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A motion planning approach to 6-D manipulation with aerial towed-cable systems

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Abstract

We propose a new approach for the reliable 6-dimensional quasi-static manipulation with aerial towed-cable systems. The novelty of this approach lies in the combination of results deriving from the static analysis of cable-driven manipulators with a cost-based motion-planning algorithm to solve manipulation queries. Such a combination of methods is able to produce feasible paths that do not approach dangerous/uncontrollable configurations of the system. As part of our approach, we also propose an original system that we name the *FlyCrane*. It consists of a platform attached to three flying robots using six fixed-length cables. Results of simulations on 6-D quasi-static manipulation problems show the interest of the method.

1 Introduction

Aerial towed-cable systems have been used for decades, mainly as crane devices. They have proved to be very useful in various contexts, such as supply delivery missions and rescue operations [3], as well as environmental monitoring and surveillance [16]. One such system has even been successful as a safe soft-landing device for a rover on the martian surface [15], for instance. In all these examples, the systems only required a certain position accuracy, for example to execute simple trajectories [14, 13]. Little work has been done on trying to govern a load in both position and orientation. To the best of our knowledge, the only existing technique for 6-dimensional manipulation with an aerial towed-cable system requires a given discrete set of load poses [12, 6]. Such a technique relies on solving the inverse kinematics problem and determining the static equilibrium for all given poses. Requiring a given set of platform poses may be too restrictive, though, especially in constrained workspaces, because it may provide no result, while there may exist solutions for other intermediate poses.

We have recently developed a new reliable motion planning approach for 6-dimensional quasi-static manipulation with aerial towed-cable systems [11] [1]. The proposed method only requires a start and goal configurations as input, and provides a feasible path to achieve the manipulation task. In addition to being feasible, the generated manipulation path will be of *good quality*, meaning that all intermediate configurations will fulfill adequate physical properties related to the forces applied to the system and to the cable tensions. This quality will be measured by a formal criterion derived from the static analysis of the system, based on a similar formulation as that used for cable-driven manipulators [5, 4]. A path-planing algorithm taking this quality measure into account [8] will then be applied to compute good-quality paths.

In addition to the methodology, this paper presents an aerial towed-cable system to perform 6-D manipulation tasks, that we call the *FlyCrane*. This system consists of a moving platform attached to three flying robots by means of six fixed-length cables linked by pairs to each robot. The 6-D manipulation of the platform

[1] This paper is a short version of the original publication [11], which should be consulted for additional details on the method.

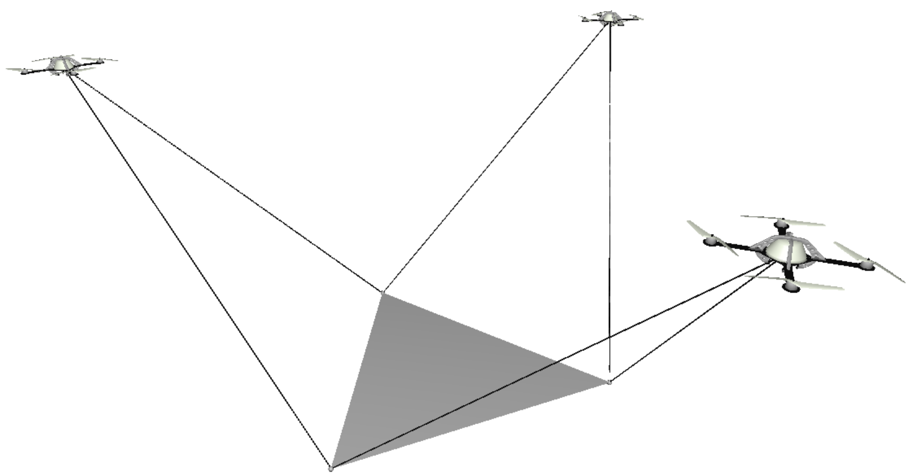

Figure 1: Octahedral version of the *FlyCrane* system.

can be performed by varying the relative positions of the flying robots. An octahedral version of this system is illustrated in Figure 1.

