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Building Tensile Structures with Flying Machines

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Abstract— **This paper presents the building of lightweight tensile structures with quadrocopters. The construction elements (such as ropes, cables, and wires) in this kind of structure are subject to tension forces. This paper identifies the basic building elements (nodes, links) required for the construction of tensile structures, and translates them into meaningful trajectories for quadrocopters. The use of a library of building elements is suggested. Hybrid force-position control strategies based on admittance control are exploited. Prototypical tensile structures are built by quadrocopters to validate the proposed approach. An accompanying video shows the building process.**

I. INTRODUCTION

Research on robotic construction in architecture dates back to the early 1990s [1]. Although highly advanced, these developments did not find access into the market since they were not flexible enough to adapt and react in different design situations [2]. In the course of the recent shift towards digital technologies in architecture, research groups have set up facilities for investigating non-standard architectural design and fabrication with industrial robots [3]–[5]. However, robot arms or CNC-machines have predefined working areas, delimiting their scale of action and thus constraining the size of the work-piece they act upon. Conventional machines are usually smaller than buildings, and this limits their use in architecture to the scale of a fragment or a small component [6]. Flying machines, however, do not have such tight boundaries of movement. The space they act upon is substantially larger than they are themselves. This feature is one that no other computer-controlled construction machine has today, and makes it possible to work at the full scale of architecture, to assemble 1:1 building structures.

As such, researchers have been motivated to study aerial construction, i.e. the use of flying machines to perform construction tasks and build structures. This multidisciplinary field requires both the development of adequate methods for hover-capable UAVs (in order to physically interact with the environment), and the investigation of nonstandard material systems and new construction processes [7]. Building upon the infrastructure developed within the Flying Machine Arena project [8], we demonstrated the ability of quadrocopters to erect structures by assembling a 6 meter tower out of 1500 foam modules during the Flight Assembled Architecture installation [9]. First steps into aerial construction of truss structures have been presented in [10], where quadrocopters were employed to build cubic structures consisting of bars containing magnets. The ARCAS project [11] focuses on aerial assembly by helicopters equipped with robotic arms.

In parallel, the past years have seen an impressive increase in published work in the related context of aerial manipulation. Various strategies for achieving cooperation among multiple hover-capable UAVs as they lift a payload are presented in [12]–[15]. In [16], the closed-loop stability of helicopters and quadrocopters carrying payloads is analyzed. The AIRobots project [17] addresses the inspection of the environment by contact. Hybrid position-force control methods have been presented for ducted-fan vehicles [18] and quadrocopters [19], [20] in contact with the environment, whereas impedance control for an aerial manipulator is investigated in [21]. Modeling and control of an aerial manipulator is also treated in [22]. In [23], we demonstrate the use of admittance control for physical human-quadrocopter interaction. Among hover-capable flying robots, quadrocopters offer an excellent compromise between payload capabilities, agility, and robustness [24] and are thus promising for research in aerial construction.

This paper explores the building of lightweight tensile structures with quadrocopters (Fig. 1), where the construction elements (such as ropes, cables, or wires) are subject to tension forces. It defines basic building elements used for the assembly of tensile structures, and translates them into meaningful quadrocopter trajectories that require hybrid force-position control strategies. Experimental results validate the feasibility of this approach and can be found in the accompanying multimedia submission.

The construction system introduced in this paper fully exploits the ability of flying machines to reach any point in space, allowing robots to: 1) move construction elements to locations otherwise not accessible by conventional construction machines; 2) maneuver in or around existing objects to fasten construction elements; and 3) fly in or around already built structures to manipulate them. The resulting structures are less constrained than conventional ones, which must adhere to traditional assembly and build-up parameters, such as the need for scaffolding to build from the ground up or the reach of a crane.

