Improving hovering performance of tethered unmanned helicopters with nonlinear control strategies

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Abstract—Hovering capabilities of unmanned helicopters can be seriously affected by wind effects. One possible solution for improving hovering performance under such circumstances is the use of a tethered setup that takes advantage of the tension exerted on the cable that links the helicopter to the ground. This paper presents a more elaborated strategy for helicopter control in this augmented setup that extends previous work on the subject by the authors. Particularly, a combination of classical PID control laws together with model inversion blocks constitutes the base of the new controller. Additionally, feed-forward action for counteracting rotational couplings is also accounted for. The resulting nonlinear control structure considers the complex and nonlinear nature of the tethered system in a better way. Several demonstrating simulations under artificially generated wind influences are presented to endorse the validity of the new proposed controller.

Keywords—Unmanned aerial vehicles, helicopter, tethered systems, modeling, model-based control, PID, stability augmentation

I. INTRODUCTION

Helicopters and other rotorcraft-based aircraft have flight capabilities such as hover, Vertical Take-Off and Landing (VTOL) and pirouette, which cannot be achieved by conventional fixed-wing aircraft. These features are consequence of their functional controllability in lateral, longitudinal and vertical directions with almost constant yaw-attitude.

The aforementioned hovering capability allows remotely piloted and autonomous helicopters to be extensively used nowadays for applications such as inspection, accurate measurement and other aerial robotic applications. However, the performance of this valuable feature can be seriously affected by external disturbances such as wind effects. The latter could be even more significant when dealing with small-size helicopters.

In order to address the performance degradation on hovering capabilities under external disturbances, an augmented setup that consists of the unmanned helicopter itself, a tether connecting the helicopter to the ground, and a ground device that is in charge of fixing certain tension values on the tether during the operation of the system was proposed in [1]. The justification for this augmented setup is the stabilizing action of the tether tension. To authors knowledge, this use of the tether tension to increase stability of hovering maneuvers in helicopters is almost unexplored in the literature. The only related precedents considering the tethered configuration for rotorcraft prototypes different from helicopters are those of [2], where the linearized equations describing the perturbed longitudinal motion of a tethered rotorcraft are presented and [3], 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. The authors of that work also propose two approaches for the design of an automatic hover controller for the tethered system. Finally, it is also worth mentioning the contributions of [4]. Although it corresponds to the different application scenario of landing a helicopter, it is referenced here since it also makes use of a tether as an additional resource for helicopter control. In those works, the benefit of the use of the tether is improving the controllability of the system rather than the stability.

In the augmented configuration proposed in [1]
the tether effect on the system has been proved to be two-fold. On the one hand, it provides robustness against external perturbations due to the stabilizing properties of the tether tension in the translational dynamics. On the other hand, 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 that makes more difficult the controllability of the system. The value of the moment caused by the tether could be similar or even larger than the moments required to control the rotation of the helicopter in free flight without any tethering device. The control strategy proposed in [1] for taking advantage of the stabilizing tethered setup considers the operation of the system under a constant tether tension, which is ensured by the ground device. Simulations performed demonstrated that even a basic linear approach for controlling the helicopter was enough to produce a significant improvement of hovering performance in presence of wind disturbances.

This paper presents a more elaborated strategy for controlling the helicopter, while adopting the same control paradigm of ensuring a constant tether tension by means of the ground device. The aim is to better consider the nonlinear nature of the system. The proposed controller combines classical PID, PI and P control laws with model inversion. In addition to this, feed-forward action is also considered to counteract the moment induced by the tether.

This paper begins with a detailed description of the tethered configuration. To this end, Section II presents the dynamical model corresponding to the augmented system: small-size helicopter, tether and ground device. Later in Section III, the improved strategy for helicopter control is explained in detail. Finally, in Section IV, several demonstrating simulations under artificially generated wind influence are presented to endorse the validity of the proposed approach. Section V is devoted to conclusions and future work.