The rest of the paper is organized as follows: Section 2 provides an overview of our approach, detailed in [11]. Section 3 presents an evaluation of our approach on two 6-D manipulation problems involving the octahedral version of the *FlyCrane* system. Section 4 provides conclusions and discusses possible directions for future work.

2 Overview of the approach

Towed-cable systems present important analogies with cable-driven manipulators, which enable us to perform their static analysis in a way similar to that presented in [4]. However, while cable-driven manipulators have to adjust the lengths of their cables to reach a precise pose of the platform, towed-cable systems have fixed-length cables and are actuated by displacing their anchor points. Manipulating the six degrees of freedom of a load requires a minimum of seven cables, unless some convenient forces reduce this number. In crane configurations, for instance, gravity acts as an implicit cable, and therefore six cables suffice for the full 6-D manipulation. Examples of such structures are the NIST Robocrane [1] or more general cable-driven hexapods [4].

In the proposed aerial towed-cable system, called the *FlyCrane*, the platform is also pulled by six cables, which, as illustrated in Figure 1, are pairwise attached to three flying robots (instead of being individually attached to six flying robots). It is worth noting that three is the minimal number of flying robots required to properly operate this system, as less robots would not allow the manipulation of the six degrees of freedom of the platform. Whenever the cable base points are also coupled, we call it *octahedral FlyCrane*, because the structure can be seen as an octahedron, comprising the following 8 triangles: the platform base points, the triangle formed by the flying robots, and the 6 triangles made of pairs of adjacent cables.

In this paper we assume that motions are performed quasi-statically, thus neglecting the dynamic analysis of the system. Although it may appear as a strong simplification, this assumption is frequently made in fine-positioning situations, where slow motion is imperative. Nevertheless, dealing with dynamical aspects can be an interesting extension for future work, as will be discussed in Section 4.

Even with six cables, the six degrees of freedom of the platform can be governed only in a subset of the configuration space of the system. Indeed, the pose of the platform is locally determined only when all cables are in tension. Therefore, it is important to prevent the cables from being slack or too tight. Besides, the flying robots must be able to counteract the forces exerted on them. These two conditions determine the feasibility of a configuration of the system. More precisely, to be feasible, a configuration must satisfy the following two types of constraints:

- *Wrench-feasibility* constraints: they guarantee that the system is able to statically counteract a set of wrenches applied on the platform while ensuring that the cable tensions always lie within a pre-defined, positive acceptance range; they are derived from the static analysis of cable-driven manipulators [5, 4].
- *Thrust* constraints: they guarantee that the thrust of the flying robots can equilibrate the forces applied on them, namely the forces exerted by the cables and the force of gravity.

The set of configurations that satisfy these feasibility constraints form a manifold in which paths have to be searched. An infinite number of feasible solution paths may exist for a given manipulation query. A way to discriminate the less appropriate ones is to define a criterion assessing their quality. A good-quality path should be a path whose intermediate configurations are attributed a low cost with respect to the physical properties of the system. A meaningful way to evaluate the cost of a configuration of the system is to derive it from the previous feasibility constraints. The idea is to define a cost function that tends to infinity when a configuration approaches the limit of a feasibility constraint (i.e. when a cable tension approaches one of its limits or when a robot approaches its maximum thrust) and that takes low positive values when a configuration is far from the non-feasible ones. Such a cost function can be written as a combination of terms from the equations that define the feasibility conditions. In addition, it is possible to show that it is a continuous differentiable function over the set of feasible configurations, which is a crucial property for a suitable performance of the path planning method applied next.