The paper is organized in the following manner: Section II describes the construction elements necessary for building tensile structures and explains how they can be translated into quadrocopter flight behaviours. Section III investigates some control strategies that can be used in the context of aerial construction. Section IV presents experimental results validating the approach. Section V presents conclusions. In

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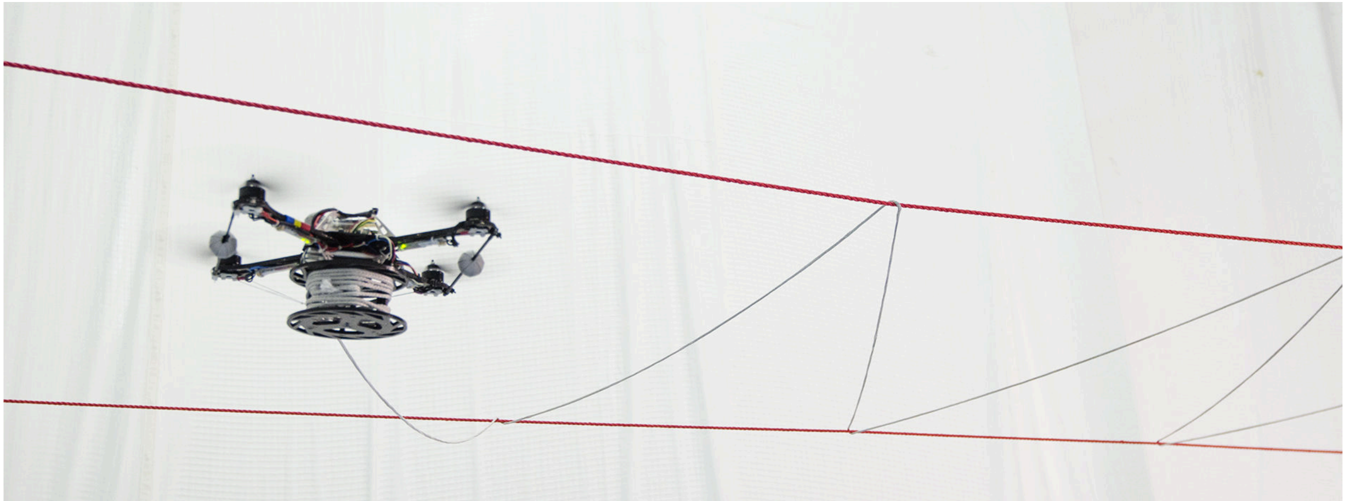

Fig. 1. A quadrocopter assembling a rope structure. The ability of the machine to easily reach any point in space allows it to build structures in otherwise inaccessible locations.

addition, a video showing quadrocopters assembling tensile structures is attached to this paper as a multimedia submission.

II. A LIBRARY OF BUILDING ELEMENTS

Tensile structures are constructed by the assembly of tensile elements. Linear elements (such as ropes, cables, and wires) are connected to existing objects or already built structural components. In this section, we identify building elements that are used during the assembly process. The sequencing of these components and their concatenation materialises the structure according to a precise digital blueprint. They are the interface between the designer of the structure and the robotic system that performs the construction. Below, we first identify adequate connection nodes and then translate them into parameterized trajectories that are executable by flying vehicles. These define a library of parameterized building primitives that is used for the design phase and during the actual construction process. In the following sections, we will refer to the linear construction element as a *rope*, as ropes were used in actual experiments. The same considerations apply to cables and wires, too.

A. Building elements

1) Node: A node is a point of intersection of a linear construction element with another object or with itself. The material characteristics of the construction elements are used as a connective method between support points by tying or weaving around them [25]. Some examples are shown in Fig. 2.

2) Link: A rope spanned between two structural support points generates a link. During the fabrication process we distinguish between static and dynamic supports. Already existing structural elements are static supports. The flying vehicles guiding the rope from one static support to another are dynamic supports. Link properties depend on the trajectory flown by the vehicles.

B. Parameterized building primitives

In this section, we suggest a parameterization of the above elements that takes into account the peculiarities of quadrocopters and exploits the possibilities offered by force control.