II. TETHERED CONFIGURATION MODEL

This section presents the model corresponding to the tethered configuration. The objective is not to present very elaborated equations for high-fidelity simulations but rather to derive the best model for control design purposes. The former criterion demands a simple and manageable model for easing the analysis to derive the control laws, but capable to accurately reproduce the main behavior of the real system at the same time.

According to the authors of [5], the dynamics of a small-size helicopter with a stiff main rotor is mainly described by its mechanical model. Their attempt to include an elaborated model for aerodynamics of the main rotor in controller design did not show significant improvements in control experiments performance. This could be considered as evidence for the fact that the approach to analyze the helicopter behavior by means of its mechanical model is suitable for practical applications. This paper follows the same assumption. Concerning the modeling approach, this paper follows Kane’s methodology [6], like in other previous works of the authors [7].

A. Tethered helicopter

The system is depicted in Fig. 1. In line with [5] the mechanical characterization of the helicopter accounts for two separated rigid bodies, fuselage $F$ and stiff main rotor $MR$ (modeled as a thin solid disk with constant angular speed) 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 of center of mass $H^O$ in the inertial reference frame $N$ is described by generalized coordinates $q_i (i = 1, 2, 3)$:

$$p^{N \rightarrow H} = q_1 n_1 + q_2 n_2 + q_3 n_3$$ (1)

Generalized coordinates $q_i (i = 4, 5, 6)$ are the Euler-angles (roll, pitch and yaw) corresponding to successive rotations (Body1-2-3 order [6]) that describe the orientation of $F$ in the inertial reference frame $N$. Thus, dextral set of orthogonal unit vectors $f_i (i = 1, 2, 3)$ fixed in $F$ and vectors $n_i$ are geometrically related by the direction cosine matrix shown in Table I.

Generalized speeds $u_i (i = 1, \cdots, 6)$ are defined as:

$$N^V H^O = u_1 n_1 + u_2 n_2 + u_3 n_3$$ (2)

$$N^w F = u_4 f_1 + u_5 f_2 + u_6 f_3$$ (3)

which leads to the following kinematic differential equations for translation:

$$\dot{q}_i = u_i \quad (i = 1, 2, 3)$$ (4)

as well as for rotation:

$$\dot{q}_4 = -(s_6 u_5 - c_6 u_4)/c_5$$

$$\dot{q}_5 = s_6 u_4 + c_6 u_5$$

$$\dot{q}_6 = u_6 + s_5 (s_6 u_5 - c_6 u_4)/c_5$$ (5)

Concerning forces and moments applied to the helicopter (see Fig. 2), main rotor generates a force $F_{MR} = f_{MR3} f_3$ applied at point $MR^O$ and moments $M_{MR,i} = t_{MR,i} f_i (i = 1, 2, 3)$ applied to rigid body $MR$, whereas tail rotor generates a force $F_{TR} = f_{TR2} f_2$ applied at point $TR^O$ and a moment $M_{F} = t_{TR2} f_2$ applied to rigid body $F$. Force of gravity $W_j = -m_j g n_3 (j = F, MR)$ applied at centers of mass $F^O$ and $MR^O$ is also considered, where $g$ is the acceleration of gravity. The application of Kane’s method leads to the following dynamical differential equations for translation:

$$m_H \ddot{u}_1 = f_{MR3} s_5 - f_{TR2} c_5 s_6$$

$$m_H \ddot{u}_2 = f_{TR2} (c_4 s_6 - s_4 s_5 s_6) - f_{MR3} s_4 c_5$$

$$m_H \ddot{u}_3 = f_{MR3} c_4 c_5 - m_H g +$$
$$+ f_{TR2} (s_4 c_6 + c_4 s_5 s_6)$$ (6)

as well as for rotation:

$$K_{4p4} \ddot{u}_4 = t_{MR,1} + d_{O-H^O,3} f_{TR2} +$$
$$+ (K_{456} u_6 + K_{45}) u_5$$

$$K_{5p5} \ddot{u}_5 = t_{MR,2} + t_{TR2} +$$
$$+ (K_{546} u_6 + K_{54}) u_4$$

$$K_{6p6} \ddot{u}_6 = t_{MR,3} + d_{O-TR^O,1} f_{TR2} +$$
$$+ K_{645} u_4 u_5$$ (7)

where $m_H$ is the total mass and parameters $K_{xxx}$ are functions of the inertial characterization of the helicopter according to the expressions given in Table II.