Any general path planner, such as the Rapidly-exploring Random Tree (RRT) algorithm [10], could be applied to compute collision-free paths satisfying the aforementioned feasibility constraints to perform 6-D manipulation tasks with the *FlyCrane* system. However, it might not produce good-quality paths. Since we are able to define a cost function over the configuration space, we can use a cost-based path planner, such as the Transition-based RRT (T-RRT) [8], in order to obtain good-quality manipulation paths. T-RRT has been successfully applied to various types of problems in robotics [8, 2] and structural biology [9]. Nevertheless, it is worth noting that, to the best of our knowledge, this is the first time it is applied to aerial manipulation problems.

3 Results

In this section, we evaluate the proposed approach on two 6-D quasi-static manipulation problems involving the *FlyCrane* system (cf. Fig. 1). The first example is a complex task (inspired by classical motion planning benchmarks) in which the *FlyCrane* has to get a 3-D puzzle piece through a hole, as illustrated by Fig. 2. The second example, presented in Fig. 3, simulates a more realistic situation in which the *FlyCrane* has to install a lightweight footbridge between two buildings to evacuate people during a rescue operation. These examples differ in terms of difficulty: the *Rescue* problem is the easiest one because the manipulation task involves translation and rotation about a single axis, whereas the *Puzzle* problem requires a complex coordinated motion, with simultaneous translation and 3-D rotation of the platform.

On both examples, we evaluate the performance of the RRT and T-RRT algorithms on the basis of their running time t (in seconds), the number of attempted expansions X, and the number of nodes N in the produced tree. To avoid generating trivially-non-feasible paths, RRT only accepts collision-free configurations that

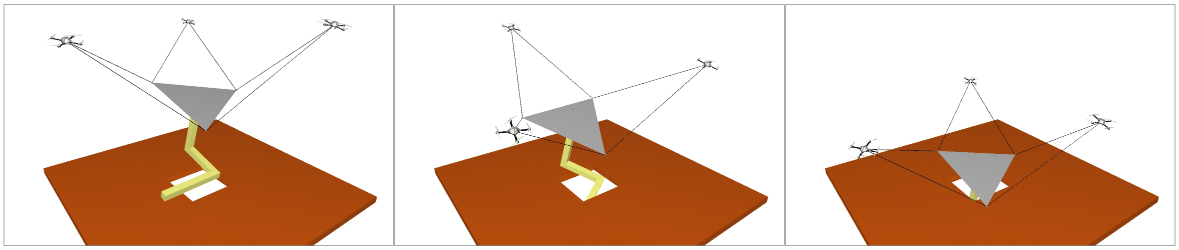

Figure 2: The *Puzzle* problem: the *FlyCrane* has to get a 3D puzzle piece through a hole.

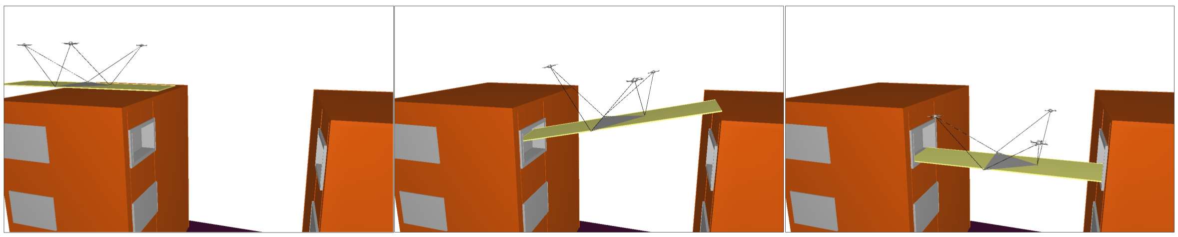

Figure 3: The *Rescue* problem: the *FlyCrane* has to install a lightweight footbridge between two buildings for a rescue operation.

satisfy the aforementioned wrench and thrust feasibility constraints. After performing a smoothing operation (based on the random shortcut method [7]) on the paths generated by RRT and T-RRT, we evaluate the path quality by computing the average cost $avgC$, the maximal cost $maxC$, the mechanical work MW, and the integral of the cost IC. The *mechanical work* of a path is defined as the sum of the positive cost variations along the path [8]. Table 1 reports values for all variables averaged over 100 runs of the algorithm.

