5.2.4 Results

This experiment has been realised repeatedly in order to examine and adjust the parameters of the building primitives. One variable that was adjusted, for example, was the tension. This was done when deploying the rope in order to create a relatively taut link. Another variable that was adjusted was the proximity of the vehicle to the support structure during knot building. This was done in order to minimise the required building space while still preventing collisions with the structure. Lastly, different numbers of turns were constructed to test the loading force of the knots. This experiment demonstrated the ability of a flying robot to erect a basic tensile structure. Its ability to fly is used to create a structure that is multiple times larger than the machine itself. As such, the vehicle navigates and fabricates independent of the ground conditions.[43] The experiment validated the concatenation of the two primary building primitives, the taut link and the round turn. The next test within this experimental series examined the fabrication of a two-dimensional mesh interlacing.

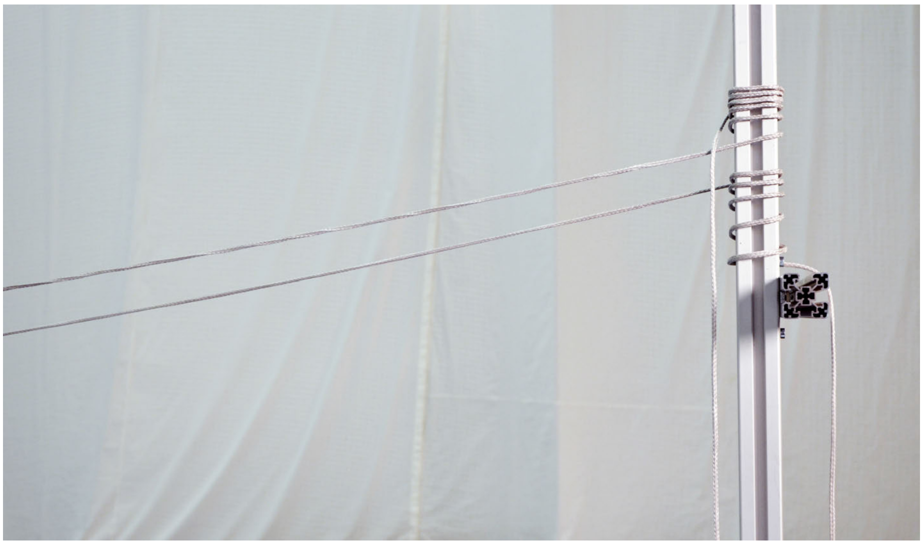


Fig. 5.6: Detail of the constructed knots on a vertical support profile.

5.3 Experiment 2: Surface structure

5.3.1 Objective

This experiment tested the fabrication of a surface mesh between two already constructed taut tensile members (Fig. 5.7). For its fabrication, it concatenated the same building primitives as in Experiment 1, the turn and the link, to build a mesh interlacing [142].

5.3.2 Methodology

The construction followed the zigzag-mesh interlacing method described in Chapter 4.1.3. One vehicle connected the two support links by flying a figure-eight trajectory around the supports, while making a forward motion perpendicularly to it. The main parameter is the angle between the erected links, which defines the density of the structure.

5.3.3 Realisation

The tensile support links were manually constructed before the start of the experiments and their end points were again digitally recorded with the aid of

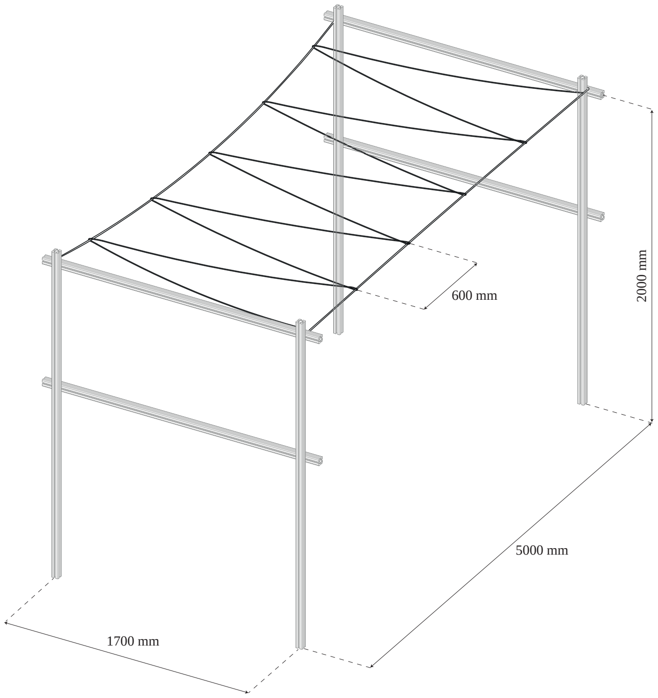


Fig. 5.7: Two-dimensional surface structure built between two taut tensile links.

the retroreflective markers and the global positioning system. A defined length of the rope was wound on the spool of the vehicle and its end was manually attached to one of the endpoints of the support structure.[44] The structure was then realised by flying half turns, successively around the support links, connecting the structure with taut links to a zigzag surface mesh (Fig. 5.9). The size of the figure-eight motion was defined by the distance between the supports and by the size of the vehicle, so that it could safely navigate around the supports (Fig. 5.8). The forward motion that follows along the supports defines the density of the structure, which is limited by the size of the vehicle. If the angle of the zigzag is too small, the machine will collide with the previously constructed link.

5.3.4 Results

Since the primary support links are taut, they are considered as a line between the two support points. The forces of the taut zigzag mesh acting on the primary support links, however, have reshaped them (Fig. 5.10). In this experiment, the movements of the flying robots around the supports were large

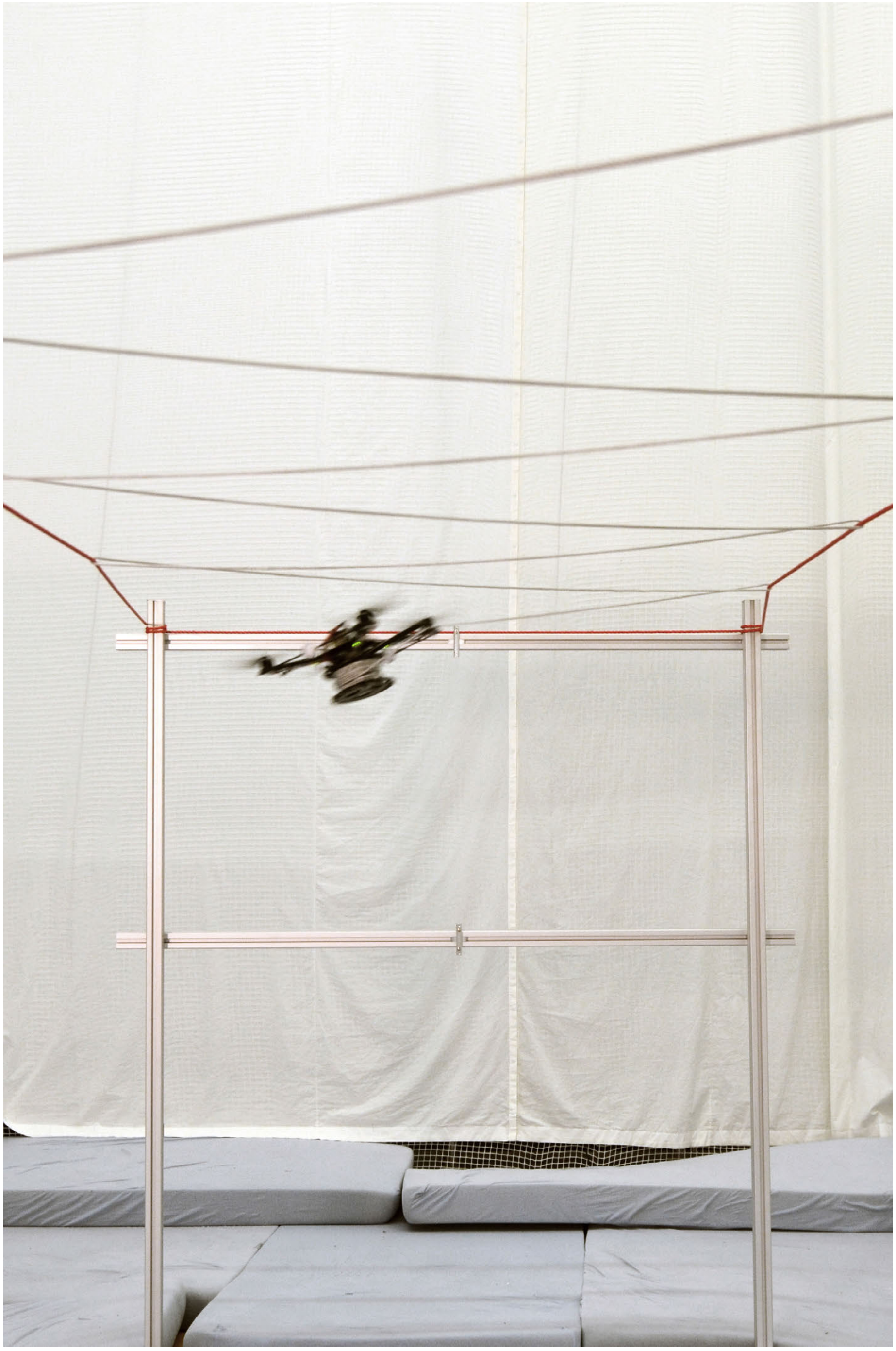


Fig. 5.8: The vehicle requires a safe distance from constructed members and support links in order not to collide with them.

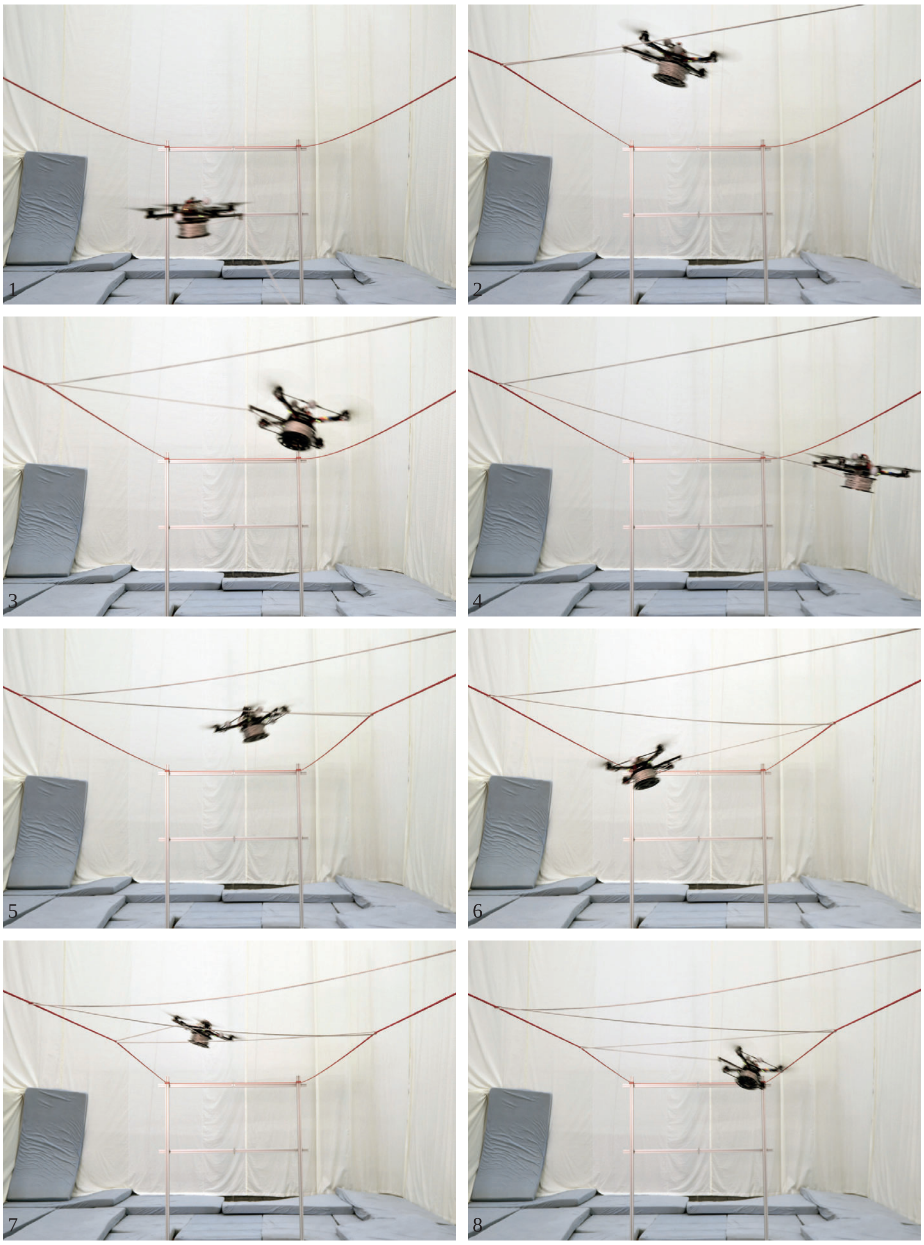


Fig. 5.9: Construction sequence of the mesh structure [142]. A figure-eight trajectory with a forward motion along the primary support links.

enough to compensate for the spatial deformation of the rope. If the support links had been less taut, or if the safety distance to fly around them had been minimised, the vehicle would have collided with the structure. This motivated the thesis to consider already constructed members not as static objects, but as a flexible assembly that adapts its geometry and position in space with every additional link that interacts with it. The observation of this problem led to the development of the sequential simulation approach described in Chapter 4.2.

The surface structure experiment demonstrated one important ability of the flying robot when building structures: the vehicle can fly through and around already constructed members while deploying the rope. In other words, the machine is physically decoupled from its environment. As such, the movements of the vehicle, not being connected to the ground or to the structure through a rigid link, enable a new spatial autonomy and relationship to the structure while building it, resulting in higher degrees of freedom. This enables the flying robot to autonomously steer material through space. This very feature differentiates the flying construction robot from other building machines. A robotic arm, in contrast, could not realise a zigzag mesh without releasing the building material at every turn. Otherwise, the arm of the machine would collide with the structure when performing the manoeuvre. This problem does not exclusively occur with the industrial robot, but with any machine that is physically connected to its environment.

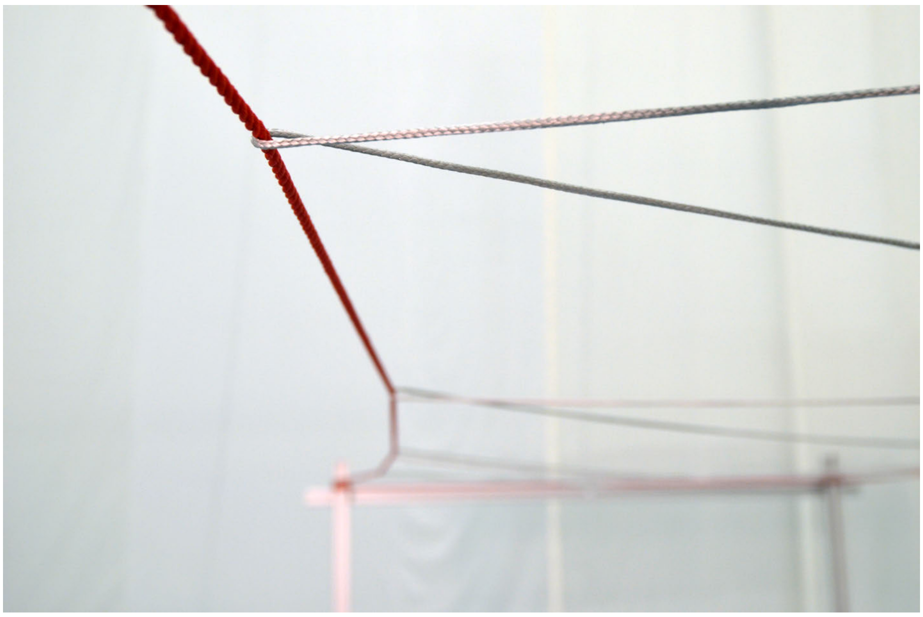


Fig. 5.10: Deformation of the tensile support links as a direct result of the redistribution of forces in the mesh.

5.4 Experiment 3: Spatial structure

5.4.1 Objective

This experiment examined the ability of flying robots to construct three-dimensional structures [142]. The goal of the experiment was the construction of a knot between two rope segments. The location of the intersection was variable within the volume defined by the solid support structures (Fig. 5.11).

