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First experimental results on enhancing hovering performance of unmanned helicopters by using a tethered setup

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HIGHLIGHTS

- The hover performance of small-size helicopters can be seriously affected by wind disturbances.
- The mechanical model of a tethered setup is analyzed to show its benefits in stabilizing translational dynamics.
- A control strategy for the tethered helicopter based on model inversions and PI-D laws is developed.
- The proposed approach is tested in successful field experiments.

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ABSTRACT

The hovering capabilities of helicopters can be seriously affected by wind. This could be even more significant in the small-size platforms used for developing unmanned aerial vehicles. One possible solution for improving performance under such circumstances is the use of a tethered setup. This approach takes advantage of the tension exerted on the cable linking the helicopter to the ground. This paper analyzes the mechanical model of this augmented setup to show its benefits in stabilizing translational dynamics. Control guidelines to exploit these potentialities are also highlighted. The latter allows the definition of a model-based control strategy consisting of a combination of classical PID laws together with model inversion blocks. Tether tension feed-forward is also included to take into account the side effects of tether tension in rotational dynamics. Experiments performed with the real platform confirm the validity of the proposed approach.

1. Introduction

When comparing different Unmanned Aerial Vehicle (UAV) configurations, helicopters and other rotor-based aircraft have capabilities such as hovering and vertical take-off and landing which cannot be achieved by conventional fixed-wing aircraft. These features allow remotely piloted and autonomous helicopters to be extensively used nowadays for aerial robotic applications such as aerial photography, inspection and monitoring, accurate measurement, search and rescue, disaster management, etc. However, hover performance can be seriously affected by wind disturbances, specially when dealing with small-size helicopters.

Although many advances in helicopter control have been proposed in recent literature [1], only a few references propose robust control techniques to deal with the specific problem of hover performance loss in presence of wind disturbances. It is important to highlight that most of these works only show simulation results [2–6] or indoor experimental results [7,8].

In order to address the problem of hover performance loss, an augmented setup consisting of a unmanned helicopter and a tether connecting the helicopter to the ground was proposed by

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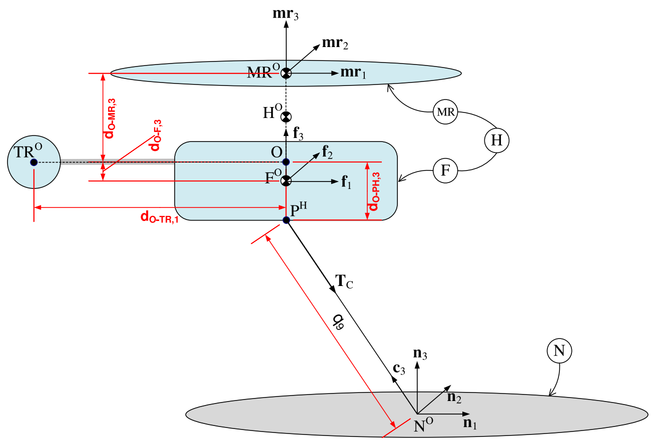

Fig. 1. Tethered helicopter scheme: description of reference frames, centers of mass and dimensions of interest for modeling purposes.

the authors in [9]. The justification for this augmented setup is the stabilizing action of the tether tension.

To the best of the author's knowledge, the use of the tether tension to improve helicopter stability at hover is almost unexplored in the literature. The first references to consider a tethered configuration for rotorcraft prototypes are those of [10], where the linearized equations describing the perturbed longitudinal motion of a tethered rotorcraft are presented, and [11], where a discussion of the control and stabilization problems involved in the tethered configuration for a rotor platform prototype is presented, with special emphasis on tether dynamics. Furthermore, two approaches for the design of an automatic hover controller for the tethered system are proposed. The contributions of [12,13] are also worth mentioning. Although they correspond to the application scenario of landing a helicopter, they are referenced here since they also make use of a tether as an additional resource for helicopter control. In those works, the benefit of tether use is the improvement of controllability rather than stability.

The device holding the tether is an universal joint which includes two magnetic encoders for measuring the tether orientation relative to the helicopter fuselage. If a radar or lidar altimeter is also equipped, in addition to the advantages in terms of stabilizing properties the use of the tether could provide an alternate helicopter position estimate whose reliability would not be affected by the lack of GPS accuracy, occasional signal outages or operation in GPS denied scenarios.