Preliminaries: When deploying a rope, we are especially interested in three aspects: 1) the path flown by the vehicle, 2) the force applied to the cable, and 3) the heading of the vehicle. First, the path is important because it defines which connections and objects are part of the structure. For example by encircling a vertical element (such as a bar, a tree, ...) or flying through a ring, this element becomes a support point of the structure. Secondly, the force applied to a rope when placing it determines its tension, thus influencing the final shape of a rope segment between two fix connections. Furthermore, since the rope release point might not be located at the center of the quadrocopter (as in our case, see Fig. 6), the heading of the vehicle plays an important role for the correct deployment of the rope: the release point should be aligned with the rope direction $\vec{e_r}$, as depicted in Fig. 3.

The rope direction $\vec{e_r}$ is a unit vector collinear to the straight line connecting the rope release point on the vehicle

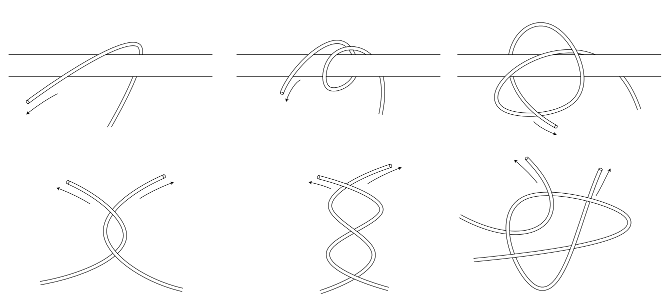

Fig. 2. Some building elements for tensile structures. From left to right, top to bottom: a) Single turn hitch, b) (Multi-) round turn hitch, c) Knob, d) Elbow, e) Round turn, f) Multiple ropes knob.

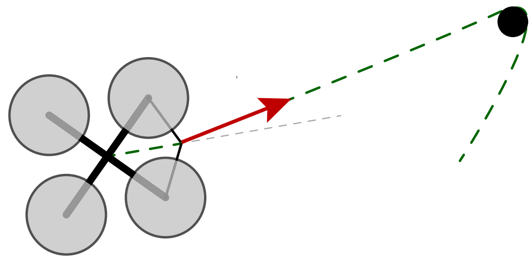

Fig. 3. The red arrow indicates the rope direction $\vec{e}_r$, a unit vector collinear to the straight line connecting the rope release point on the vehicle to the last structure support point. To ease the rope deployment, the vehicle should be oriented in such a way that the dashed gray line coincides with the rope direction.

to the last structural support point. In addition to indicating the orientation that the vehicle must have in order to correctly deploy the rope, it also provides the direction of the force that the quadrocopter must apply in order to make the rope taut. Thus when deploying a rope, the desired yaw angle ψ_{d} (indicating the vehicle heading) and the desired force vector $\vec{f_d}$ will be defined as follows:

$$\psi_{\mathrm{d}}(t) = \angle\big(\vec{e}_r(t)\big) + \psi_0, \tag{1}$$

$$\vec{f_{\mathrm{d}}}(t) = -f_{\mathrm{d}} \cdot \vec{e}_r(t), \tag{2}$$

where ψ_0 is an offset indicating the orientation of the rope release point in the vehicle body frame and f_{d} is a scalar indicating the force applied to the string. We use the symbol $\angle(\vec{q})$ to define the angle given by the projection of a vector into the inertial xy-plane relating it to the vehicle heading:

$$\angle(\vec{q}) = \mathrm{atan2}(\vec{q}_y, \vec{q}_x). \tag{3}$$

Indeed, for pitch and roll angles smaller than 90 degrees, the projection of the vehicle x-axis into the inertial xy-plane indicates the yaw angle.

Next we present some elements that are part of our building library.