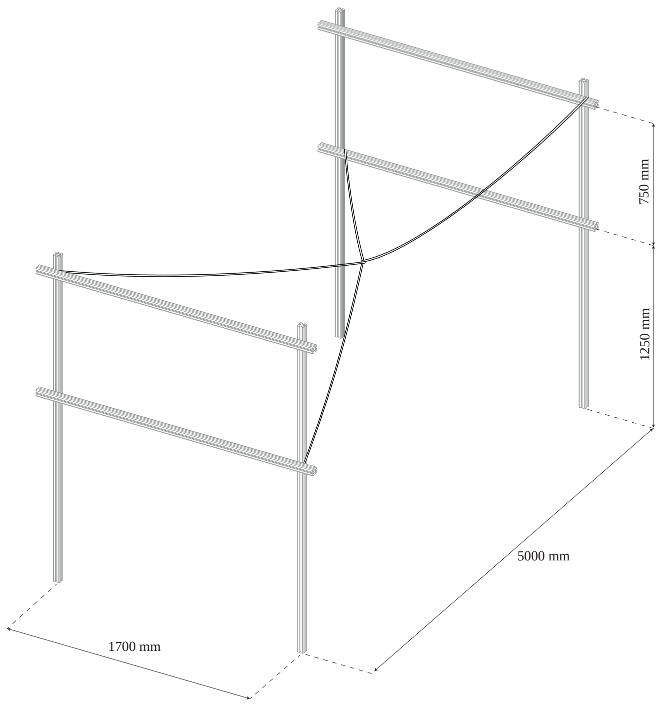


Fig. 5.11: Three-dimensional positioning of a knot between two rope segments within the building space.

5.4.2 Methodology

There are two ways to construct a knot at a defined position in space, but they do not offer the same degrees of freedom. The first option, which can be performed with a single vehicle, is to create a sagging link between two support points with a defined rope length, followed by a second link connected with a turn to the already constructed link. The turn knot between the two ropes constitutes a sliding connection between the two ropes. Its location is determined by the tension on the individual links. If one link is longer than the other, the knot shifts towards the shorter one. Since this method builds a sliding connection, the location of the knot is always exactly midway between the two support structures. The second option to construct a knot in three-dimensional space – the one chosen for this experiment – makes use of two vehicles. By building the links simultaneously instead of sequentially, the knot can be positioned variably between the supports (Fig. 5.12). Multi-vehicle cooperation enables the flying robots to create a solid fastening by moving around each other, tying a multiple-round turn knot (Fig. 5.13). As such, having two vehicles coordinate their movements amongst themselves during the construction enlarges the design space of aerial robotic construction.

5.4.3 Realisation

The same support structure as in the previous experiments was used here, and the support locations were again measured with the motion capture system. Both vehicles used in the experiment had rope of a defined length wound on the rollers and the rope ends were manually attached at a designated location on the support structure. The structure was realised with two vehicles flying around each other in a synchronised rotary motion, keeping enough distance between them. The machines first established a knot between the ropes before building a new link to the support structure. If the vehicles had flown a simple turn around each other, the result would have been a sliding connection with an equilibrium in the centre of the structure. However, having the vehicles turn around each other several times allowed them to fabricate a non-sliding connection that could be positioned not just in the centre of the structure, but freely within a three-dimensional volume.

5.4.4 Results

The experiment demonstrated that having multiple-machines coordinate their movements amongst themselves can increase the design spectrum. The construction of a multiple-turn knot by two vehicles circling around each other resembles the braiding primitive introduced in Chapter 4.1.3. However, whereas a braid is built along an axis with a starting and ending point, the multiple-turn knot shown in this experiment did not comprise a translation along a vector, and hence, rested simply in a knot.

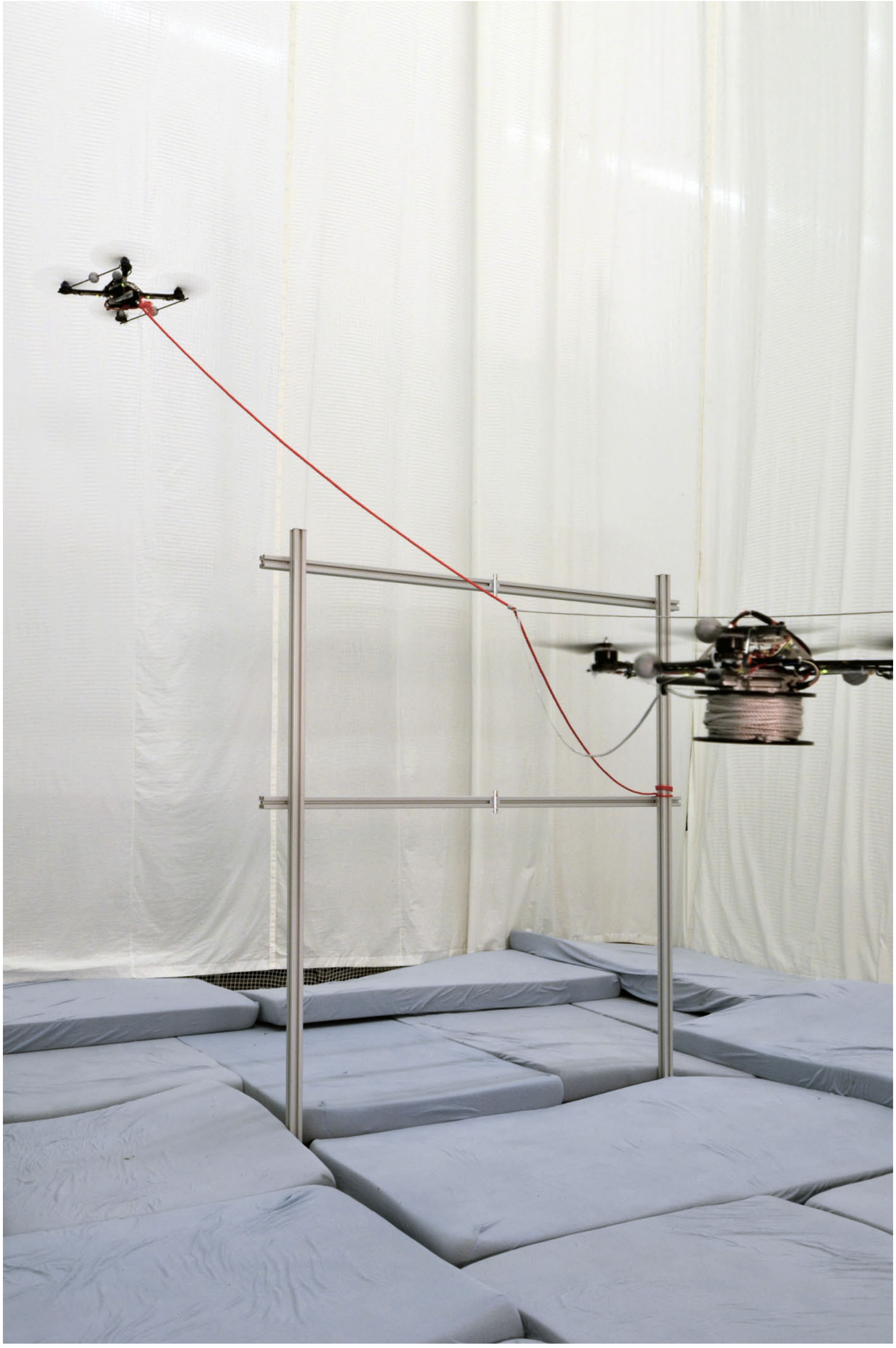


Fig. 5.12: A two-turn knot between the links establishes a non sliding connection between the ropes that can variably be positioned within a volume of the building space by adjusting the length of the link segments.

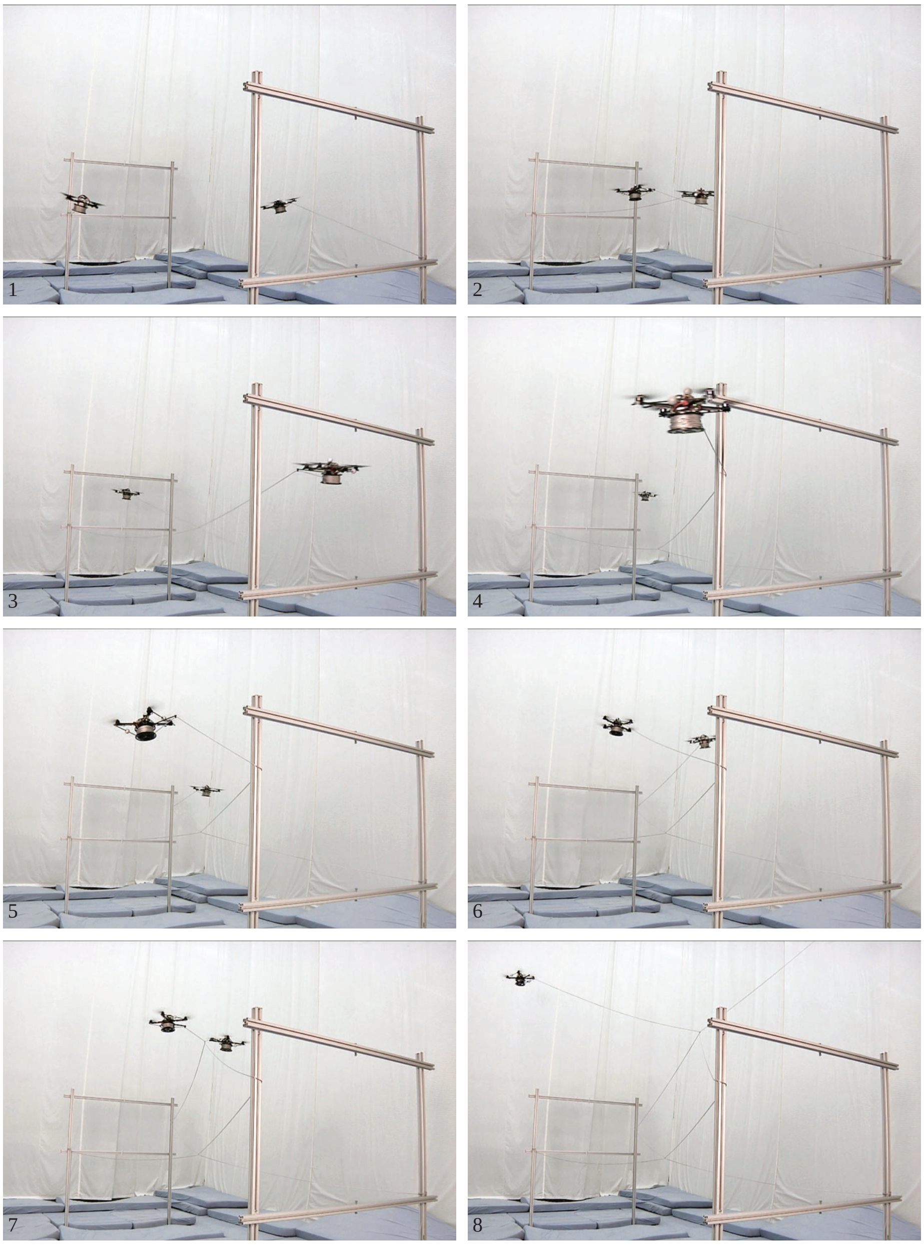


Fig. 5.13: Construction of a sliding connection in the center of the structure (1-3), and construction of non-sliding knot at a designated location within the building space (5-7) [142].

The experiment challenged the relationship between design and fabrication space with respect to the support conditions. Of course, as mentioned in the previous chapter, a tensile structure requires solid support points to build from. As already shown in Experiment 1 and 2, the possible designs are largely influenced by the location and condition of the support elements. However, this was even more evident in this particular experiment. Rather than understanding the support structure as a series of individual points that can be connected in three-dimensional space, the experiment motivated the thesis to contextualise it as a spatial network that defines a building volume, a design space for tensile fabrication.

The experiment encouraged the thesis to consider links not only as taut connections (see Experiment 1 and 2), but also as tensile elements that can have a defined sagging (Chapter 4.1.2), thus increasing the design possibilities and the variety of buildable structures. This was further explored in Experiment 4.

5.5 Experiment 4: Bridge structure

5.5.1 Objective

The goal of Experiment 4 was to interlink the individually developed and tested techniques and tools and test their synthesis in the construction of a prototypical architectural structure. In order to do that, multiple flying robots constructed a full scale, load-bearing footbridge, spanning 7.4 m [144]. While the structure was inspired by existing typologies of suspension footbridges [145], the specific design reflected the abilities of the flying robots and the methods and techniques developed in this thesis. The structure was functionally and structurally tested by having different people crossing it.

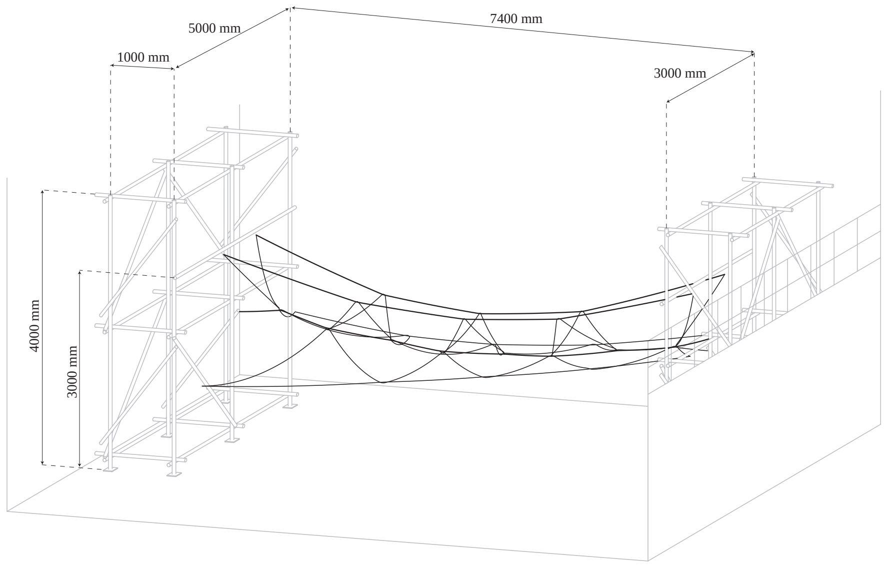


Fig. 5.14: Drawing of the simulated final assembly of the footbridge.

5.5.2 Methodology

The bridge was fabricated in three consecutive stages. The first stage connected the two sides of the bridge with linear links. The second stage interconnected these links into a three-dimensional network and finally, the last stage stabilised the assembly. This division into three stages reflected the structural dependencies among the primary, secondary, and tertiary structural members, and allowed the practical implementation of individual parts to be tested.

5.5.3 Primary structure

In the first building stage, the primary element of the structure was built. Three tensile links bridged the two support structures by creating fixed knots at each side with taut links in between. In section, the three suspension elements were arranged in a V-shape (Fig. 5.15). The bottom link acted as a footrope, supporting the feet of the user when crossing, while the two parallel upper links constituted the handrails. The three building elements created the primary structure of the bridge, on which additional tensile members were added.

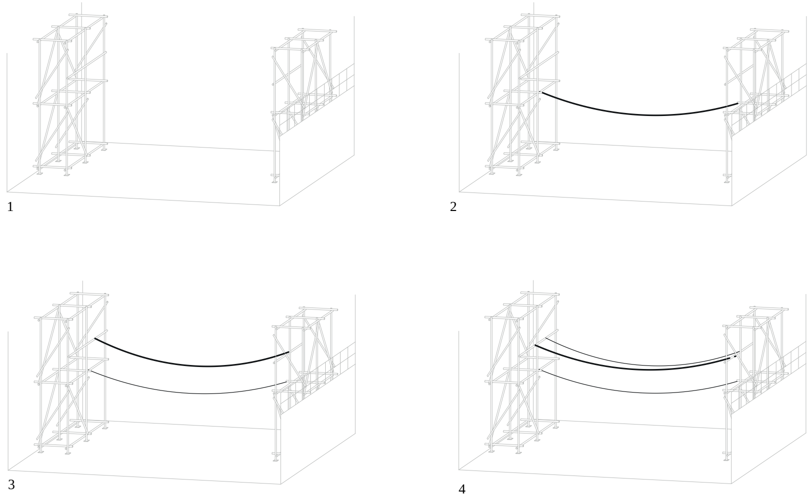


Fig. 5.15: Simulated building sequence of the construction of the primary links.

5.5.4 Secondary structure

The second fabrication stage joined the three main links into an interconnected structure (Fig. 5.16). The braiding primitive was used to connect the primary structures to one another, creating segments of non-uniform three-strand-braids (described in 4.21.3) on the footrope. Two interacting vehicles were required to construct the secondary structure and create the bracing elements of the bridge. While the braid created a non-sliding connection on the footrope, the simple turns around the handrails resulted in sliding connections. The fixed knots defined how the forces were distributed when the structure was loaded, and the sliding turns around the handrails allowed the bridge to dynamically adapt its shape to find an equilibrium in different loading cases.