Since only the mechanical model will be used for modeling analysis and subsequent derivation of the controller, as was discussed at the beginning of this section, the forces and moments exerted on the system will be considered as system inputs for control design. More precisely, the subset of these forces and moments whose values can be fixed independently of each other by the controller is given by $f_{MR3}, t_{MR,1}, t_{MR,2}$ and $f_{TR2}$. In the implementation of controllers for real helicopters these inputs will be transformed to servo positions using simple linear functions with only three unknown constants: the first constant describes the relation between the main rotor collective pitch and
the lifting force \( f_{MR,3} \), the second one the relation between the main rotor cyclic pitches and moments \( t_{MR,1} \) and \( t_{MR,2} \) and the third one the relation between the tail rotor collective pitch and the force \( f_{TR,2} \). These constants can be identified in experiments. In [5] this approach for characterizing linearly the aerodynamics was verified successfully in flight experiments.

When accounting for the tether effect into the model, it is assumed for the sake of simplicity that the tether end at ground coincides with the origin of the inertial frame \( N \). On the other end, the tether is connected to helicopter point \( P \) as depicted in Fig. 1.

Since the elastic model adopted for tether tension in next steps will depend on the instant longitude of the cable, it is more convenient for the manageability of the resulting dynamic model that helicopter position in inertial frame \( N \) is defined by means of the generalized spherical coordinates \( q_{7,8,9} \) represented in Fig. 1 and Fig. 5a. As can be seen, angular variables \( q_7, q_8 \) correspond to two successive rotations at point \( N^O \) that align vector \( n_3 \) with the tether direction, defined by vector \( c_3 \).

The remaining configuration coordinate \( q_9 \) defines the instant length of the tether. Hence, position of point \( P \) is given by:

\[
P^{N^O \rightarrow P} = q_9 c_3
\]  

Since the tether is modeled as an elastic element, the tension acting at point \( P \) (See Fig. 2) is then given by:

\[
\mathbf{T}_C = -T_C c_3 = -K_C (q_9 - L_N) c_3
\]

\[
K_C \begin{cases} 
= 0 & \text{for } q_9 < L_N \\
> 0 & \text{for } q_9 > L_N
\end{cases}
\]  

(9)

where \( L_N \) and \( K_C \) are the natural length and elasticity constants of the tether, respectively.

The use of spherical variables as the configuration variables for helicopter position at the same time that the motion variables are still Cartesian, makes it necessary a new analysis on the kinematics of the system. To this end, \( \frac{\text{d} \mathbf{p}_{N^O \rightarrow H^O}}{\text{d} t} = \mathbf{p}_{N^O \rightarrow H^O} \) is compared against (2), taking into account that \( \mathbf{p}_{N^O \rightarrow H^O} = \mathbf{p}_{N^O \rightarrow P} + \mathbf{p}_{P \rightarrow O} + \mathbf{p}_{O \rightarrow H^O} \). The resulting equations are solved for \( \dot{q}_{7,8,9} \), which yields the following:

\[
\begin{bmatrix} \dot{q}_7 & \dot{q}_8 & \dot{q}_9 \end{bmatrix}^T = \mathbf{M} \cdot \begin{bmatrix} u_1 & \cdots & u_6 \end{bmatrix}^T
\]  

(10)

where matrix \( \mathbf{M} \) is function of generalized coordinates \( q_i (i = 4, \ldots, 9) \) and parameters \( d_{O-H^O,3} \) and \( d_{O-P,3} \). While it is true that kinematical equations (10) are more complex than those of (4) (\( \mathbf{M} \) is a dense matrix), the real advantage of using spherical configuration variables together with Cartesian motion variables is given by the resulting dynamical differential equations, since they are much more compact for the tethered configuration than those corresponding to Cartesian coordinates for both configuration and motion variables. Final expressions for the dynamics of the tethered configuration are given by:

\[
\begin{align*}
m_{H} \ddot{u}_1 & = RHS_1 - T_C s_8 \\
m_{H} \ddot{u}_2 & = RHS_2 + T_C s_7 c_8 \\
m_{H} \ddot{u}_3 & = RHS_3 - T_C c_7 c_8
\end{align*}
\]  