1) Single turn hitch: A single turn hitch is achieved by encircling a bar-like support element. The building primitive thus translates into a circular motion specified by a constant radius r_{d} and angular velocity ω_{d}. In polar coordinates it reads:

$$r(t) = r_{\mathrm{d}}, \tag{4}$$

$$\theta(t) = \omega_{\mathrm{d}}\, t + \theta_0, \tag{5}$$

where θ_0 represents the starting point of the circular trajectory and depends on the location of the last point supporting the rope. Similarly, the motion ends when $\theta = \theta_0 + \Delta\theta$, with this parameter depending on the next foreseen support point. For this connection we have

$$0 < |\Delta\theta| < 2\pi. \tag{6}$$

For the case of a cylindrical vertical support element, the rope direction can be determined as follows:

$$\angle\big(\vec{e}_r(t)\big) = \theta(t) + \arcsin\left(\frac{r_b}{r_{\mathrm{d}}}\right), \tag{7}$$

where r_b represents the radius of the vertical element being encircled.

2) Round turn hitch: Similarly, a multiple turns hitch can be created by encircling the support element multiple times ($|\Delta\theta| > 2\pi$). When a rope is wound around a cylinder, exerting a very small force on one end of the node enables higher loads on the other end. A simplified description of this fact is given by the Capstan equation [26]: if S_1 and S_2 are two forces acting at the two extremities of a node, with $S_2 > S_1$, the rope will not slide if the following relationship holds:

$$S_2 < S_1 \exp\big(\mu\ |\Delta\theta|\big), \tag{8}$$

where μ is the static friction coefficient between the rope and the cylinder. Because of its exponential nature, only a few rotations are required to actually fix the rope at one end. Therefore, the design parameter $\Delta\theta$ defines whether the result is a gliding connection or a fix knot with a given holding force. This result is observable in our experiments, where a quadrocopter autonomously creates a fixed connection that is able to sustain large loads (see Section IV).

3) Control points: As discussed above, the path of the vehicle influences the properties of a tensile structure: for example, it defines structural links by incorporating external objects into the structure. During the design of a tensile structure, therefore, the designer must on occasion define control points, i.e. locations in space that must be crossed by the machine deploying the cable. A control point is described by its location in space $\vec{\Lambda}_{\mathrm{P}}$, the velocity of the vehicle $\dot{\vec{\Lambda}}_{\mathrm{P}}$, and its acceleration $\ddot{\vec{\Lambda}}_{\mathrm{P}}$.

The rope direction $\vec{e}_r$ at the control point is given by the straight line connecting the vehicle to the last support point, if the location of the latter is known. Otherwise, if the location of the previous support point is not exactly known, a good strategy is to orient the vehicle in such a way that the rope release point lays behind it. Using the velocity vector this yields:

$$\vec{e}_r = -\frac{\dot{\vec{\Lambda}}_{\mathrm{P}}}{\|\dot{\vec{\Lambda}}_{\mathrm{P}}\|}. \tag{9}$$

Section III presents a control strategy based on admittance control that copes with inaccuracies in the location of the support points.

4) Multi-vehicle building primitives: Flying vehicles can reach locations otherwise inaccessible and, unlike robot arms or cranes, are able to cross each other when deploying ropes. This allows the creation of building elements comprised of multiple ropes intersecting each other, as illustrated in the second row of Fig. 2.

Multi-vehicle building primitives can be defined with the use of control points. However, in addition to knowing the vehicle's position, velocity, and acceleration at the control point, temporal information that links two or more control points is required. This concept is illustrated in Fig. 4: in order to create the depicted node, two quadrocopters must fly through the red control points at the same time.

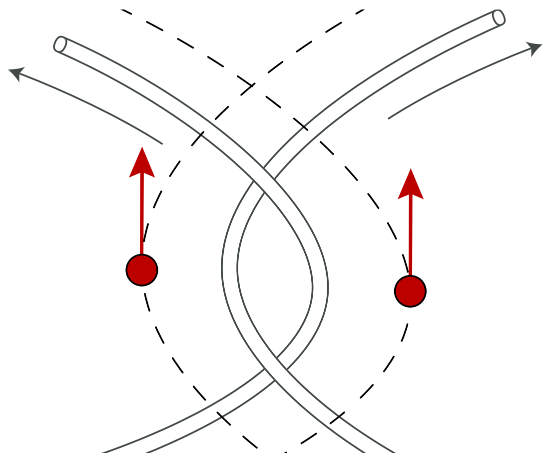

Fig. 4. A multi-vehicle building primitive. The quadrocopters must fly through the control points (red) at the same time. The red arrows indicate the desired velocity at the control points.