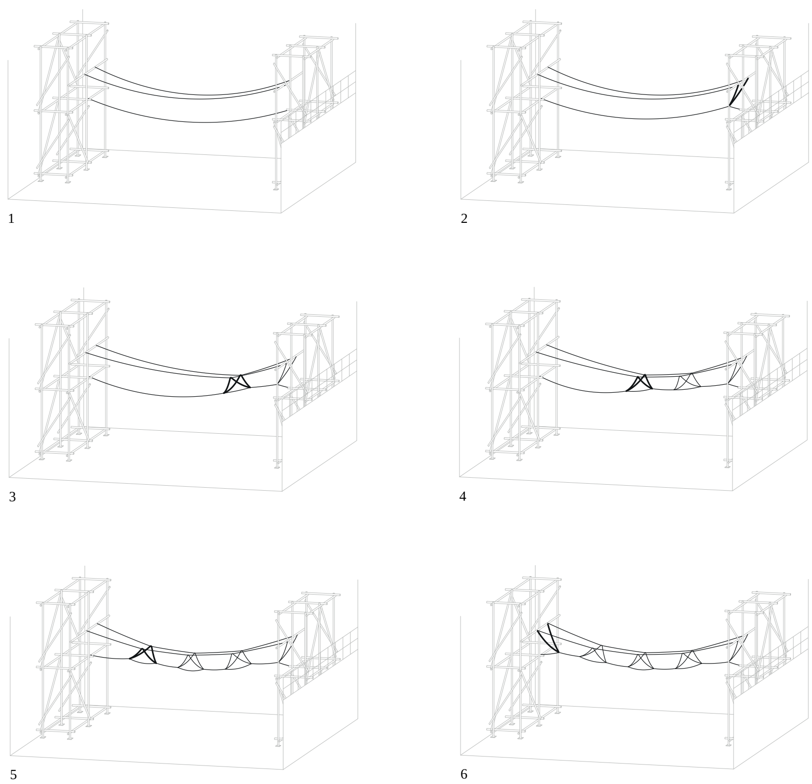


Fig. 5.16: Simulated building sequence of the braiding segments.

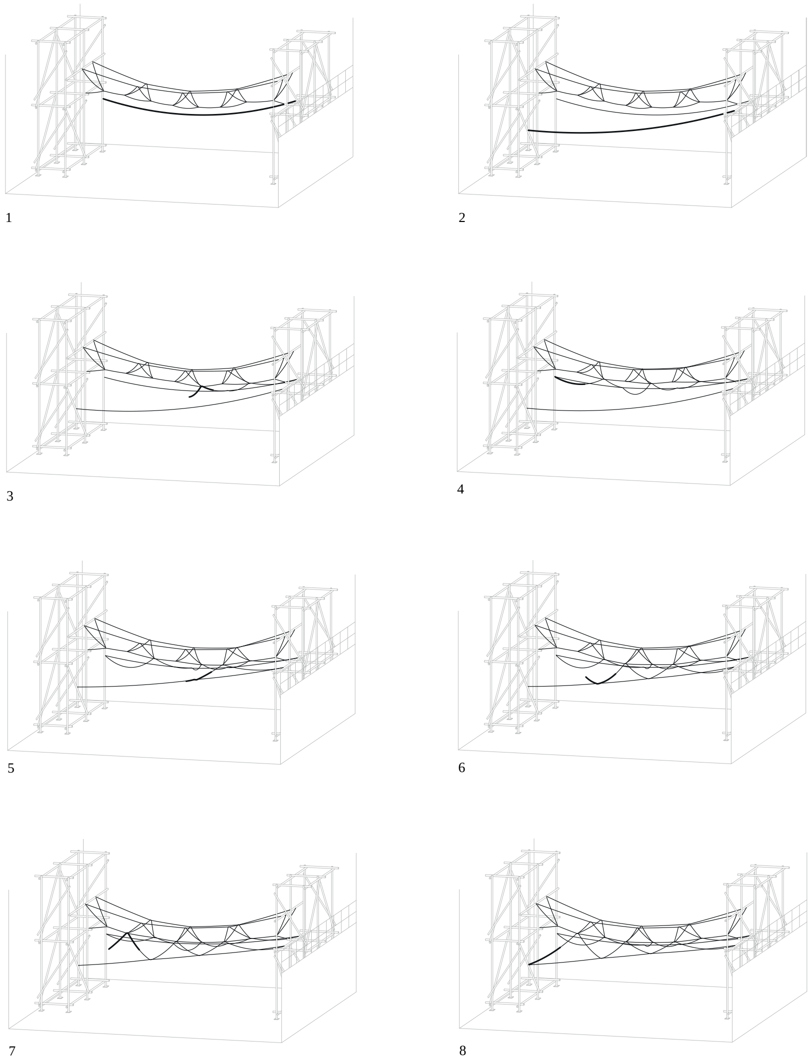


Fig. 5.17: Simulated building sequence of the tertiary structure (some steps are skipped in this drawing).

5.5.5 Tertiary structure

The last fabrication part stabilised the whole assembly by implementing additional links below the structure (Fig. 5.17). A zigzag mesh restrained the primary footrope from changing the shape in response to the variable loading conditions. It absorbed non-uniform loads and possible lateral and uplift forces, making the crossing more comfortable.

5.5.6 Realisation

Support structure

Two scaffolding towers were erected on either side of the space. Tension forces of up to 1000 kg can act on support points if, for example, a person weighing 80 kg stands on a relatively taut link. To stop the scaffolding towers from tipping over, they were secured to standing parts in the space at different points and different heights. The positions of the support points were measured by the motion capture system and translated into the digital model, so that the design could be adapted accordingly.

Primary structure

The primary structure was erected simultaneously by three vehicles, each building one link.[45] In order to make the crossing of the bridge as comfortable as possible, as well as to facilitate the fabrication of the braid in the next step, the goal was to make the primary links as taut as possible. During the fabrication, however, two challenges arose. Firstly, since these links were responsible for sustaining all the loads, the knots attaching them to the support bars had to be as robust as possible. Various knots were subsequently tested, and it was found that a knot would tighten the first time it was loaded, making the respective link sag substantially. This depended on how the vehicle would fly a knot. The circular motions around the support elements required a certain distance to the knot centre point, in order to prevent collisions with the structure. This resulted in placing the rope not only at the very centre point of the knot, but also along the axis of the support element. When applying force on the connection, the material would move towards the centre point of the knot, making the link sag (Fig. 5.20). As a result, after qualitatively testing different knots, two knots were chosen because they only minimally expanded

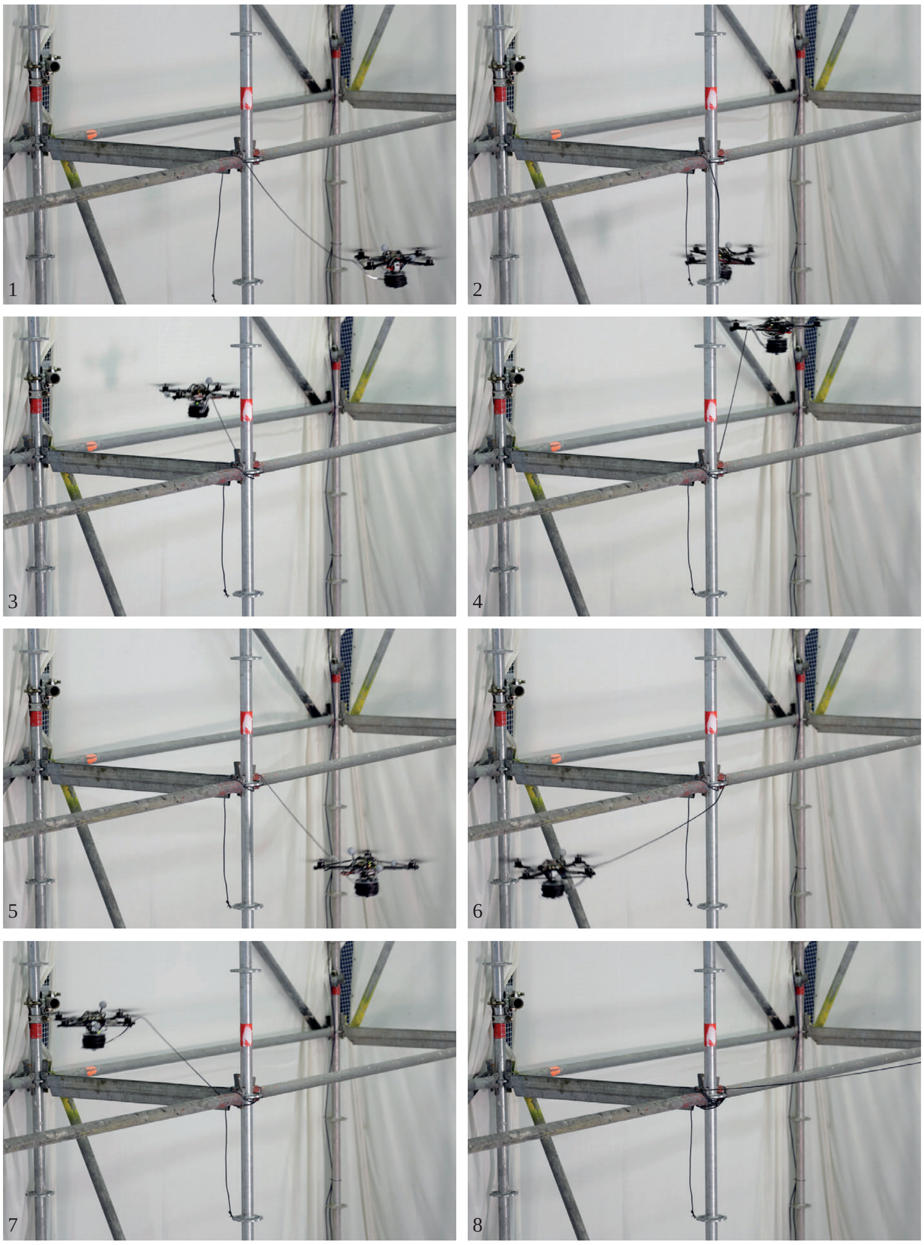


Fig. 5.18: Construction sequence of the first knot for the footrope link [144].

Fig. 5.19: Parallel knot construction of the first knot of the handrail links to the support scaffolding [144].

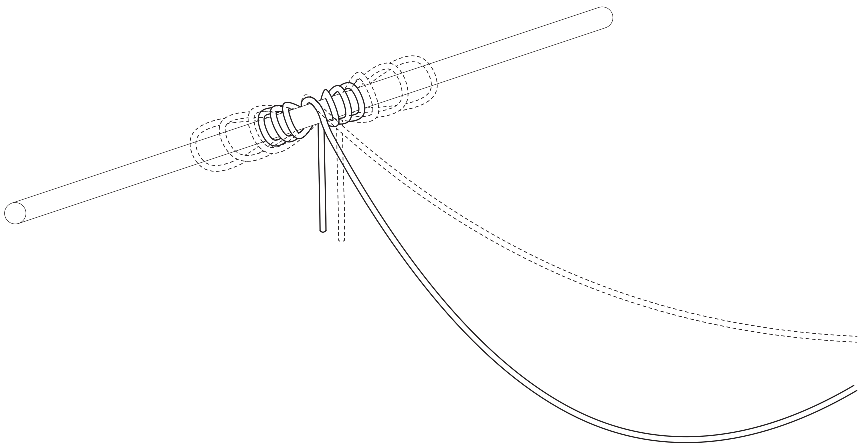


Fig. 5.20: Multiple-turn knot with crossing around the centre point. The dashed rope indicates the situation before a force is applied on the knot, and the continuously drawn rope shows how the link starts to sag after it is temporarily loaded because the turns around the support bar have moved towards the centre point.

along the support points. The starting knot of the three links was a variation of a simple multiple turn knot, making multiple diagonal turns across the knot centre point (Fig. 5.18, Fig. 5.19 and Fig. 5.22). Once loaded, the knot secured itself immediately due to the crossings over the standing part. To finalise the links after load testing different knots, a multiple-munter knot was chosen as a second knot to solidly fasten the primary elements at the other end of the space.

The second challenge that occurred when performing the manoeuvre was to apply maximal tension when spanning the links, so that the ropes sagged only minimally. To achieve that, before fixing the link with the second knot, the rope was blocked at the roller so that the vehicle could apply the maximum tension on the link before flying the knot. Furthermore, to increase the friction of the support bars, the handrail supports were covered with neoprene.[46]

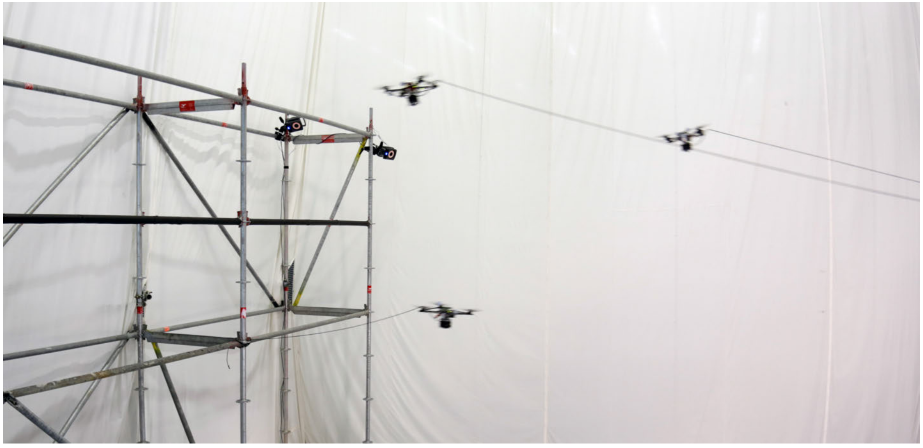


Fig. 5.21: Simultaneous erection of the three main links by three vehicles. Two machines start building the handrails on one side, while the third machine fixes the footrope on the other side [144].

Fig. 5.22: Constructed starting knot of the footrope link. A series of diagonal turns cross the centre point of the knot.

Secondary structure

The secondary structure braced the footrope and the two handrails into a linked assembly. Four braiding segments were constructed on the footrope and connected to the handrails with three turns. In contrast to the primary structure, this manoeuvre could not be realised by a single vehicle. The braiding required two interacting vehicles (see 4.21). The sequence began by having two machines simultaneously erect a fixed knot on the starting point of the handrails. Then, a series of braids were created on the footrope, with single turns around the handrail links in between (Fig. 5.23). The braiding segments were 800mm long and the distance between them was 1000mm. This left enough space for the vehicles to fly through the openings when fabricating the tertiary structure. The density of the braid reflected the amount of rope a vehicle could carry, and the building time it needed to fabricate the structure. The machines had limited battery power, allowing them to fly for only about 15 minutes. Depending on the aggressiveness of the manoeuvres and the payload the vehicles carried, the flight time could decrease to 10min. In the construction of the links, where the building time was only a matter of seconds, this was never an issue. For the secondary structure, however, the building time became relevant, because the machines had to assemble the whole element in one go and the building time was directly influenced by the density of the braid. For this reason, the secondary structure was designed to take only 5 minutes to make. Another problem that occurred during the construction was that the manoeuvre required more building space than anticipated. The footrope was not a static element and it would move during the construction of the braid. This was particularly evident towards the middle of the footrope, where the rope was least constrained. Since there was enough free space on either side of the footrope, the building space could be increased.