(11)

for translation, whereas rotational equations are given by:

\[
\begin{align*}
K_{4p4} \ddot{u}_4 & = RHS_4 + T_C (d_{O-P,3} - d_{O-H^O,3}) \cdot (c_7 c_8 (s_4 c_6 + s_5 s_6 c_4) - s_7 c_8 (c_4 c_6 - s_4 s_5 s_6) - s_6 s_8 c_5) \\
K_{5p5} \ddot{u}_5 & = RHS_5 + T_C (d_{O-P,3} - d_{O-H^O,3}) \cdot (s_7 c_8 (s_6 c_4 + s_4 s_5 c_6) - c_7 c_8 (s_4 s_6 - s_5 c_4 c_6) - s_8 c_5 c_6) \\
K_{6p6} \ddot{u}_6 & = RHS_6
\end{align*}
\]  

(12)

where \( RHS_i \) is the right hand side of the corresponding equations in (6) and (5). The values of the model parameters that have been used for simulation purposes in this work are shown in Table II.

B. Ground device for tether tension control

The ground device is in charge of controlling the tether tension during the operation of the system. Since tether tension was modeled as an elastic element in (9), a natural way to control the tether tension by the ground device would be varying the natural length \( L_N \), that is, reeling in/out the tether. Then, the model corresponding to the ground device must define a relationship between the variation in the natural length that is
For the purpose of being reeled in/out and certain system input that allows to control such variation. For the purpose of this paper the following simple model shall suffice:

\[
\frac{dL_N}{dt} = U_C
\]

where \(U_C\) is the control signal that allows to wind or unwind the tether.

### III. CONTROL STRATEGY

The controller proposed for the tethered configuration is based on the control scheme for free flight presented in [5] and depicted in Fig. 3. The gray blocks denote the helicopter dynamics whilst the white blocks denote the controller itself. Although the resulting controller is nonlinear, the underlying approach is quite simple since it is based on linearization through model inversion and PID control.

The main idea is to adjust the orientation of the main rotor plane and therefore of the lifting force in order to generate the translational accelerations required to reduce the position error. The inputs for the control scheme are given by the desired position \(q_1^*, q_2^*, q_3^*\) and the desired yaw angle \(\theta^\circ\). As can be seen in Fig. 3 the complete scheme consists of three control loops, presented in more detail in Fig. 4.

The outer loop controller \(C_{TRAS}\) calculates from position errors the required translational accelerations \(\dot{u}_{1,2,3}^\circ\) to reduce such deviations, and this is implemented by means of a PID control law:

\[
\dot{u}_i^* = K_P^\circ (q_i^* - q_i) + K_I^\circ \int (q_i^* - q_i) \, dt - K_D^\circ u_i \quad i = 1, 2, 3
\]

These accelerations are converted into the desired orientation for the main rotor plane \(q_4^\circ\), and the desired lifting force \(f_{MR,3}\), through the inversion of translational dynamics in block \(D_{123}^{-1}\). For the purpose of this inversion, input \(f_{TR,2}\) is considered a disturbance and hence neglected. Resulting expressions after some additional algebraic manipulations are given by:

\[
f_{MR,3} = m_H \sqrt{(\dot{u}_1^\circ)^2 + (\dot{u}_2^\circ)^2 + (\dot{u}_3^\circ + g)^2}
\]

\[
q_5^* = \arcsin \left( \frac{m_H \dot{u}_1^\circ}{f_{MR,3}} \right)
\]

\[
q_4^* = \arcsin \left( \frac{-m_H \dot{u}_2^\circ}{f_{MR,3} \cos^2 q_5^*} \right)
\]