Unsurprisingly, Table 1 shows that T-RRT provides better-quality paths than RRT on both examples: on the *Puzzle* problem, all cost statistics are more than one order of magnitude lower for paths generated by T-RRT; on the *Rescue* problem, they are between three and 50 times lower. Since it generally requires more expansion attempts to find configurations with acceptable cost, T-RRT is often slower than RRT, as is the case on the

Table 1: Evaluation of RRT and T-RRT on the *Puzzle* and *Rescue* problems. Average values over 100 runs are given for: the average cost $avgC$, the maximal cost $maxC$, the mechanical work MW, the integral of the cost IC, the running time t (sec.), the number of nodes N in the tree, and the number of expansion attempts X.

	Puzzle						
	$avgC$	$maxC$	MW	IC	t (s)	N	X
RRT	1130	11,684	11,651	300,793	34	2654	15,609
T-RRT	78	229	193	30,352	169	4698	78,501

	Rescue						
	$avgC$	$maxC$	MW	IC	t (s)	N	X
RRT	102	575	554	80,750	126	1361	193,517
T-RRT	36	42	11	24,588	54	379	207,778

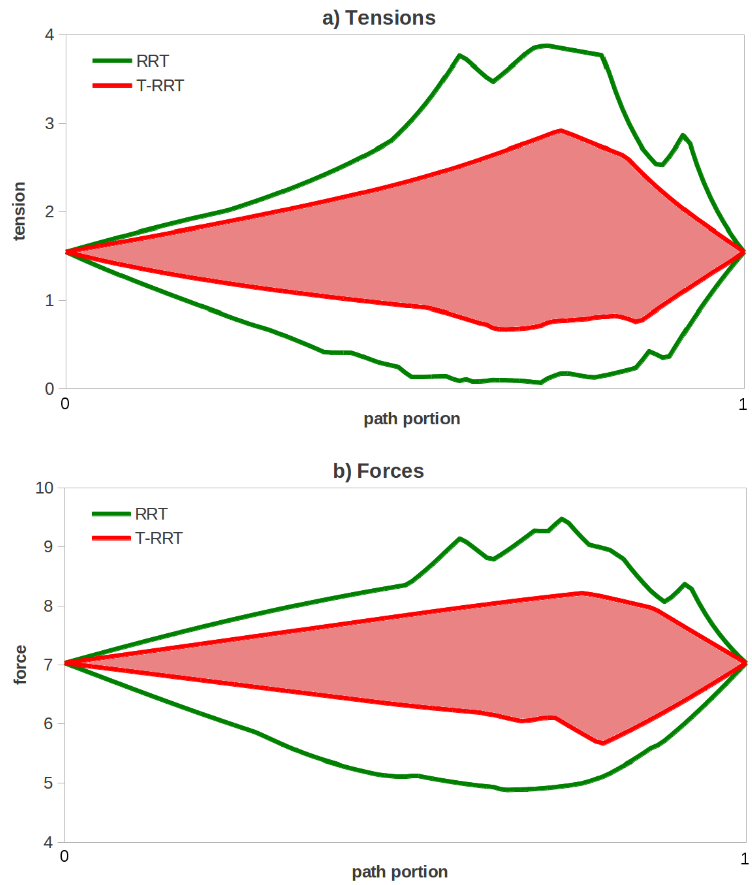

Figure 4: Profiles of a) the tension range and b) the force range, observed over 100 paths produced by RRT and T-RRT on the *Rescue* problem. The filled areas between the red curves represent the ranges for T-RRT; the areas between the green curves represent the ranges for RRT.