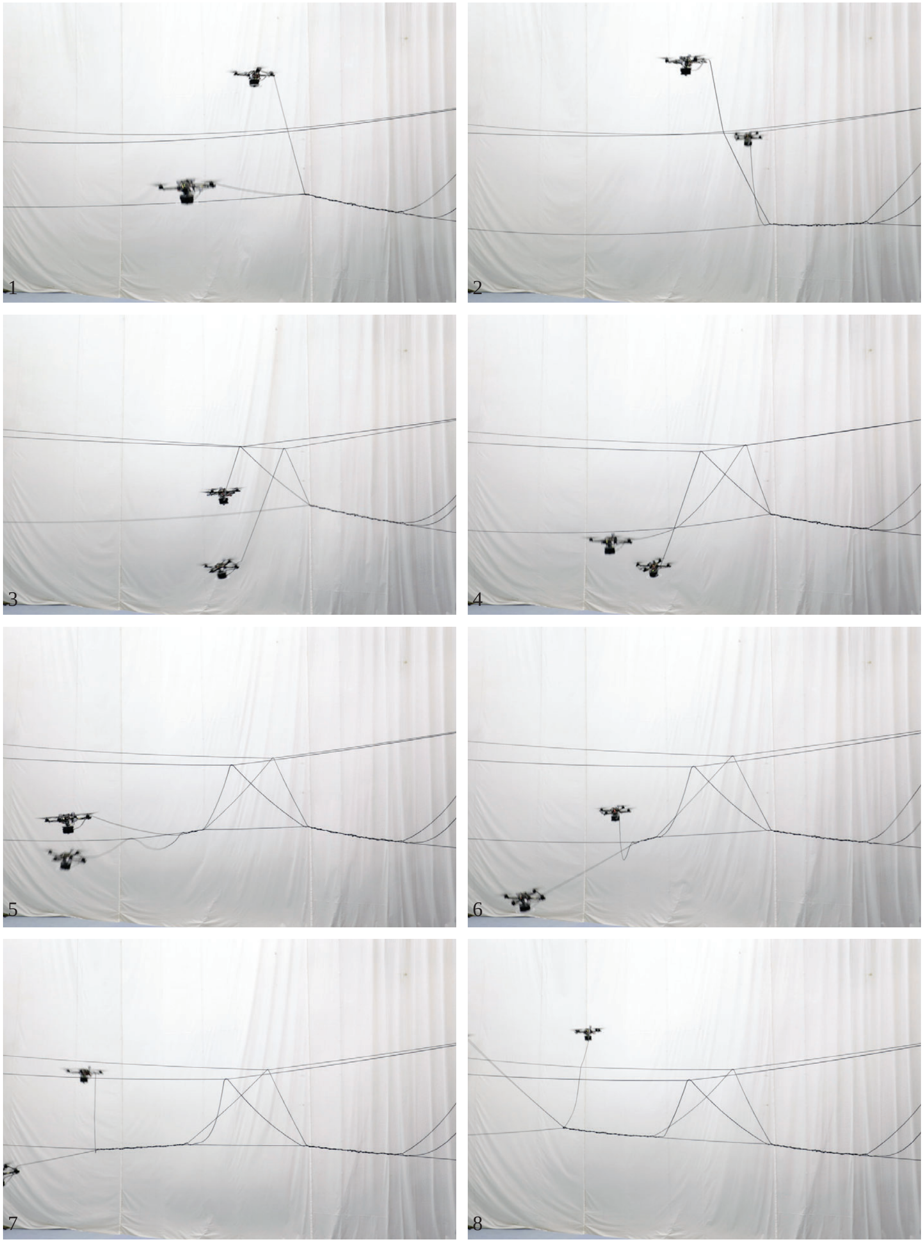


Fig. 5.23: Fabrication sequence for a braid segment. The vehicles create a turn around the handrail links before creating a 800 mm braid on the footrope [144].

Tertiary structure

The stabilising structure was constructed in two steps. In the first step, two sagging links were erected on either side of the bridge, below the footrope, connecting the two support structures. In the second step, these two links were integrated in the already built structure by creating a zigzag mesh between them and the bridge structure. This was done by flying through the openings between the footrope and the handrail links. During the fabrication, two problems emerged. First, the anticipated locations of the openings did not correspond to the simulation. Second, the openings were tight. The combination of these two issues often resulted in the vehicle colliding with the structure (Fig. 5.24). The discrepancy between the digital and the physical model was mostly related to the fact that the vehicles created the links with higher tolerances than initially presumed. Small tension variations in the primary structure would effect the shape of the secondary structure and tolerances and errors would accumulate. To create the tertiary structure, three options emerged. First, the openings in the secondary structure could be increased, allowing higher tolerances. Second, a smaller vehicle could be used, also allowing higher tolerances. Last, a scanning process could be integrated to provide feedback about the deformation of the structure in regard to the digital model. Since the first option would result in scaled-up cross-section that would not be congruent to the human proportions, and a smaller vehicle did not offer the same payload capacities, the scanning option was preferred. A feedback process was emulated by the motion capturing system, measuring the middle points of the openings before the start of the fabrication of the tertiary structure. With this semi-autonomous approach, the last construction step was finally be realised (Fig. 5.25).

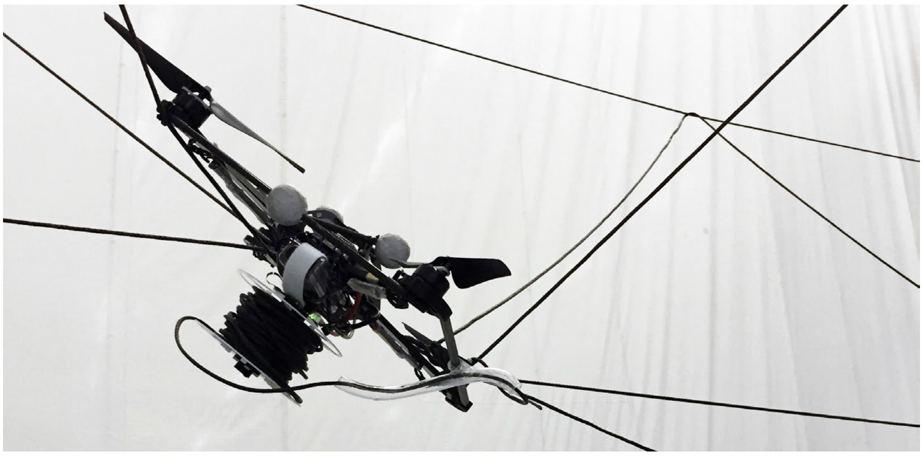


Fig. 5.24: Collision of the vehicle with the structure when flying through a tight opening.

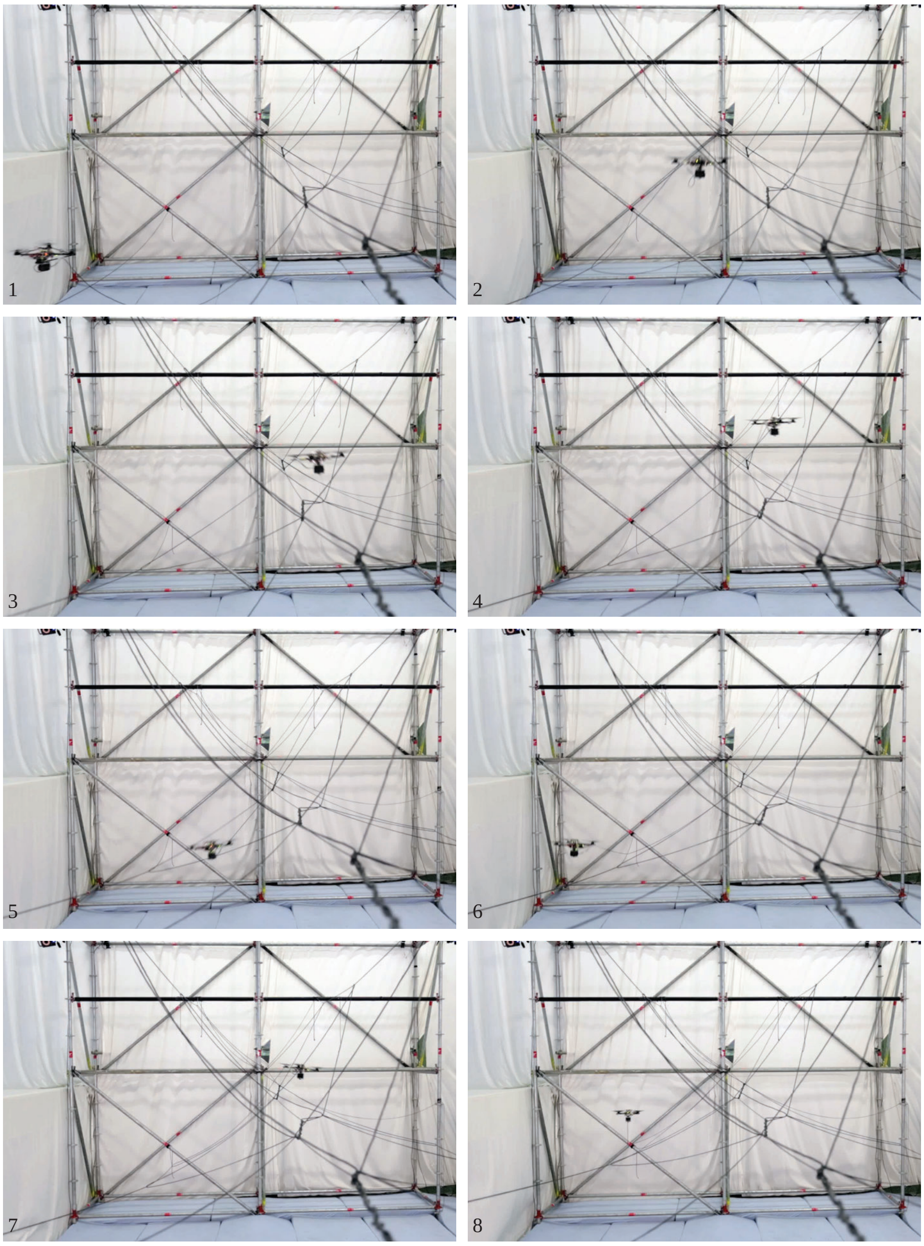


Fig. 5.25: Construction sequence of the zigzag mesh on one side of the structure [144].

5.5.7 Functionality

The bridge structure was functional directly after the fabrication of the primary structure, but the secondary structure increased its usability. The dynamic forces were better distributed, thus preventing substantial sagging of the footrope. And, overall, the secondary structure spatially defined the assembly as a basic bridge structure. The tertiary structure again increased the functionality of the structure. The variable loading conditions were restrained, making the crossing much more comfortable. The sliding knots allowed the structure to adapt in a constraint-based manner, helping to reduce the forces on the individual support points of the scaffolding structure (Fig. 5.26). When crossing the bridge for the first time, the knots tightened, making the aggregation sag minimally. The structure was built and safely crossed several times.[47]

5.6 Results

This experiment demonstrated for the first time the use of flying robots for the construction of a full-scale, load-bearing architectural structure. The tools that were developed in Chapter 4, the building primitives, the computational design strategies, and the insights that were gained in the previously performed experiments all informed the specific design and realisation of this last structure. As mentioned in the description of the realisation of the structure, various challenges occurred that are specific to this experiment.[48] Still, the bridge structure validated the sequential design approach and the ability of flying robots to build tensile structures consisting of multiple interconnected members. The flying robots acted as spatial autonomous manipulator that allowed the rope to be interlooped into a usable architectural artefact. As such, the bridge presented a clear architectural function - the bridging - and its performance was validated by crossing it.

Even though the structure was inspired by existing footbridges, it was designed and realised congruent to the abilities of the vehicles. As such, the realised bridge did not mimic the usual manual process used to build such a structure, but reinterpreted it as an aerial robotic construction process.

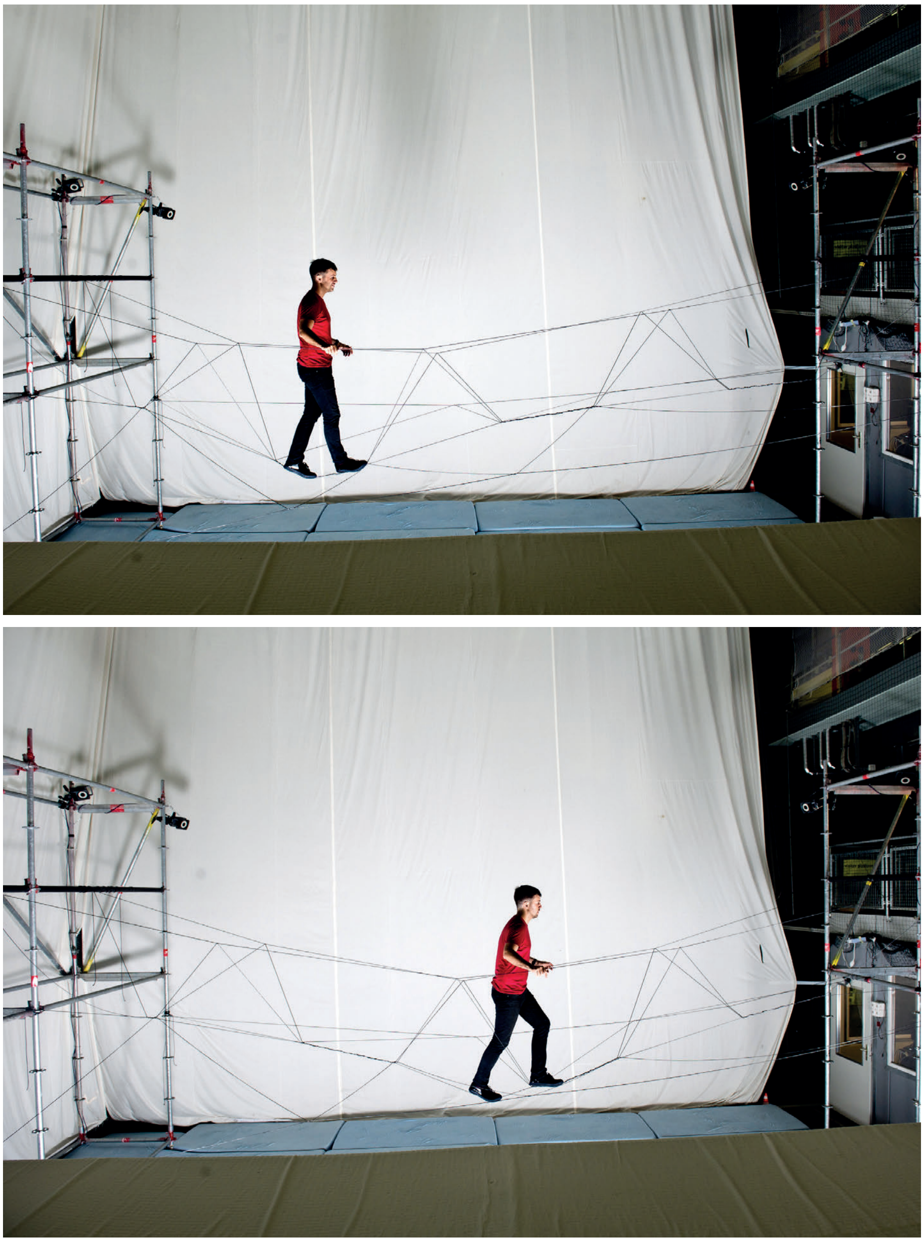


Fig. 5.26: Bridge crossing. The structure adapts its shape in response to variable loading conditions [144].

Fig. 5.27: Detail view of the final structure. The stabilising elements distorted the braid segments due to their non-symmetrical arrangement.

Notes

[39]A sample export to create a link with a *munter*, where (p) describes the location of the knot, (l) the tension or length of the link, (a) the approach direction, (k) the knot type, and (b) the orientation of the support element:

1. p$\{p_x, p_y, p_z\}$, l$\{s\}$, a$\{a_1, a_2, a_3\}$, k$\{2, 3, 4, 6, 7, 8//0, 0, 1, 0, 0, 5//3, -4, 2, -1, 2, 2\}$, b$\{b_1, b_2, b_3\}$;

[40]The two support structures are built from rectangular aluminium profiles (*BLOCAN* F-Profile 40x40 [146]) that can be flexibly positioned within the building space.

[41]The Flying Machine Arena in Zurich uses eight 4-megapixel Vicon MX-F40 cameras. The angle of view of each camera is 66 x 52 degrees. Standard near-infrared strobes are used in combination with retroreflective 3–4 cm markers to track objects. The camera can detect objects up to 23 m away. Two cameras must see a marker to deduce its position, but for robustness a minimum of three cameras is required. [79, 80]

[42]To avoid self-collision between the vehicle and the rope when fabricating the knot, a vertical support element is used.

[43]Whether the linear structure is built in close proximity to the ground (like in the Experiment) or erects a link between two points (such as two skyscrapers or the two sides of a deep valley) does not affect the construction methodology.

[44]The experiment focuses solely on the construction of the mesh interlacing, not on the construction of the starting and ending knot already demonstrated in the previous experiment.

[45]Surely, the links could have been constructed sequentially by one machine. However, the cooperation through parallelisation substantially sped up the process.

[46]3 mm Polychloroprene (Neopren) mat with a hardness of 70 shore A.

[47]Different people, weighing between 70 kg and 85 kg, crossed the structure.

[48]The most important challenge was that the discrepancy between the simulation and the fabrication increased over time. This was because increasingly higher tolerances had to be taken into account as the number of layers of interaction between the tensile elements grew. This was mostly evident in the construction of the tertiary structure, where errors from the previous construction steps accumulated, making the fabrication repeatable only with major tolerances. Here, an integrated feedback process that senses how the tensile configuration changes its shape over time could provide valuable data. The obtained information could be fed back to the design environment, to adapt the digital model. This would allow interconnected tensile structures with many more fabrication steps to be created. Furthermore, feedback information could be used for more than just to accommodate for tolerances. For example, if a vehicle makes a construction mistake and thus creates an unplanned configuration, this error could be used as a new design input.

Chapter 6

Conclusion

6.1 Summary of experiments

This thesis identified the fabrication of tensile structures as a particularly suitable construction technique for aerial robotic construction. It developed a methodological framework for designing and constructing tensile structures with quadrocopters that fosters the unique spatial possibilities of the flying machines for aerial construction. A series of building experiments presented strategies and techniques that integrate the design and construction process. The following conclusions can be drawn from the experiments.