The desired orientation for the main rotor plane \(q_4^\circ\) given by \(C_{TRAS}\) is controlled in the inner loop \(C_{ROT}\) through a proper calculation of moments \(t_{MR,1}\) and \(t_{MR,2}\). To this end, desired Euler angle derivatives \(\dot{q}_4^\circ, \dot{q}_5^\circ\) are calculated from angular errors using a Proportional gain:

\[
\dot{q}_j^\circ = K_P^\circ (q_j^\circ - q_j) \quad j = 4, 5
\]

These Euler angle derivatives are then converted into the desired angular speeds \(\dot{\theta}_1^\circ\) in block \(K_{156}^{-1}\) by means of the inversion of rotational kinematics (5):

\[
\dot{\theta}_1^\circ = c_5 c_6 \dot{q}_4^\circ + s_6 \dot{q}_5^\circ
\]

\[
\dot{\theta}_5^\circ = -c_5 s_6 \dot{q}_4^\circ + c_6 \dot{q}_5^\circ
\]
Then, desired angular accelerations $\ddot{\varphi}_4, 5$ are calculated from deviations in angular speed using another Proportional gain:

$$\ddot{\varphi}_j = K_{P, j}^u (\dot{\varphi}_j - \varphi_j) \quad j = 4, 5 \quad (18)$$

These resulting angular accelerations are converted into moments $t_{MR,1}$ and $t_{MR,2}$ by the corresponding inversion of rotational dynamics in block $D_{456}^{-1}$. Again considering $f_{TR,2}$ and $t_{TR,2}$ as disturbances, and assuming $u_6 = 0$ (tail rotor controlled dynamics several times faster than angular dynamics in longitudinal and lateral axes), algebraic manipulation of (7) yields the following:

$$t_{MR,1} = K_{45} \ddot{\varphi}_4 - K_{45} \int \dot{\varphi}_5 \, dt$$

$$t_{MR,2} = K_{54} \ddot{\varphi}_5 - K_{54} \int \dot{\varphi}_4 \, dt \quad (19)$$

Finally, the desired yaw angle $\varphi_6^*$ is controlled separately with the third loop controller $C_{TAIL}$. To this end, desired angular speed $u_6^*$ is calculated from angular error using a PI control law. Then, tail rotor force $f_{TR,2}$ is calculated from angular speed error using a Proportional gain:

$$u_6 = K_{P, q_6}^q (q_6^* - q_6) + K_{I, q_6}^q \int (q_6^* - q_6) \, dt$$

$$f_{TR,2} = K_{P, u_6}^u (u_6^* - u_6) \quad (20)$$

**Feed-forward action**

As was mentioned before, tether effect on the system is two-fold. On the one hand, it provides robustness against external perturbations due to the stabilizing properties of the tether tension in the translational dynamics (11). On the other hand, the moment induced by the existing offset between the tether tension application point $P$ and the center of mass $H^O$, produces undesired coupling in (12) between rotational and translational dynamics that makes more difficult the controllability of the system. It is important to notice that the value of the moment caused by the tether could be similar or even larger than the torques required to control the rotation of the helicopter in free flight without any tethering device. In order to account for that undesired rotational influence, a feed-forward action based on estimating the tether tension is needed. To this end, a force sensor (load cell) for measuring the tension magnitude is used. Additionally, in order to establish the orientation of the tension vector, the device holding the tether is an universal joint that includes two optical encoders for measuring the angles, as illustrated.
in Fig. 5a. The setup of these sensors is similar to the load transportation device described in [8].

Once the estimation for the tether tension vector is available, a compensator block $C^F-f_{\text{fwd}}$ calculating the tether moment

$$t_i^{\text{tether}} = \left( \mathbf{p}_{\text{P->HO}} \times \mathbf{T}_C^{\text{est}} \right) \cdot \mathbf{f}_i, \quad i = 1, 2$$

is added to the orientation controller in order to subtract its value from moments calculated in the orientation controller as shown in Fig 5b.