Last but not least, the cable connecting the helicopter to the ground can also be potentially used as unlimited power supply for long-duration missions and wideband data link for transmission of huge volume of data.

In [9], adding a tether to the system has been proven to cause two main effects. Firstly, it provides robustness against external disturbances due to the stabilizing properties of tether tension in translational dynamics. Secondly, the moment induced by the existing offset between the tether tension application point and the center of mass, produces undesired coupling between rotational and translational dynamics, making it more difficult to control the system. The proposed control strategy assumes the operation of the system under a constant tether tension. Simulations demonstrated that even a basic linear approach for helicopter control sufficed to produce a significant improvement in hover performance.

This paper presents a more elaborate strategy for helicopter control in the tethered setup that extends previous contributions on the subject by the authors. In particular, a combination of classic PID control laws and model inversion blocks constitutes the basis of the new controller. Additionally, feed-forward action to counteract rotational couplings is also taken into account. Furthermore, this control hierarchy has been implemented in the real platform, and first field experiments have been carried out. These can be regarded as the first world's first successful experiments with a small-size tethered unmanned helicopter. The results endorse the validity of the proposed approach.

With respect to the contents of the paper, it begins with a detailed description of the tethered configuration. To this end, Section 2 analyzes the mechanical model of this augmented setup to show its benefits in stabilizing translational dynamics. Control guidelines to exploit these potentialities are also highlighted. Section 3 presents the combination of classical PID control laws and model inversion blocks that constitutes the basis of the new controller. In Section 4 the experimental setup as well as the results are described and analyzed in detail. Finally, Section 5 is devoted to conclusions and future work.

2. Modeling and analysis of the system

This section presents the resulting model for the tethered configuration (see Fig. 1). A more detailed derivation following Kane's methodology [14] can be found in previous works of the authors [15,9]. The section ends with an analysis of the stabilizing properties of the system, followed by a discussion on the control guidelines to exploit such potentialities.

2.1. Helicopter model

According to the authors of [16], the dynamics of a small-size helicopter with a stiff main rotor are mainly described by its mechanical model. Their attempt to include an elaborate main rotor aerodynamic model in controller design did not show significant improvements in performance during experiments. This could be considered evidence for the fact that the approach of analyzing helicopter behavior by means of a mechanical model is suitable for practical applications. This paper embraces the same assumption.

The mechanical characterization of the helicopter system H accounts for two separated rigid bodies, fuselage F (with mass m_F) and stiff main rotor MR (modeled as a thin solid disk with mass m_{MR} and constant angular speed ω_{MR}), whereas the tail rotor TR will only act as a force application point on the fuselage. This characterization arises from the fact that for most commercially available small-size helicopters, the inertial effects of the main rotor (gyroscopic effects) become the main component influencing the rotational dynamics of the whole mechanical system, whilst the tail rotor inertial influence is negligible.

The position $\mathbf{p}^{N^O \to H^O}$ of center of mass H^O in the inertial reference frame N is described by generalized coordinates $q_i(t) \quad (i = 1, 2, 3)$, whereas generalized coordinates $q_i(t) \quad (i = 4, 5, 6)$ are the Euler-angles (roll, pitch and yaw) corresponding to successive rotations (Body1-2-3 order [17]) that describe the orientation of F in the inertial reference frame N. Regarding motion variables, the velocity ${}^N\mathbf{v}^{H^O}$ of center of mass H^O in the inertial reference frame N is described by generalized speeds $u_i \quad (i = 1, 2, 3)$, whereas $u_i(t) \quad (i = 4, 5, 6)$ describe angular velocity ${}^N\boldsymbol{\omega}^F$ expressed in axes of frame F. These definitions are better illustrated with the following expressions:

$$\begin{aligned} \mathbf{p}^{N^O \to H^O} &= q_1\mathbf{n}_1 + q_2\mathbf{n}_2 + q_3\mathbf{n}_3 \\ {}^N\mathbf{v}^{H^O} &= u_1\mathbf{n}_1 + u_2\mathbf{n}_2 + u_3\mathbf{n}_3 \\ {}^N\boldsymbol{\omega}^F &= u_4\mathbf{f}_1 + u_5\mathbf{f}_2 + u_6\mathbf{f}_3. \end{aligned} \tag{1}$$