Linear structure One-dimensional suspension structures can be fabricated independently of the conditions on the ground, by creating links and knots. In relation to the specific loading case, a connection can be designed as a dynamic, moving knot, or as a fixed joint. The linear structure is an efficient method to span space. The length of the tensile link, and as such the size of the tensile structures that are possible to build with flying robots, is to a large degree scalable, depending on the lifting capacities of a vehicle.

Surface structure Two-dimensional surface structures can be obtained by creating a mesh between supports or previously built linear links. A vehicle can fly between, around, and through obstacles without colliding with them. This is a fabrication manoeuvre that can only be performed by a machine that can kinematically decouple itself from the structure it is building. Thus, this method of moving material is particularly coherent with the abilities of a flying robot.

Spatial structure The construction methodology allows three-dimensional cable grid structures to be created. Multi-vehicle cooperation increases the design and fabrication spectrum. The construction of sagging links that are deformed sequentially in proceeding fabrication steps increases the flexibility and variety of buildable structures.

Bridge structure Knots and links can be fabricated in a sequential manner, adapting the form of the structure over time. The vehicles can erect fixed and sliding connections, braids, and links at various lengths with variable tension so that they can support a person. Still, tolerances and errors during the construction might accumulate over time, creating discrepancies between the digital and the physical model.

6.2 A methodology for aerial robotic construction

After investigating the benefits and the disadvantages of the flying robot in relation to possible material and construction systems, the aggregation of linear tensile members was identified as a congruent approach to the subject matter. Consequently, this thesis has developed and experimentally validated the following overall methods and techniques:

Material and construction The research brings forward tensile structures as a connection of basic building primitives. Using this method, a variety of complex structures can be designed and built by mastering a few basic building primitives. The building primitives that were identified as being essential for the proposed construction system are: the knot (the primitive that creates tensile joints), the link (the building primitive that spans space by linking two knots with rope), and the braid (a building primitive consisting of interworked tensile members). By combining these primitives, various tensile structures can be described, whereas the interlacing (a pattern combination of knot and link primitives) presents a special type of such a concatenation.

Robotic fabrication Breaking down a tensile structure into individual basic building primitives reduces the fabrication complexity for the robotic system. It provides a generic construction approach since the individual primitives can be generalised and validated with physical experiments. Within the experimentally identified limits, these primitives can be used and adapted for various geometric configurations. An interface that describes knots and links numerically has been developed, allowing digital design data to be linked to robotic fabrication.

Design and simulation Designing structures that consist of ropes is challenging. Because of their intrinsic instability, their physical assembly continuously changes their shape with every newly placed interacting tensile member. This thesis proposes a sequential design approach that reflects the assembly order of placing tensile members. The work developed three computational design components that help the designer to simulate different designs, to determine feasible construction sequences, and to evaluate structures before building them.

6.2.1 Discussion

The following key characteristics of using flying machines in architectural fabrication have emerged over the course of this thesis:

Spatio-temporal design Aerial robotic construction offers a new approach to digital fabrication and challenges traditional means of how architecture is designed and materialised. Flying robots enable spatial interlooping of material, increasing the present capacities of digital fabrication. As Experiment 4 has shown, the spatial geometry of tensile structures can change during construction. The sequential design approach of this thesis takes this into account. It is a time-based system that describes how and in which fabrication order material is interworked, and regards aerial robotic construction as a spatio-temporal performance of material interaction.

Architectural-scale manipulation The operating range of flying robots is not limited by the size of the machine. Conventional robotic arms and CNC-machines have constrained working spaces that limit their application in architecture to the fabrication of building components. The working envelope of a flying robot, however, allows points in space to be reached that would otherwise not be accessible to computer controlled construction machines. This ability of the vehicle to relocate the tip of the end-effector to virtually any point in space has been demonstrated in Experiments 1-4. The realised structures were substantially larger than the machines that constructed them and indicated the potential to operate beyond the building component; that is, at the full scale of architecture.

Cooperativeness A heavy piece of rope that exceeds the lifting capacity of a standard vehicle by a factor of ten can either be lifted by a flying machine with ten times the payload capacity, or by 10 vehicles that collaborate on the lifting task. Digital control enables flying robots to communicate and synchronise their actions. But, as the braiding primitive discussed in Experiment 4 has demonstrated, the potential of these vehicles goes beyond the mere distribution of payload, and allows them to perform building tasks that a single machine, independent of its size, would not be able to accomplish.

Conventional robots also have the capability to cooperate. Unlike flying robots, however, robots that are connected to the ground would in many cases limit each other's operational range and are thus less suited for complex cooperative construction tasks.

Spatial autonomous materialisation Antoine Picon argues that robots alter the dependency on rectilinear motions, and thus force architects to think in three-dimensional space:

> "[...]robots do force designers to think in a truly three-dimensional space in which there are no longer any privileged directions. Moreover, they remind us of the foundational character of rotation in the analysis of motion. The movements of our body are themselves based on the various rotations of our members. But we have for a very long time forgotten the simple fact and used rectilinear motion as the standard spatial operation, from mechanics to design. Modernist industrialisation itself relied heavily on repetition by rectilinear motion. In short, robots introduce us to a profoundly different geometric world. Even if gravity will continue to make us distinguish between the vertical and the horizontal, while translational motion will remain an important feature of mechanics, the mental landscape of design is about to shift." [147, p. 59]

The rotational movements of an industrial robot, however, are still constrained to the body of the machine: its deposition or manipulation device, the end-effector, is physically connected to the workspace, extending it from a base through a series of links and joints. Conversely, the flying robot *is* the end-effector. By eliminating the kinematic structure of the fabrication machine that physically couples it to the workspace, it enables the end-effector to be spatially and autonomously steered, and thus can aggregate material in *truly* three-dimensional space. This fusing of the material with its deposition apparatus enables a conceptually different design and materialisation of architectural artefacts. As such, flying robots loaded with material move independently of the structure they are building, before they temporary physically interact with it at a desired location in space. This freedom of movement differentiates aerial robots from all the other construction machines. Any devices connected to a base would either collide with the already built structure or with themselves when, for example, tying an overhand knot, when moving through openings in the structure to pull a rope through, or when constructing a braid with two cooperating devices.

6.3 Future work

The presented research investigates the potential and the limitations of architectural production with flying robots. The developed methods and techniques constitute the fundamental conceptual and practical tools necessary for a prospective architectural use of such a novel construction paradigm. The research outlines several questions that demand further investigation. Possible directions in which research on aerial robotic construction can be further developed are identified here.

Aerial robotic system Aerial robotic construction is not limited to the use of quadrocopters. The specific fabrication constraints of vehicles with four rotors (like the orientation limitations in a quasi-static hover mode) do not necessarily hold true for other flying machines. Today, different kinds of flying robots are subject to robotic research. Some machines can tilt the rotors, to apply force dynamically in all directions. Others have a protective cage that allows them to collide with objects without crashing. A particular machine can be developed for a particular construction task.

Experiment 4 exposed the problems that can occur when the vehicles deploy links in an unreliable manner. While this might not be an issue when only a few members are constructed, when multiple links are interacting sequentially, tolerances add up and are more difficult to integrate and consider in the design environment. A sensor system that constantly measures the actual rope configurations would allow the trajectory to be adapted to the vehicles during construction and compensate for tolerances. Additionally, such a feedback system would provide the option to act as a design input.[49]

Another future challenge for aerial robotic construction is to get out of the controlled, indoor environment of the laboratory and build in an unstructured outdoor environment, whereby several additional new challenges would have to be addressed. The one that stands out is the requirement of a reliable localisation method that provides robustness and high accuracy. Currently, robotic researchers are working on different methods to allow such outdoor localisation. Real Time Kinematic navigation and laser-based systems such as Lidar are becoming more affordable and easier to use. Various robotics research groups are also developing and refining ultra-wideband radios for positioning, and Parallel Tracking and Mapping for visual navigation.

Construction system Only a selection of building primitives developed in Chapter 4 have been thoroughly tested to gauge whether they could be implemented in a larger assembly of tensile members. This is true especially in the case of the interlacing: While the zigzag-mesh and the three-strand-braid have been experimentally validated, other combinations of building primitives would be worth investigating further, particularly closed-surface weaves. The experiments in Chapter 5 all present skeletal, minimal structures. The weave interlacing would also allow the creation of enclosed spaces or surfaces to walk on. The main area of interest in this thesis has been tensile structures. However, as laid out in Chapter 3.3, flying robots can also be applied to other lightweight construction systems. Furthermore, the developments in lightweight material systems (for example carbon-fibre–reinforced thermoplastics) also offer interesting options for aerial construction processes.

In contemplating future construction scenarios, aerial robotic construction has the potential to lead to a new spatial autonomy and scalability in digital fabrication. A flying robot with a diameter of only a few centimetres and a payload capacity of only a few grams is able to fly through tiny openings between existing structural members and aggregate very delicate structures. Conversely, a much larger vehicle with a payload capacity of a few kilos can lift and place much heavier building members or apply higher forces to manipulate them. However, both machines, the tiny and the large, while having specific skills when performing construction tasks, can operate and collaborate in the same design space. This design space is novel in digital fabrication, not only because of its potentially limitless dimensions, but because of the autonomous accessibility it brings to virtually any position in space.

Notes

[49]The coupling of a design system and a robotic construction process via a feedback system is an important aspect of any future research in aerial robotic construction. Yet it brings forward challenging questions about authoring robotic construction processes. For example, a decision making process between design and fabrication based on sensory data can foster emergent behaviour or indeterminate physical materialisation (see for example the SEEK project in Chapter 2.3.1).

Appendix A

Historic Aerial Architecture

The narratives of the flying house (for example in the tale of the *Santa Casa di Loreto* [148]) and the aerial city (for example in the book *Gulliver's Travels from 1726* [149]) have been used in art and literature for centuries. Flight, construction, and machines, however, were linked for the first time in Leonardo da Vinci's studies and sketches that show human-powered mechanical flying machines inspired by winged animals in the 15th century [150]. Ever since then, architects and designers have speculated about the relationship between architecture and flying devices.

Appendix A addresses the reoccurring interest in aerial architectures by examining visionary architectural projects that involve flying machines. First, it investigates the types of flying machines used in conceptual projects. Second, it analyses how different types of flying devices inform architectural design. Third, it examines the architectural function of the flying machine in the environment it constructs.

This appendix addresses uncompromising, conceptual architectural projects, including references from literature and art [151], rather than physically feasible construction work (see Appendix B for the use of flying machines in construction engineering). Most of the concepts attempt to overcome gravity with some sort of an apparatus, and combine utopian, speculative ideas with progressive technological inventions. To analyse and compare different models, adequate architectural projects are collected by searching through historic collections of speculative design work. Further, this appendix analyses and compares the projects in order to categorise them. Finally, it draws conclusions from the categorisation and relates the findings to the subject matter of this thesis, the application of flying robots in architectural production.

Chronology

> "Un moulin porte des ailes;
> N'est-ce pas pour voltiger?"
> J.J. Grandville, *Un Autre Monde*, 1844, p. 144

Before the invention of manned flight, concepts of aerial machines in architecture usually derived from bird flight with mechanically actuated flapping wings. J.J. Grandville in 1844 for instance reinterprets the blades of a windmill as wings and launches the miller inside of it into the sky [152]. Many such projects, however, do not provide an explanation of how lift is generated, and simply assume antigravity [149]. In 1783, the *Age of the Enlightenment*, less than a decade before the *French Revolution*, the Montgolfier brothers invented the hot air balloon [153]. The discovery of lighter-than-air technology (aerostat) at the end of the 18th century gave rise to a whole new way of thinking about flying: For the first time, humans could physically access airspace, rather than just speculate about it. Architects imagined buildings that would float above the surface of the earth, flying wherever the wind takes them, and moor like a ship in the sky at changing locations [154, 155].

By combining the aerostat with propellers, the airship introduced a steerable method of aerial transportation. The possibility of not just floating in the air, but being able to access any point in three-dimensional space, changed (once again) the idea of what airspace can be in the construction of architecture. In the context of 1920s post-revolutionary Soviet Constructivism, Vesnin and Popova, for instance, proposed to stage a temporary *Mass Festival* for the Third International by incorporating airships in the design set [156]. Half a century later, in 1968, the*Archigram* group replicated the concept with the *Instant City* project [157]. In contrast to static, lighter-than-air vehicles, the invention of the airplane and the fixed wing at the end of the 19th century initiated a dynamic, heavier-than-air technique of aerial transportation (aerodyne). The flying machines became mechanically more complex, faster and smaller. Architectural concepts involving fixed wing aircrafts reflect this new method of dynamic flight. Symbolising a new ideology of cultural progress, the notion of weightlessness (of the balloon and the airship) was replaced by the speed and mobility [158,159]. Rotorcrafts such as helicopters altered (once again) the conditions of how airspace was perceived by designers and architects. Combining strong payload capacities with precise manoeuvrability, the helicopter soon became the architect's flying machine of choice, replacing the popular airship. In the 1950s, Richard Buckminster Fuller was one of the first designers to demonstrate the lightweight nature of his space frame domes by lifting them up and transporting them to remote locations with a helicopter [160]. The helicopter came to symbolise a tool for aerial manipulation, which saw lightness, mobility, and airspace as new parameters leading to new architectural experience.

However, the history of aerial architecture is not always a response to contemporary technological and cultural developments. In *The Wonderful Wizard of OZ* from 1900, Frank Lyman Baum imagined a cyclone that aerially transports a house [161]. Ives Klein used intensities like pressure in constructing a ballistic architectural experience with pneumatic rockets and shooting water and fire arches in 1959 [162]. In the 1960s, Raimund Abraham [163] and Haus-Rucker-Co [164] allowed the users of their buildings to experience verticality with jetpacks. Lebbeus Woods ascended his tethered structure like a kite in 1988 [165], while Peter Garfield in 1998 literally allowed existing houses to fly by lifting them into the sky with a helicopter before releasing them to gravity [166]. The following list shows examples of architectural concepts involving flying machines in chronological order.

Examples of speculative aerial architecture

1291 - Unknown author, Painting of the Santa Casa di Loreto in the Basilica in Trsat (Rijeka)

1638 - Francis Godwin, The Man in the Moone

1726 - Jonathan Swift, Gullivers Travels

1844 - JJ Grandville (Jean Ignace Isidore Gérard), Un Autre Monde

1876 - W.J. Lewis, Flying Car

1893 - Paul Balvin, Aero Home

1900 - Frank Lyman Baum, The Wonderful Wizard of Oz

1906 - Wenzel Hablik, Entwürfe für Flugobjekte und fliegende Siedlungen

1908 - Alexander Graham Bell, Kite

1921 - Windsor McCay, The Flying House

1921 - Alexander Vesnin and Liubov Popova, The Struggle and Victory of the Soviets

1928 - Richard Buckminster Fuller, 4D Tower

1928 - Georgii Krutikov, The City of the Future

1932 - Frank Lloyd Wright, Broadacre City

1944 - Casto Shaw, Casa Aerotransportada

1950 - Johann Ludowici, Kugelhaus

1955 - Geodesics Inc., US Marine airlifting a geodesic dome in Raleigh, NC

1959 - Yves Klein, Architecture De L'Air

1960 - Chanéac, Cellules Polyvalentes

1960 - Richard Buckminster Fuller and Shoji Sadao, Cloud Nine

1969 - Richard Buckminster Fuller and Shoji Sadao, Dome over Manhatten

1960 - Jacques Polieri, Theater der komplexen Bewegung

1961 - Wilhelm Holzbauer, Helikopter-Haus

1962 - Hans Hollein, Überbauung Salzburg

1963 - Guy Rottier, Maison De Vacances Volante

1965 - Richard Dietrich, Metastadt

1966 - Raimund Abraham, Living Capsules for the Space City

1966 - Jeanne-Claude and Christo, 42390 Cubic Feet Package

1966 - Akira Shibuya et.al.,Urban Residences and their Connective Systems

1968 - Onyx, Parsec City

1968 - Peter Cook (Archigram), Instant City

1968 - Haus-Rucker-Co, Environment-Transformer

1968 - Matti Suuronen, Futuro

1969 - Justus Dahinden, Freizeitstadt Kiryat Ono

1969 - Nicolas Schöffer, La Ville Cybernétique

1970 - Glen Small, Flying House

1971 - Gianni Pettena, Imprisoment

1971 - Superstudio, Spaceship City

1973 - Wolf D.Prix and Helmut Swiczinsky, Haus mit dem fliegenden Dach

1972 - Architectural Design (AD), Cities in the Sky

1974 - Graham Stevens, Desert Cloud

1979 - Jan Kaplicky, Case Study Structure

1986 - Gilles Ebersolt, Radeau Des Cimes

1988 - Lebbeus Woods, Aeroliving Labs

1988 - Lebbeus Woods, Photon Kite

1998 - Peter Garfield, Harsh Reality

2007 - Laurent Chehere, Flying Houses

2010 - La Machine, Aeroflorale II

2011 - Gramazio & Kohler and Raffaello D'Andrea, Flight Assembled Architecture

Recurring images Architectural concepts involving flying machines occur and reoccur in different eras. It was in the 20th century, however, that the experience of human flight was transformed from the experimental to the commercial, where it is now a global mass market phenomenon. Thus the 20th century inspired a significant conglomeration of aerial architecture concepts, which can be further characterized by two peaks of varying intensity. The first peak, and the smaller of the two, began after the First World War and lasted until the beginning of the Great Depression. In the 1920s, when everything seemed to be feasible through modern technology (automobiles, radio, and cinema hit the market), visionaries like Buckminster Fuller in America and Georgii Krutikov in the Soviet Union, among others, generated utopian projects at the intersection of human flight and architecture. The second, and by far larger, peak occurred in the 1960s. This subversive era after World War II fostered a variety of speculative work involving flying devices. On the one hand, this can be explained culturally as a new way of thinking about individual freedom, mobility, and weightlessness (counterculture movement) [110]; and on the other hand, it can be explained scientifically as the exploration of outer space (Space Race). This technological optimism and creative enthusiasm came to an end with the economic reality of the energy crisis in the 1970s.