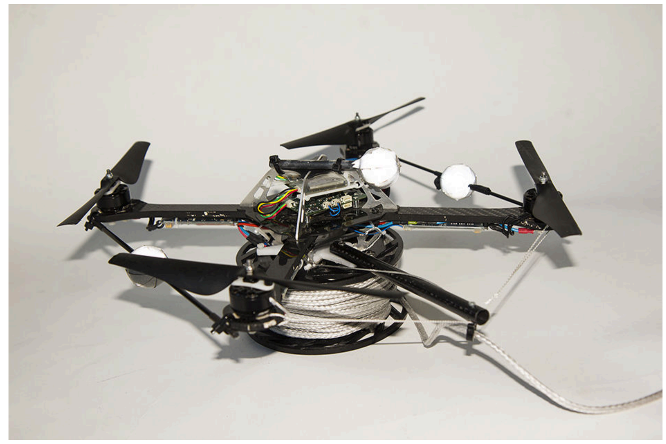

Fig. 6. A quadrocopter equipped with a passive roller to deploy the rope. The friction of the roller is adjustable, influencing thus the torque required to unroll the rope. The rope release point is located between two propellers.

C. *Concatenation of building primitives*

Once the single building primitives (and thus the blueprint of the structure) have been defined, these elements must be appropriately concatenated. Therefore, an algorithm able to generate a feasible trajectory leading the vehicle from the final state of a building primitive (specified by heading, position, velocity, and acceleration) to the initial state of the next one is required. In [27], we presented a method for generating collision-free trajectories for multiple vehicles from a set of initial states to given final states. The method enables the user to specify various trajectory constraints (such as jerk, acceleration, velocity or position limits), in order to generate trajectories that satisfy the physical limits of the vehicle, respect space boundaries, and guarantee a minimum distance between vehicles. Alternatively, algorithms similar to [28] or [29] can be used.

III. Realization strategies

The parameterization of building elements provided in the previous section requires the quadrocopter to track trajectories and, at the same time, to apply a constant force along the rope direction. Furthermore, it must adapt its heading. This naturally leads to the use of hybrid force-position control strategies. In this section, we assume the use of an underlying trajectory-tracking controller (details can be found in [30]) and we present the use of admittance control for torque and force control based on the results of [23].

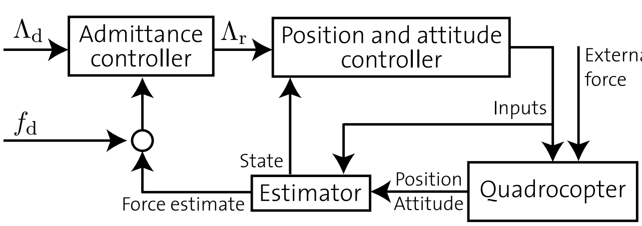

Fig. 5. The admittance control strategy presented in [23] is extended to track a desired force (or torque). Input to the system are: desired trajectory Λ_d and desired force (or torque) f_d along any desired dimension. The admittance controller adjusts the reference trajectory Λ_r accordingly.

A. *Admittance control*

Admittance control allows users to define the apparent inertia, damping, and stiffness of a robot, thus determining the way it reacts to external forces [31]. In [23], we show the suitability of admittance control for physical human-quadrocopter interaction. External forces and torques acting on the quadrocopter are first estimated from position and attitude information, then compared to a reference value, and finally input to the admittance controller, which modifies the vehicle reference trajectory accordingly. The reference trajectory is tracked by an underlying position and attitude controller. The approach is schematized in Fig. 5. The user specifies a desired trajectory Λ_d and a desired force (or torque) f_d. The dynamic behaviour of the reference trajectory Λ_r is then captured by the following mass-spring-damper system:

$$M(\ddot{\Lambda}_\mathrm{d} - \ddot{\Lambda}_\mathrm{r}) + D(\dot{\Lambda}_\mathrm{d} - \dot{\Lambda}_\mathrm{r}) + K(\Lambda_\mathrm{d} - \Lambda_\mathrm{r}) = -f_e, \quad (10)$$

where f_e is the force (or torque) tracking error. The tuning parameters M, D, and K define the apparent inertia, damping, and stiffness of the vehicle along the desired dimension.