Puzzle problem (169 s vs 34 s). However, it is worth noting that T-RRT runs faster than RRT on the *Rescue* problem (54 s vs 126 s), thanks to the lower number of nodes added to the tree (379 vs 1361), which makes the nearest-neighbor search faster.

We were interested in finding out what made path quality differ between RRT and T-RRT. For that, we computed the tensions exerted on each cable and the forces exerted on each quadrotor, along the paths produced by RRT and T-RRT, after dividing every path into 100 steps corresponding to intermediate configurations of the system. Then, for each path-step, we computed the minimal and maximal tensions (over all cables) and forces (over all quadrotors) over the 100 paths produced by RRT and over the 100 paths produced by T-RRT. Therefore, for each step, we obtained the tension ranges and the force ranges yielded by RRT and T-RRT. Fig. 4 presents the profiles of the tension range and of the force range, respectively, on the *Rescue* problem. Similar plots have been obtained on the *Puzzle* problem. We can see that using T-RRT leads to smaller tension and force ranges than using RRT. Most importantly, we observe that RRT produces paths along which a tension or a force can be dangerously close to a bound of its validity interval. For example, Fig. 4.a shows that, along some path, at least one tension comes close to zero, meaning that at least one cable almost goes slack. Similarly, on the

Puzzle problem, one force comes close to the maximal thrust value. As a conclusion, we argue that integrating the path-planning T-RRT algorithm into the proposed 6-D manipulation approach allows us to plan safer paths for the *FlyCrane* system.

4 Conclusion

We have presented an approach for the 6-dimensional quasi-static manipulation of a load with an aerial towed-cable system. The main contribution of the approach lies in the combination of results deriving from the static analysis of cable-driven manipulators with a cost-based motion-planning algorithm to solve manipulation queries. The link underlying this combination is the definition of a quality measure for the configurations of the system. First, this quality measure is based on the wrench-feasibility constraints applied to cable-driven manipulators and on additional thrust constraints, and allows: 1) to discriminate non-feasible from feasible configurations, and 2) to favor configurations that are far from violating these constraints, by attributing them a low cost. Second, this quality measure leads to the definition of a cost function, thus allowing for the use of a cost-based motion-planning algorithm, namely the Transition-based RRT (T-RRT). As a result, rather than simply computing collision-free paths, the proposed approach produces good-quality paths, with respect to the constraints imposed on the system.

As part of our approach, we have additionally proposed an aerial towed-cable system that we have named the *FlyCrane*. This system consists of a platform attached to three flying robots by means of three pairs of fixed-length cables. We have evaluated the approach, in simulation, on two 6-D manipulation problems involving an octahedral version of the *FlyCrane* system. The results of the evaluation show that the proposed motion planning approach is suitable to solve 6-D quasi-static manipulation tasks. Furthermore, they have confirmed that RRT, which is the original variant of T-RRT that does not take the cost into account, may produce paths that occasionally approach dangerous situations, while T-RRT produces safer paths.

The proposed approach allows for extensions in several ways. In particular, we expect to extend the method to consider positioning errors for the flying robots, which could be due to external force perturbations and to errors in the localization methods. Additionally, an interesting and challenging extension to this work is the introduction of dynamics in the motion of the load and of the flying robots, as they play an important role in the overall manipulation of the system.

In this paper, we have applied the proposed approach in simulated environments. As part of our future work, we plan to implement this approach in a real aerial towed-cable system. This will serve as a testbed for the validation of the method and its further extensions, providing relevant feedback on the real limitations of the approach and the system. In real-life situations, the proposed approach could be helpful in various applications. As illustrated by the simulated *Rescue* problem, one possible application is the construction of platforms for the evacuation of people in rescue operations. Another application could be the installation of platforms in uneven terrains for the landing of manned or unmanned aircrafts. More generally, it could be useful for the assembly of structures in places difficult to access for humans.

Acknowledgments

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