Most of the projects developed in the 20th century are unbuildable or were never meant to be built in the first place. As a result, the conceptual ideas were usually represented visually in the form of drawings or, occasionally, scale models. Comparing drawings from different projects discloses in many cases conceptual and visual resemblances between works from different time periods. The *Instant City* project from the Archigram group [157], for example, constructs a temporary architectural event with mobile airships and balloons, in conjunction with fixed, existing structures (Fig. A.1). A very similar concept and visual language had already been proposed by Vesnin and Popova [156] almost half a century earlier. Their *Mass Festival*, staged for the Third International, also uses mobile airships to provide temporary structural support in combination with fixed architectural elements (Fig. A.1). In 1928, with the *4D*

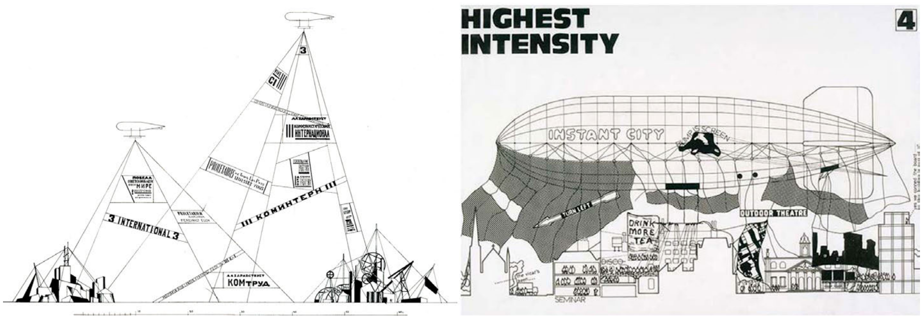


Fig. A.1: Temporary mobile aerial structures. On the left, *Mass Festival* (1921) by Vesnin and Popova. On the right, the *Instant City* project (1968) by the *Archigram* group.

Tower and the *4D House* (Fig. A.2) [103], Fuller proposed a lightweight building system that uses new materials (plastic and aluminium) where the floors are attached to a central mast and suspended with tensile elements. The construction is supposed to be light enough to be transported by airship to various locations. In 1906, more than twenty years earlier, Hablik created designs for flying colonies and aerial architectures [167] (Fig. A.2). His *Luftgebäude* is also a lightweight construction with a central mast from which floors are suspended. In contrast to the *4D Tower*, the aerial device is integrated in the structure using a series of rotorcrafts to generate lift.

The architectural function of the flying machine

Technological invention and the design of architectural concepts involving flying machines developed alongside each other. Here, the appendix analyses the collected projects in terms of the role of the flying device in the architectural experience it constructs. By comparing the collected work independently of their origin or era, the role of the machines can be sorted according to three distinct architectural functions: the task of fabrication, the role of transportation, or the meaning of providing structural support.

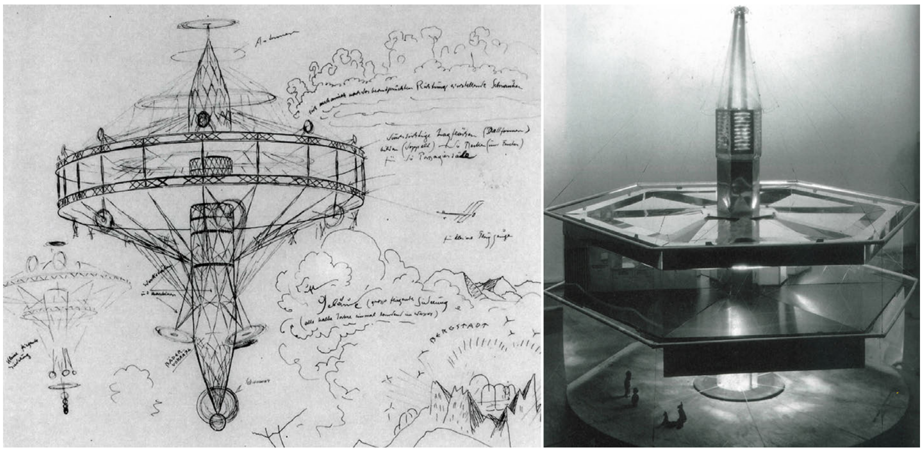


Fig. A.2: Aerially transportable lightweight structures. On the left, *Luftgebäude* (1906) by Hablik [167]. On the right, *Dymaxion House* (1929) by Fuller [160, p. 122-145].

Fig. A.3: Reliefs of aerial buildings. On the left, *Santuario della Santa Casa di Loreto*. On the right, a Vimana on an Indian temple.

Fabrication

> "Tubes, dont les portées et les agencements seront calculés pour les grands chantiers par des cerveaux électroniques, seront élevés et mis en place à l'aide d'hélicoptère remplaçant les grues." Michel Ragon, *Où vivrons-nous demain?*, 1963, p. 102

Helicopters are a reality on today's construction sites [168]. It is the helicopter's ability to freely access points in space and hover that made this machine popular for specialised construction tasks, for example in highline or bridge construction (see Appendix B). Conceptually, before the invention of the helicopter, Fuller proposed a scheme for aerial construction with airships [160]. In his *4D Time Lock* Manifesto [103], he describes the erection of a 50-m tall tower house with the aid of a 200-m long airship. The idea was that the tower would be prefabricated and mounted horizontally on the airship (Fig. A.4). The flying machine would then transport the building to a designated location before releasing an anchor high above the building ground. The operators would then release a bomb from the airship to create a crater that would become the excavation for the foundation of the tower. The tower would then be lowered from the airship, positioned in the crater and fixed to the ground by pouring concrete into the hole. After the assembly, the airship would fly away to erect the next tower.

In 1959, thirty years later, Fuller demonstrated a slightly modified concept (excluding the bomb) that involved aerially transporting his lightweight space frame domes with a helicopter [160]. While the progression from the airship to the helicopter constitutes an enormous technological step, the architectural function remains almost the same. Fuller also proposed the use of helicopters to erect his unbuilt *Dome over Manhatten* [169].

> "A fleet of 16 of the large Sikorsky helicopters could fly all the segments into position for a 1.6-km high, 3-km wide dome in three months at a cost of 200 million Dollars." Buckminster Fuller, 1960 [170]

In addition to Fuller, numerous other architects proposed the use of helicopters in the construction of architecture. Particularly in the 1960s, often in the context of modular building systems, the helicopter was seen as an alternative to a crane and was often referred to as a *Skycrane* (Sikorsky S64) [171] or a *Skyhook* (K-Max) [172]. In fabrication, helicopters are usually a means to an end: they tend to solve logistical problems such as transporting material or assembling it

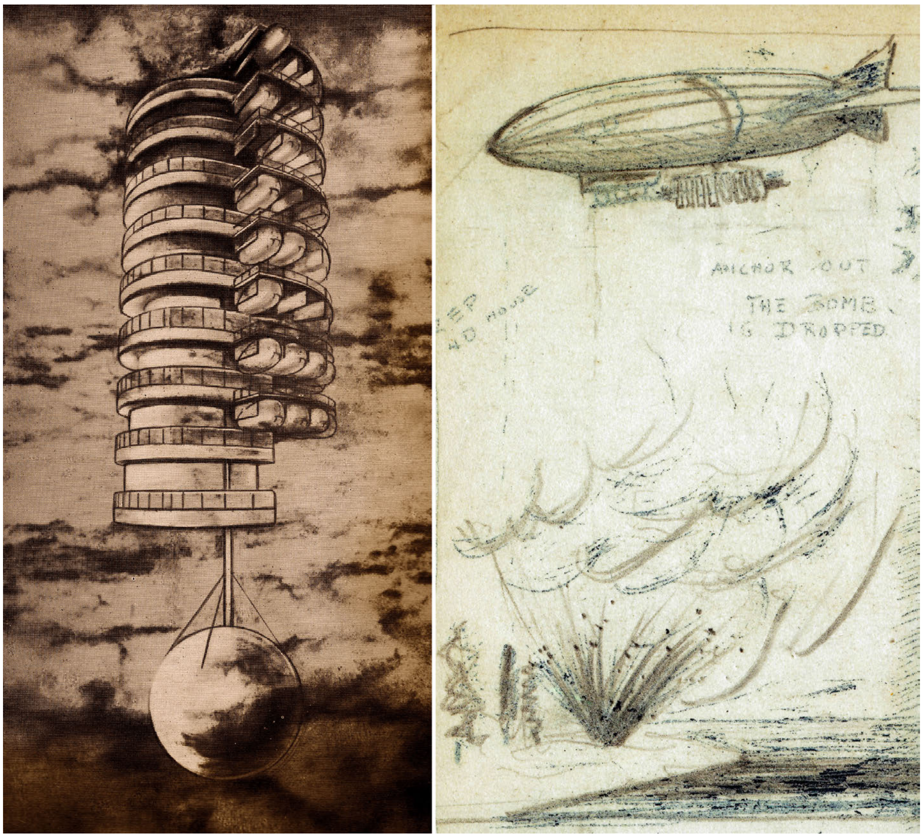


Fig. A.4: Examples of aerial fabrication. On the left, *The City of the Future* (1928) by Krutikov. On the right, an explanation of aerial fabrication using airships and bombs (also 1928) by Fuller [160, p. 100].

at an otherwise inaccessible point in space. As radical as the concept of using helicopters in the construction of architecture might seem, once the job is done and the building built, it is difficult to distinguish it from a building constructed by a crane.

Transportation The archetype of aerial architecture is airborne transportation of buildings. For centuries people have envisioned that houses or whole human settlements would be untied from their enrooted locations on the surface of the earth and taken up into the sky. The tale of the Santa Casa di Loreto, for example, tells us that the house at Nazareth in which Mary (Mother of Jesus) grew up was transported by a group of angels through the air in 1291 to a hill in Trsat (Rijeka, Croatia) because it was threatened with destruction [148] (Fig. A.3). Similarly, the Vimana is a mythological flying palace that can be found in Sanskrit and Hindu epics [173] (Fig. A.3). In literature and art this narrative occurred over and over again in different time periods with different technical explanations of how lift was generated. Angels, birds, balloons, airships, rockets, and fixed and rotary wings provide means of the elevation of the built environment into airspace. The common denominator of all these concepts is to provide aerial mobility to the architecture and its users. In 1928,

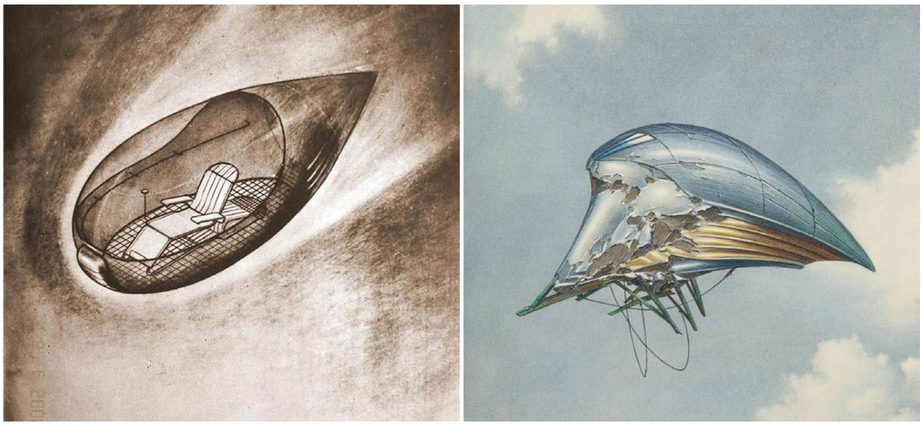


Fig. A.5: Examples of aerial transportation. On the left, speculative flying machines in *The City of the Future* (1928) by Krutikov. On the right, *Aeroliving Labs* (1988) by Lebbeus Woods.

for example, *VKhUTEIN*[50] architecture student Georgii Krutikov presented his diploma project *The City of the Future* at the public defense for architecture students in Moscow. His project proposes a vision of a flying city suspended above the earth, and explores the consequences of new means of urban transportation. Compact living cells, packed together in large cylindrical structures and connected to a lighter than air flying system, create a combination between a house and a flying machine [155] (Fig. A.4). Inhabitants of the already moving dwellings could also be aerially transported individually by using portable living cells that could move in the air, on earth, and in water (Fig. A.5). The project gained a lot of attention after it was published in the newspaper Postrojka with the title "Soviet Jules-Vernes. *VKhUTEMAS* Trains Dreamers instead of Builders". It caused a scandal; the utopian ideas were too daring for post-revolutionary soviet culture [174].

A project closer to realisation is Guy Rottier's *Maison de vacances volante* from 1963-64 [175]. It combines a helicopter with a caravan, and has a cockpit, beds for the parents and for the children, a kitchen, a toilet, and a shower. The fuel tank is positioned underneath the floor to give more room for living.

> "Cette forme d'habitat de vacances rend accessibles des lieux jusque-là réservés aux seuls alpinistes. En ce qui concerne l'étendue pouvant être parcourue, de vastes parcs pourront être aménagés en dehors desquels il ne serait pas souhaitable d'évoluer afin d'éviter toute promiscuité avec d'autres types de maisons. [...] Elle offrait le luxe de s'échapper et de jouer avec les lois, les esprits, les propriétés, en d'autres termes de s'offrir un peu de liberté. C'était une idée qui aurait pu devenir réalité, une idée qui se réalisera un jour." (Guy Rottier) [176]

Structural support The third function of aerial machines in architecture is connected to the flying machine's structural capacity, where the machine acts as a structural element in the artefact. Traditionally, loads that act upon a building are carried through structural elements (such as columns, walls, and plates) that are connected to one another and to the ground. Similar to other structural architectural elements, the flying machine can also carry loads [177]. However, it is physically decoupled from its environment. As a structural element, the flying machine radically alters the conditions of how architectural elements are linked. The flow of forces through interconnected structural members becomes obsolete, opening up new forms of materialisation. One project that demonstrates this approach is the *Aeroliving Labs* (1988) by Lebbeus Woods [178]. It represents a group of heavier-than-air moving structures that drag sheets of light-weight fabric through the atmosphere and dock at existing structures in the air over Paris. The project visualises an architecture that is fluid, dynamic, and exposed to the flow of air, rather than one that is static. The experimental flying devices build the structure by negotiating gravity and wind. They can react to changing conditions and reform the spatial environment. Similarly to the Russian Constructivists [156] and the *Instant City* project [157], Woods' work stands in the tradition of speculative architectural work, where flying devices don't just temporarily interact with the building elements, but become a substantial part of the architecture itself.

Another interesting approach to providing structural support via flying machine was expressed by Gianni Pettena. Critiquing modernism in general, and specifically the grid and geometric rigour, Pettena's *Imprisonment* [179], pictures a series of planes weaving a grid from their exhaust (Fig. A.6). The flying machine materialises a different structural expression - a temporary spatial environment of intensive boundaries - before evaporating in the clouds. The machines' ability to fly around each other, something a crane or any other machine attached to a fixed base could not do, is reflected in the design. In other words, the machine's ability is congruent to its architectural manifestation.

Fig. A.6: *Imprisonment* (1971) by Gianni Pettena.

Conclusion This appendix illustrates the strong relationship between conceptual architectural work and scientific developments. New technological inventions often breed new ideas for their implementation in architectural work. The flying robot must be situated within this tradition. It, too, is a new technological development, a device that questions existing methods. It, too, is a novel machine, that fosters architectural speculation. This appendix has shown that, independent of the technical or historical context, the actual architectural function of the vehicles can be broken down into three categories: 1) the purpose of fabrication; 2) the purpose of transportation and mobility; and 3) the purpose of providing structural support. While the flying robot could be applied in any of the three categories, this thesis focuses on its application in the making of structures, i.e. aerial robotic fabrication.