B. *Yaw compliance through torque control*

In the previous section we discussed why the vehicle heading is fundamental for the correct deployment of a rope. The rope direction $\vec{e}_r$ is defined ahead of time for many building primitives, specifically when the exact locations and properties of the support points are known. However, in real world situations this might not always be the case: for example when the actual position, shape, and size of a supporting object can only be estimated up to a certain accuracy, or if dynamic support points behave differently than expected. These errors could interfere with the correct deployment of the rope.

For these reasons, compliant behavior of the vehicle heading is desirable. Admittance control is used to modify the

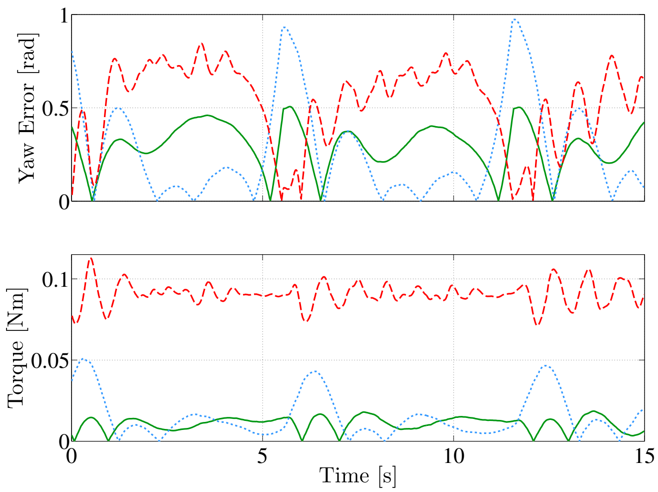

Fig. 7. The machine flies through control points placed around two supporting elements whose exact locations are unknown. The above plot shows the yaw trajectory error (deviation from the ideal yaw, given by the straight line connecting the quadrocopter with the last support point). The bottom plot indicates the external torque acting on the quadrocopter as detected by the force estimator. Three cases are considered: 1) no yaw compliance ($K \to \infty$), dashed red; 2) yaw compliance, solid green; 3) full yaw compliance ($K = 0$), dotted blue. Strategies 2 and 3 result in a small external torque acting on the quadrocopter, thus facilitating the deployment of the rope. Strategy 1 causes a large external torque because the yaw reference trajectory does not adapt to the rope: the controller tries to counteract the torque exerted by the rope on the vehicle.

reference yaw angle according to the actual torque acting on the robot. The torque produced by the rope when the rope release point is not aligned to the rope direction is input to the admittance controller, which adjusts ψ_{r} accordingly. This strategy allows the system to cope with unforeseen structural behaviours or modeling/detection errors of the support points.

The choice of the controller parameters K, D, and M depends on the situation. For example, if we are confident about our knowledge of the environment, we should pick large values for K, which represents a very stiff spring: the actual yaw angle will then be very close to the feed-forward term ψ_{d}.

C. Force tracking

During the deployment of a rope, the force input $\vec{f}_e$ to the admittance controller is calculated as follows:

$$\vec{f}_e = -(f_{\mathrm{d}} - \vec{f} \cdot \vec{e}_r) \cdot \vec{e}_r, \tag{11}$$

with $\vec{f}$ being the estimate of the external forces acting on the quadrocopter. The desired force f_{d} to tense the rope is a design parameter specific to the different building primitives.