**Control objective for tether tension**

As was mentioned before, the ground device is in charge of fixing a certain tension value on the tether during the operation of the system. To that end, the measured magnitude of the tether tension $T_{C}^{\text{est}}$ is compared against the reference tension for the tether $T_{C}^{\text{ref}}$. For this purpose, it is necessary to define the desired temporal profile for this value. The objective is to maximize the benefits of the stabilizing effect in translational dynamics of the tether, while at the same time the undesired rotational influence remains under control. The complexity of satisfying both objectives simultaneously suggests the definition of a simple profile that ease the design process of the controller for the helicopter. Accordingly, the selected profile for the tether tension is given by a constant value of $T_{C}^{\text{ref}}$. While it is true that high values for this profile would reinforce tether stabilizing action in translational dynamics, it should also be accounted that the higher this value is, the higher the control degradation for helicopter rotational dynamics could be. Then, a trade-off criterion suggests that the maximum value for tether tension should be defined in such a way that the induced tether moment is always less than the maximum moment exerted by the main rotor control action, which corresponds to the saturation of the cyclic pitch. By using an estimation of the previous limit for cyclic saturation for a typical commercial small-size helicopter, it was concluded in [1] that the magnitude of the tether tension should not exceed 20% of the lifting force at hovering.

The error between measured tension and reference value is used to generate the actuation signal $U_C$ in (13) by means of a PI type control law:

$$U_C = K_P^C \cdot (T_{C}^{\text{est}} - T_{C}^{\text{ref}}) + K_I^C \int (T_{C}^{\text{est}} - T_{C}^{\text{ref}}) dt$$

where the controller gains are set to $K_P^C = 1$ and $K_I^C = 0.1$.

**Tuning controller parameters**

The parameters of the helicopter controller have been tuned by means of the classical pole assignment method, as described in [5]. After a basic analysis of the mechanical limitations of the system by means of experiments providing step inputs, it is concluded that all the poles should be set around -1 for translational and rotational dynamics and -10 for tail rotor dynamics. This is a trade-off value that guarantees a proper dynamic range at the same time that the mechanical limits of the system are not reached.

Concerning translational and rotational controllers $C_{\text{TRAS}}$ and $C_{\text{ROT}}$, the expressions that relate the control parameters with the desired poles $p_1,...,9$ for the corresponding close-loop system are shown below:

$$K_P^{q_i} = -(p_1 + p_2 + p_3 + p_4 + p_5)$$

$$K_I^{q_i} = p_4 p_5 + p_3 (p_1 + p_5) +$$

$$+ p_2 (p_3 + p_4 + p_5) +$$

$$+ p_1 (p_2 + p_3 + p_4 + p_5)$$

$$K_P^{q_i} = -(p_3 p_4 p_5 + p_2 (p_4 + p_5) + p_4 p_5) +$$

$$+ p_1 (p_2 (p_3 + p_4 + p_5) +$$

$$+ p_3 (p_4 + p_5) + p_4 p_5)/K_P^{q_i}$$

$$K_I^{q_i} = (p_2 p_3 p_4 p_5 + p_1 (p_3 p_4 p_5 +$$

$$+ p_2 (p_3 (p_4 + p_5) + p_4 p_5)))/K_P^{q_i}$$

$$K_I^{q_i} = -p_1 p_2 p_3 p_4 p_5/K_P^{q_i}$$

(23)
The same equivalence but for the tail controller $C_{TAIL}$ is the following:

\[ K^{ui}_P = p_7 + p_8 + p_9 \]
\[ K^{q6}_P = - (p_7p_8 + p_9 (p_7 + p_8)) / K^{ui}_P \]
\[ K^{q6}_I = p_7p_8p_9 / K^{ui}_P \] (24)

All these expressions have been obtained after deriving the transfer functions of the closed-loop linear systems that result from the application of model inversion and the different PID, PI and P control laws:

\[ \frac{q_i}{q_i} = \left( K^{q_i}_P (K^{q_i}_I + K^{q_i}_P s) \right) / \left( K^{q_i}_P K^{q_i}_I + K^{q_i}_P K^{q_i}_P s + K^{q_i}_P K^{q_i}_P s^2 \right) \]
\[ \approx 0 \] for $i = 1, 2, 3$

\[ \frac{q_6}{q_6} = K^{q6}_I (K^{q6}_I + K^{q6}_P s) / \left( K^{q6}_I K^{q6}_I + K^{q6}_P K^{q6}_P s + K^{q6}_P K^{q6}_P s^2 + s^3 \right) \] (25)