Although the architectural functions of flying machines repeat, they inform the design of aerial architectures in different ways. This is a result of the different abilities and constraints they offer. A balloon, which simply generates lift and floats with the wind, influences the design in a distinctive manner since its position in space can only be controlled along the Z-axis. By comparison, an airship, which offers additional methods of control in accessing points in space, alters the design conditions, and offers for the first time functionalities of aerial fabrication, for instance. Similarly, the helicopter, today's flying device of choice in construction, also changes the constraints of architectural design. It offers greater manoeuvrability and control, and enables novel methods of interacting with the environment. In the context of this research, the flying robot presents a different set of abilities yet again. As a result, the appendix suggest that designing and fabricating with aerial robots equally establishes a novel form of architectural materialisation and design.

Notes

[50]Earlier *VKhUTEMAS*

Appendix B

Flying machines in construction engineering

Flying machines have been applied on building sites since the 1950s [168]. They are used for specialised construction tasks that traditional machines cannot perform. Though the most common aerial machine used in construction is the helicopter, various other technologies have been developed, including ballistic rockets and lighter-than-air vehicles such as airships. Each technology has its advantages and disadvantages.

Rotorcrafts The aerial machine of choice in construction is the helicopter. It offers the right compromise between manoeuvrability and payload capacity. Helicopters are most often used at building sites where a lack of street access prevents other kinds of construction machines from being installed. This may be the case, for example, when building infrastructural projects in the mountains, or when erecting a structure on top of another building in an urban area. The use of helicopters in construction is one of the most dangerous activities for the pilot and the crew. Despite safety precautions, accidents repeatedly occur when performing such tasks [180]. Rotorcrafts in construction require a whole group of people working on the ground and communicating with the pilot. In the early days of helicopter aided construction, the lack of efficient radio communication did not allow the crew on the ground to directly communicate with the pilot and give fabrication instructions. Assistants would stand on the side of the helicopter to maintain visual contact with the building site, and transfer construction instructions between the pilot and the workers on the ground (Fig. B.1). It was the pilot's job to maintain the position of the vehicle and manage wind gusts while the crew assembled the building elements [181]. Today, dedicated construction helicopters are often used for such specialised tasks (for example the *Kaman K-Max* helicopter [172]). These machines are narrow and equipped with bubble-windows, so that the pilot can see the construction site. They are also equipped with radio communication, which allows the pilot to receive information from the ground crew, and control systems (such as gyro stabilisers), which help with accurate navigation. Because it can hover and flexibly access

Fig. B.1: Aerial construction of a pylon with a Agusta-Bell 204B helicopter by Heliswiss (Walter Tschumi as pilot) in Sondrio, Italy, in 1969 [181].

points in space, the helicopter is suitable for a wide variety of construction tasks. These, however, fall into two main application areas. First, helicopters are used as aerial cranes to either transport building material or entire buildings to remote locations. Dedicated heavy duty helicopters, also called *Skycranes*, have lifting capacities of up to 10 tons [171]. This allows the aerial transportation of lightweight buildings, completely prefabricated with insulation, windows, and installations [182](Fig. B.2). Buildings like the *Futuro House* [183, 184] or the *Kugelhaus* [185] were specifically designed to be aerially delivered, which is also evident in their aerodynamic shapes. The benefit of this method is that, aside from the preparation of the site, no construction tasks have to take place once the building is delivered and no skilled builders have to be present. All the fabrication is performed off-site, in a controlled environment, making it a ready-to-use structure. Integrating all components in one single unit makes the scale of the building limited by the payload capacities of the rotorcraft, however. Therefore, only small and light designs can be realised with this method. In

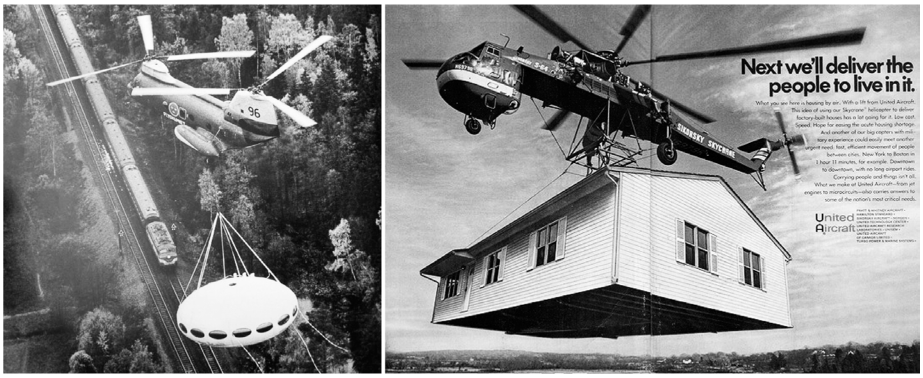


Fig. B.2: Transportation of entire buildings by heavy-lift rotorcrafts. On the left, *Futuro House*. On the right, a prefabricated house is lifted with a Sikorsky S-64 *Skycrane*.

addition to delivering entire buildings, helicopters can also be used to transport raw building material (such as concrete or wood) or pre-assembled building components (Fig. B.3). Because such building elements are smaller, lighter, and less effected by wind gusts than entire buildings, smaller helicopters can be used. While using this transportation method means that builders must be on site to assemble the structure, it can be used to help erect buildings at a variety of scales because the structure can be split into pieces. The helicopter must usually make several trips between the material pickup location and the building site, and each trip adds to the cost and safety hazard for the pilot and the workers. The second application for helicopters in construction engineering is aerial assembly (Fig. B.4). Here, the helicopter is not merely akin to a crane with a larger range of reach. It can also be used to perform assembly tasks *in situ*. For example, helicopters are used to string cables between the support poles of bridges, in order to create a link between the two sides [187, 188]. In high-line construction, rotorcrafts are also applied to erect power cables between masts. The use of helicopters in assembly work is one of the most challenging tasks for the machine and the crew, for the vehicle must interact with the environment and is often physically coupled to it. Collisions between rotors and the structure often lead to severe accidents.

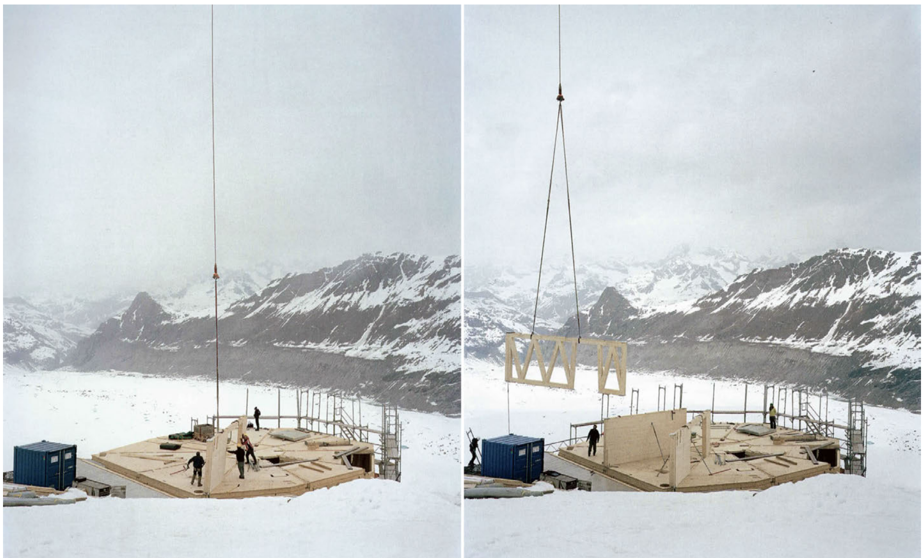


Fig. B.3: Aerial transportation of building components during the fabrication of the *Monte Rosa Hut SAC* in 2009. The hut is 2883 meters above sea level, close to Zermatt, Switzerland. [186, p. 139]

Fig. B.4: Helicopter stringing power cable in high-line construction. A worker stands on the pole to fasten the cable after the deployment. [189]

Lighter-than-air machines The concept of using balloons and airships in construction existed before the invention of the helicopter (see Appendix A). Lighter-than-air technology enables high lifting capacities. The payload capacity is to a large degree scalable. The larger the volume of the machine, the greater the weight that can be lifted. This large physical volume, however, also has drawbacks. An airship, for example, requires a lot of space to safely navigate, and its large surface area makes it easily affected by winds. As a result, it is challenging to manoeuvre these machines precisely, or to maintain their position in a specific location. Still, in comparison to a helicopter, they can lift more weight, and this has led to various experimental projects. The *CycloCrane*, for instance, was a hybrid airship developed for heavy lift operations (Fig. B.5) in the 1980s [190] by the Aerolift company. The concept proposed a means of keeping the vehicle in the air for many hours at a time using a combination of aerostatic lift, aerodynamic lift, and thrust. It was meant to replace heavy-lift helicopters, which could only carry enough fuel for a few hours of flight time. A mechanically complex cycloidal-rotor allowed the airship to navigate during its first manned flight in 1984. It was predicted that the machine would be able to lift payloads of up to 75 tons, but while several versions of the machine were constructed, the anticipated payloads capacities could not be reached. [191]. When its funding ended in 1990, the project was terminated. Another concept

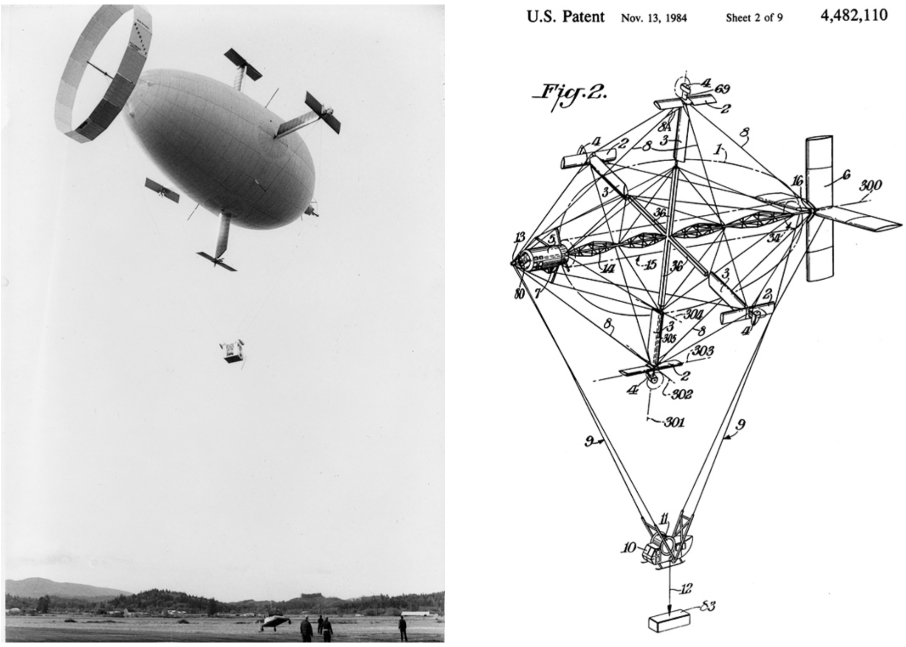


Fig. B.5: On the left, the CycloCrane during its first manned flight in Tillamook, OR, in 1984 [191]. On the right, a drawing from the CycloCrane patent, indicating the principle [192]. The person operating the vehicle sits in a cabin between the payload and the machine, suspended from the airship.

for construction machines that use lighter-than-air technology is the *CargoLifter* project. This project used tethered, unmanned helium balloons to generate lift and carry building elements (Fig. B.6). The position of the balloon and hence the location of the cargo can be controlled by adjusting the length of the three tethers, which are anchored with winches that are spread over the building site [193]. The method principally allows heavy payloads to be accurately positioned in space.

Fig. B.6: From 2005 onwards, various physical prototypes have been realised by *CargoLifter*. The patent drawing indicates the general concept [194].

Rockets Yet another aerial construction technique was used to assemble the Siduhe River Bridge, a suspension bridge spanning a 500-m deep valley. Because of the site's limited accessibility, conventional means of making the first connection between the two sides of the valley (usually accomplished via boat or helicopter) were not possible. Instead, a rope-placing method involving military rockets was developed to help place the two pilot cables: 1300-m long ropes made of elastic chinlon yarn were attached to two rockets and then fired over the canyon, covering a distance of 1100 m. The installation of the two cables took less than 10 seconds [195]. Since 2006, this construction method has been applied three times (Fig. B.7) [196].

Fig. B.7: Tethered rocket for the erection of the pilot line for the main cable, in 2015, of the Puli Bridge in Pulixiang, China [196].

Appendix C

Aerial construction of space frame structures

Objective In order to match the limited lifting capacities of flying robots and to make use of energy and resources efficiently, this research focuses on lightweight construction systems such as space frame structures [11, p. 446]. This proof of concept study examines the ability of flying robots to assemble a space frame structure in order to validate an alternative approach to the fabrication of tensile assemblies, and to provide important findings about the constraints of aerial robotic construction (see Chapter 3).

Space frame structures depend on the geometrical configuration to ensure stability. To form a stable truss structure composed of nodes interconnected only by axially loaded bars, a fully triangulated structure must be formed [112, p. 15]. The conditions that must be met in order to ensure the stability in a space frame assembly can be calculated using Föppl's equation (C.1) [197, p. 6], where m_{min} is the minimum number of bars and n is the number of joints in the structure.

$$m_{min} = 3n - 6 \tag{C.1}$$

Comprising six bars and four joints, the tetrahedron is the simplest stable, three dimensional, pin-jointed bar and node structure. Therefore, this appendix concentrates mainly on the construction of a tetrahedron space frame (Fig. C.1). Presented is a sequence for the construction of non-standard triangulated space structures that can be assembled by two cooperating vehicles. Following the payload limitations of the quadrocopters, a non-loadbearing prototype is assembled from carbon-tubes. The construction approach, however, is scalable to architectural applications.

Methodology In the context of the discussion presented in Chapter 3, which defines the constraints of aerial robotic construction, two challenges stand out when attempting to fabricate a triangulated space truss structure with flying robots.

First, the vehicles must be able to grab a building element and then place it at a given orientation. This demands that a gripper attached to the machine must not only hold but also orient the bar with one degree of freedom. In addition, it must compensate for the rotation limitations of the quadrocopter in a quasi-static position (rotation around the X and Y-axis, see Chapter 3.1.1). Furthermore, the gripper must be lightweight, in order to not overly influence the payload and hence the manoeuvrability of the machine (the more weight that is used for the gripper, the less that is available for the building element). This led to the development of a prototypical ultra-lightweight end-effector, based on the universal jamming gripper [198]. In the prototype, Styrofoam balls are used as the granular jamming substance instead of coffee grounds, reducing the overall weight of the gripper (Fig. C.2). The concept is that the carbon tube is picked up by the flying robot in its final spatial orientation and does not need to be reoriented in the air by the jamming gripper, which only needs to preserve its pose. The same strategy is adopted for the vehicle itself, whereby the needed vacuum is generated at the ground station. Once the bar is lifted and moved to the desired position, the clamping can be released by opening the valve (Fig. C.5). Since the energy to hold and release the building element is generated at the ground station and the holding force is ensured with air-pressure, the gripper weighs only a few grams.