IV. Results

A. Experimental setup

We demonstrated the ability of quadrocopters to build tensile structures on small custom robots in the Flying Machine Arena [32], a 10 x 10 x 10m testbed for quadrocopter research (see accompanying video). The space is equipped with a motion capture system that provides vehicle position and attitude measurements. This information is sent to a PC, which runs algorithms and control strategies, and sends commands to the quadrocopter at approximately 50Hz.

The quadrocopters are equipped with a passive rope dispenser (Fig. 6). The friction of the roller can be adjusted, thus changing the torque required to unroll it and the maximum tension that can be applied to the rope. The rope release point is located between two propellers. Together with the yaw compliance strategy described before, this prevents the rope from hitting the propellers.

The rope used for these experiments is made out of Dyneema, a material with a low weight-to-strength ratio and thus suitable for aerial construction. Of little weight ($7\,\mathrm{g}$ per meter), a $4\,\mathrm{mm}$ diameter rope can sustain $1300\,\mathrm{kg}$; this equals a tensile strength of $1015\,\mathrm{MPa}$.

In the following experiments, we first demonstrate how admittance control effectively modifies the heading of the vehicle according to the external torque acting on it. Second, we present various tensile structures that result from different combinations of building primitives.

B. Unknown location of the support points

The first experiment demonstrates the use of admittance control for yaw compliance behaviour, as discussed in Section III-B. The vehicle flies through control points placed around two supporting elements whose exact locations are unknown. The desired heading ψ_{d} (input to the admittance controller) is chosen accordingly to Equation (9). During the deployment of the rope, the quadrocopter estimates the external torque acting on it, and adjusts its heading accordingly. As a result, the rope release point is located near the straight line that connects the vehicle to the last support point, thus allowing for a smooth rope deployment even with unknown supporting points locations. Fig. 7 compares the yaw trajectory error and the torque acting on the vehicle for three different cases: 1) no yaw compliance ($K \to \infty$); 2) yaw compliance; 3) full yaw compliance ($K = 0$). The results show that the use of yaw compliance minimizes the external torque acting on the quadrocopter, thus allowing for a smooth deployment of the rope.

C. Prototypical tensile structures

The building process of the three structures described below is featured in the accompanying video.

1) Linear structure: The linear structure is a tensile element spanning two support points. Multi-round turn hitches (Fig 2b) fix the rope at both ends. The quadrocopter is able to fix the rope to the supporting element on its own without the need for external help. This demonstrates how a flying vehicle can be used to reach otherwise inaccessible locations and perform building tasks that result in load-bearing structures.

2) Surface structure: The two-dimensional intersection of linear structures constitute a surface structure, see Fig. 1. The loads and stresses of the intersecting ropes interact to find a structural equilibrium. Because of its small size and unconstrained workspace, the quadrocopter can fly through already built elements to manipulate the structure.

3) Multi-vehicle assembled structure: This experiment demonstrates the use of control points for multi-vehicle assembly, as described in Section II-B.4. Further investigation into the cooperation of multiple vehicles for construction tasks is required, but may yield novel methods of architectural production.

V. Conclusions

In this paper, we presented methods and control strategies for the building of tensile structures. This is part of a body of research in aerial construction, a field that addresses the construction of structures with the aid of flying machines. The use of flying machines enables the assembly of structures that are less constrained by conventional assembly parameters and fosters new forms of architecture and construction methods. These topics are further discussed in a companion paper that explores the architectural aspects of them [33].

A preliminary library of building primitives suitable for tensile structures has been suggested, and prototypical tensile structures have been realized by quadrocopters. The experiments presented in this paper (and shown in the attached multimedia submission) demonstrate the ability of quadrocopters to autonomously build load-bearing tensile structures.

Future work includes a deeper analysis of how additional torques and forces acting on the quadrocopter affect the dynamic characteristics of the system. It also encompasses the expansion of the library of building elements and the investigation of multi-vehicle building primitives. Furthermore, the system must account for already placed elements and generate trajectories accordingly. We also foresee applying torque control directly on the rope dispenser to actively adjust the force applied to the rope.

Acknowledgments

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