IV. SIMULATION RESULTS

The control approach presented in previous section have been tested in simulation with the complete set of non-linear equations derived for the extended tethered configuration (5), (10), (11) and (12). These simulations show the response of the system in presence of artificially generated wind influence. Additionally, in order to better illustrate the advantages of the improved controller proposed in this paper over the work presented in [1], simulations corresponding to such linear control approach have been also considered for comparison purposes. Likewise, the behavior of the unmanned helicopter in free flight is also shown in some graphs for recalling the benefit of the tether configuration.

The reference value adopted for tether tension is assumed to be approximately \(20\%\) of the helicopter total weight, i.e. \(25\,N\). Initial conditions for state variables correspond to hovering equilibrium. Two different simulations have been performed to test the performance of the proposed control strategy under the effect of wind disturbances. In the first one, a longitudinal disturbance in the translational dynamics is simulated by means of a pulse force \(F_{w1} = 20\,n_1\) at instant \(t = 10\,s\) and a sinusoidal force \(F_{w2} = 20\sin(2\pi \cdot 0.1 \cdot t)\) starting at time \(t = 30\,s\). In a similar way, the second simulation under study consists of a lateral disturbance in the translational dynamics simulated by means of the combination of a pulse force \(F_{w2} = 20\,n_2\) at instant \(t = 10\,s\) and a sinusoidal force \(F_{w2} = 20\sin(2\pi \cdot 0.1 \cdot t)\) starting at time \(t = 30\,s\) applied at helicopter center of mass. Fig. 6 illustrates the response of the state variables mainly affected by such perturbations, \(q_1\) and \(q_2\) respectively. As can be seen, the behavior of the improved controller is better than in the free case. Furthermore, when comparing to the linear controller presented in [1], a significant improvement can be seen in \(q_2\).

For completing the evaluation of the improved nonlinear control structure presented in this paper, a more exhaustive comparison of the complete set of variables for simulation 2 is shown in Fig. 7. These graphs include the evolution of all state variables as well as the tether tension \(T_C\), tether natural length \(L_N\) (tether length deployed by ground device) and the helicopter control inputs \(f_{MR3}, t_{MR1}, t_{MR2}, f_{TR2}\) (including feed-forward action based on \(T_{C}^{RF}\)). Clearly, the response of the nonlinear controller is more precise due to the nonlinear nature of the system. 3D animations of both simulations can be seen in [9].

V. CONCLUSIONS

This paper extends previous contributions of the authors about the use of tethered configurations for improving performance in hovering maneuvers performed by unmanned helicopters. More precisely, this work presents a more elaborated strategy for controlling the helicopter, while adopting the same control paradigm of ensuring a constant tether tension by means of the ground device.

The aim was to better consider the complex and nonlinear nature of the system. To this end, instead of the basic linear scheme employed for the first proof of concept, a combination of classical PID control laws together with model inversion blocks constitutes the base of the new controller. Additionally, feed-forward action for counteracting rotational couplings are also accounted for.

The analysis of the simulations confirms the benefits of the new controller. On the one hand, the
response of the state variables directly related to the perturbation signals is better than in the linear case. On other hand, when analyzing the complete set of variables, it is evident that the behavior of the nonlinear controller is more precise due to the complex nature of the system.

Although previous analysis concluded that the new approach yields better performance, there seems to be still room for improvement. To this end, more advanced techniques belonging to the control branch specifically devoted to nonlinear systems will be investigated in future work.

Last but not least, in order to endorse the validity of the conclusions obtained in these simulation works, next step will be the realization of field experiments. There is already some preliminary work carried out in this line, like the design of the ground platform required for the experimental setup.

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Fig. 7: Simulation 2 results. Dash-dot for controller reference, dashed for tethered helicopter (linear controller) [1] and solid for tethered helicopter (nonlinear controller)