The second challenge is the definition of the proper assembly order for the singular tubes. Even though the tetrahedron is stable in its final configuration, it is not stable during the build-up. Of course, the bars could be assembled simultaneously by collaborating vehicles. The investigation of possible assembly sequences has shown that two collaborating vehicles are enough to construct any triangulated space frame (Fig. C.3). This is based on the assumption that one flying machine can stabilise the bars temporarily, until the structure is stabilised. As figure C.3 shows, two bars are placed by two vehicles and, while one of the vehicles is picking up another building element from the ground station, the other vehicle momentarily changes its function and acts as a structural

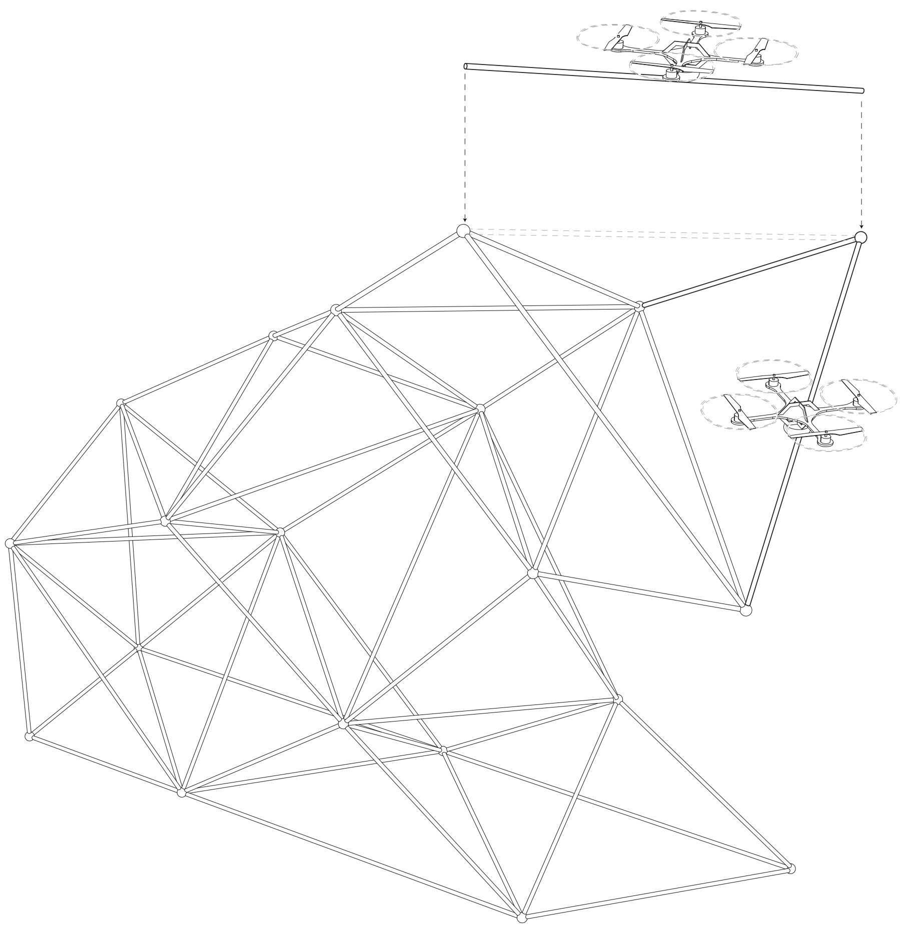


Fig. C.1: A conceptual, aerially assembled space frame structure consisting of bars with different lengths and joints with variable angles.

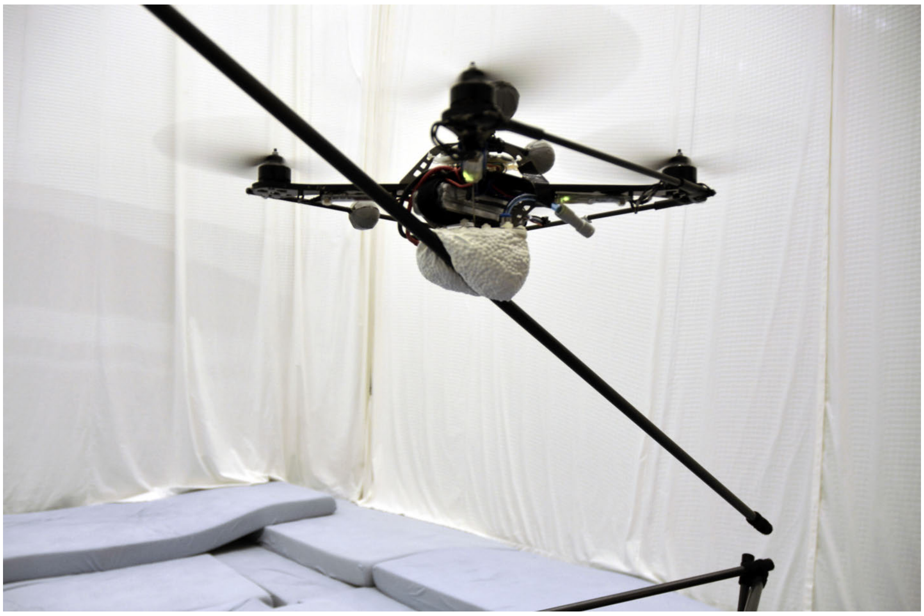


Fig. C.2: Jamming gripper. The gripper uses negative pressure to compress granular filling material (Styrofoam balls) contained in a membrane (balloon) to rigidly grasp a round carbon tube at variable angles.

support to balance the unstable assembly until the third bar is placed and the structure is triangulated and stable.

Excecution A fabrication experiment was conducted with the setup described in the Chapter 5.1. The structure was built from pultruded carbon tubes with a 14mm diameter and variable lengths between 80cm and 120cm. The bars were fitted with hook-and-loop (Velcro) fasteners at their ends to connect the building elements. This joining method is not load-bearing. The tetrahedron was constructed on a manually pre-assembled space frame that was far enough from the floor to prevent accidents caused by ground effect. The goal of the experiment was to examine the ability of the vehicles to place a building element and collaborate during the build up. The building material was fed manually to the gripper and the valve controlling the pressure was also operated manually.

- The first test involved one vehicle, which was loaded with a tube and programmed to fly to the placing location and connect the building element to the existing members (Fig. C.2). Despite the accurate tracking system and the ability of the joining method to compensate marginally for the tolerances, the joint was difficult to realise. The main reason for this diffi-

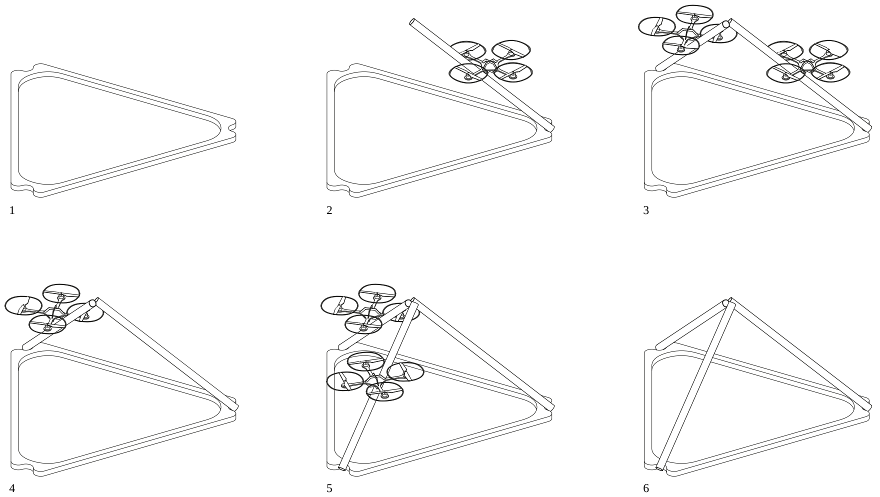


Fig. C.3: Principle assembly sequence for creating a triangulated structure using two collaborating quadrocopters.

culty was that the vehicle is inherently unstable. It constantly adjusts its position based on the discrepancy between where it is and where it should be. These constant movements around the center point of the vehicle are amplified towards the end of the bar, and the greater the distance between the end point of the tube and the center point of the vehicle, the larger the movements at the joint location, making the assembly increasingly difficult.

- The goal of the second test was to simultaneously place two bars using two vehicles (Fig. C.4). Here, in addition to the problems that occurred in the first test, another critical issue emerged: that the dynamics had not been fully modeled to account for the bar and how it impacts the length, angle, and weight of the system. The vehicle is assumed to have a symmetrical structure, with the four arms resembling a cross, but the building element attached to the machine changes the structure of the vehicle. If the end of the tube comes in contact with the environment, a moment acts on the center point of the vehicle, causing the machine to react to the forces acting upon it. In order to compensate these forces, the dynamic model of the vehicle must be redefined, integrating the bar, its length, angle and weight into the system. When performing the test, the dynamics of the system had not been modelled, which caused the machines to behave in an unstable manner as soon as they came in contact with each other or the structure.

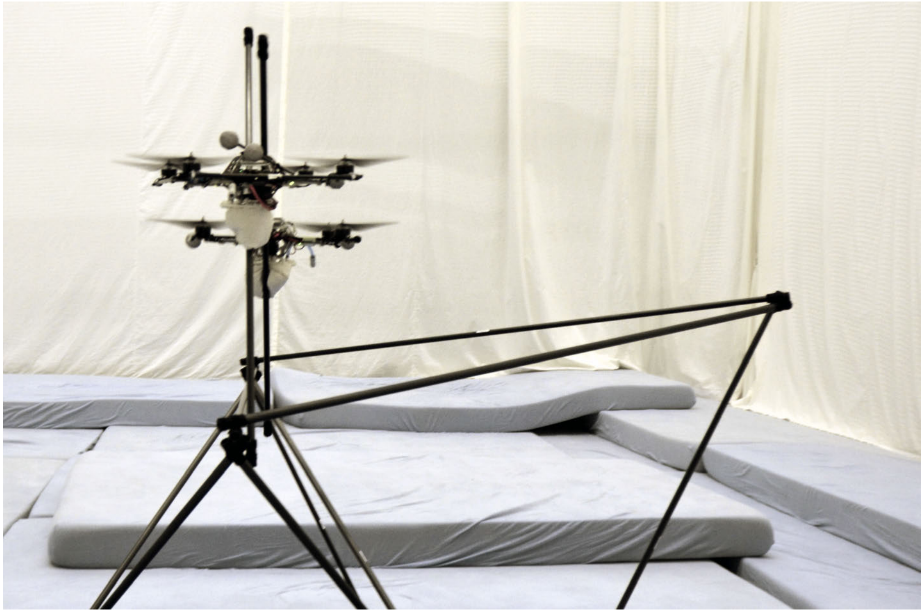


Fig. C.4: An attempt to place two bars simultaneously using two vehicles.

- The third test examined the jamming gripper by investigating the assembly of the final element of a triangulated space frame. Here, the balancing of the already placed tubes was emulated by a person. One flying robot was then charged with a bar at a specified angle. The vacuum to hold the element in place was generated on the ground and was sealed with a pneumatic valve. After that, the machine manoeuvred along a programmed path to the placement location. The vacuum was then manually released, disconnecting the building element from the machine and allowing the vehicle to fly away, in order to pick up the next tube (Fig. C.5). The lightweight jamming gripper was able to grasp building elements of different cross sections at variable angles. [51]

Results The fabrication of non-standard space frame structures offers an interesting construction method for aerial robotic construction that could not be further pursued within the scope of this thesis. Considering the ability of the vehicles to not only place single building members but also momentarily stabilise multiple tubes, a variety of structures could be realised with just two collaborating vehicles. The jamming gripper offers an appropriate technique to grasp a variety of objects at variable orientations, while still remaining lightweight. Furthermore, with the integration of a digitally controlled ground station, some of the tasks, for example generating the energy to hold the element, can be kept on the ground, reducing weight. The carbon tubes used in the experiment are load-bearing and could be used for architectural applications. Other materials, such as aluminium tubes or bamboo, could also be considered. To build load-bearing structures, a new joining method must be developed; however this is beyond the scope of this thesis. The connection system is crucial to the construction methodology: it must transfer the forces that occur when the structure is loaded, and yet must also be robotically buildable. As the first test has shown, during the positioning of a bar, the building element is constantly moving. While this could be improved to a certain extent by modelling the forces, another more suitable method would be to integrate the possible tolerances into the joining method. A conical node, for instance, could guide an element into place. In addition to developing an appropriate joining method, the fabrication of space frame structures with flying robots requires further development in vehicle control. The dynamics of the system must be modelled in order for the vehicles to physically interact with each other and the structure. Because it was beyond the scope of this thesis, the alternative approach to aerial fabrication of tensile structures presented herein was not fully pursued. The construction method did not fully exploit the abilities of the vehicles, for example to fly through and around objects and to manipulate autonomously material in space. However, it demonstrated some of the challenges of spatially aggregating structures with rigid discrete elements, which provided necessary findings for the further research, for example the definition of the machinic construction constraints (Chapter 3.1). Further, the study motivated the examination of self-compacting construction methods such as tensile structures.

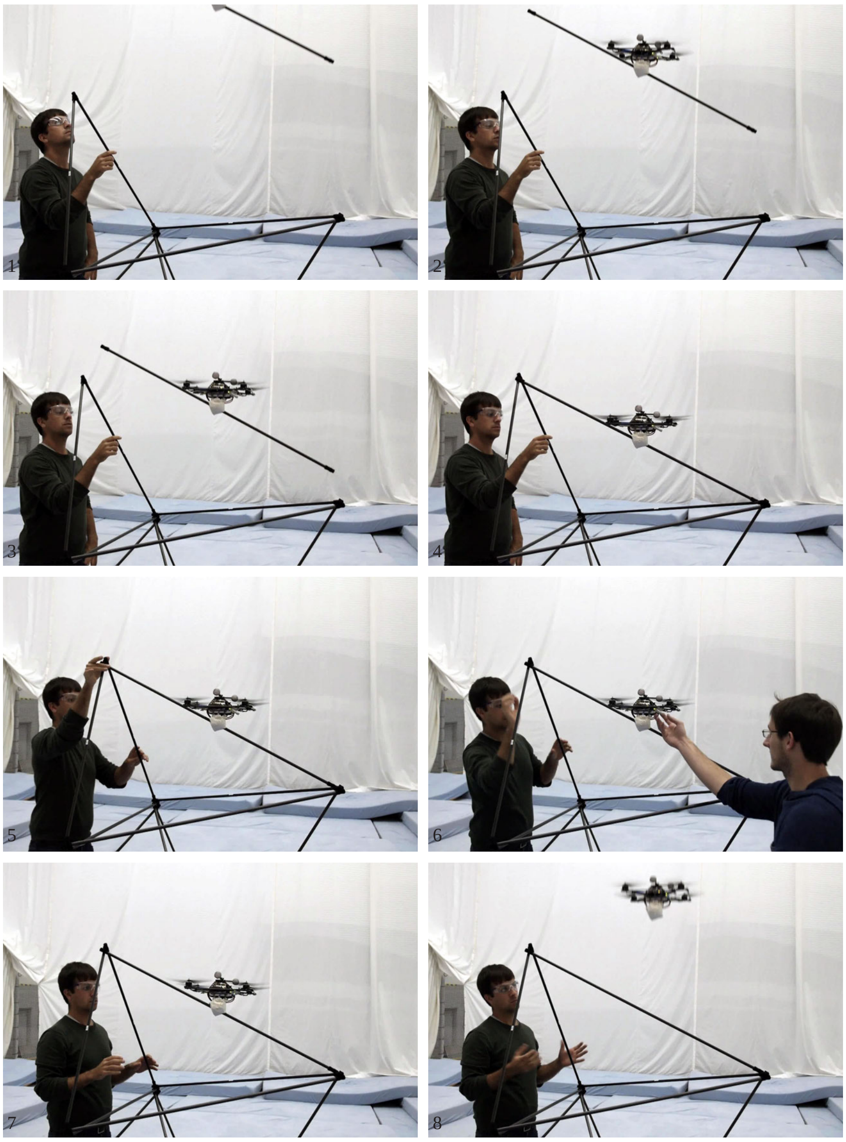


Fig. C.5: Assembly sequence of the third bar to triangulate the structure. The vehicle that stabilises the two already constructed members is emulated by a person, and the holding force of the gripper (the negative air-pressure) is realised manually.

Notes

[51] In order to automate the pick-up station, further development would be required. Also, the vacuum was released manually. This could be automated by using an electronic valve (for example a solenoid-valve) that is controlled by the integrated micro-controller on the quadrocopter.

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List of Figures

Project credits

This thesis builds upon the ETH Grants research project *Aerial Construction*, a collaboration between the Institute for Dynamic Systems and Control and Gramazio Kohler Research at ETH Zurich from 2013-2015, with the objective to develop methods and techniques for robotic aerial construction. The work was supported by the Hartmann Mueller-Fonds on ETH Research Grant ETH-30 12-1.

The experiments in Chapter 5 were performed in the Flying Machine Arena at the Institute for Dynamic Systems and Control at ETH Zurich.

IDSC PhD student Federico Augugliaro was responsible for developing and implementing the experimental control strategies for the vehicles in the FMA. He also developed the actuated rope dispenser. The machinic constraints outlined in Chapter 3.1 and the topological descriptions of the knots outlined in Chapter 4.1 were developed collaboratively. IDSC master student Emanuele Zarfati worked on the knot representation framework, and IDSC master student Maximilian Schulz assisted in the development of flying machine manoeuvres required to construct the braids in the load-bearing structure described in [Chapter 5.5]. The following people form IDSC contributed in the development of the rope dispenser: Mina Kamel, Gregory Baettig, Marc-André Corzillius, Alexander Selwa, and Evan Wilson. All the experiments in this thesis build upon prior contributions by the numerous collaborators of the Flying Machine Arena project.

Augusto Gandia has worked as an intern on the project at Gramazio Kohler Research. He supported the development of the computational design tools described in Chapter 4.2 and assisted in the realisation of knot the experiments in Chapter 4.1.

Appendix A is based on an essay that was written under the supervision of

Prof. Dr. Laurent Stalder.

The Space Frame experiment described in Appendix C was conducted in the Flying Machine Arena in collaboration with Federico Augugliaro.