Data-driven attitude control law design for a variable-pitch quadrotor

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Abstract— **In this paper, the problem of tuning a cascade attitude control system of a variable-pitch quadrotor UAV is tackled, adopting a fast data-driven procedure based on a modified Virtual Reference Feedback Tuning (VRFT) approach. The proposed method allows to tune both the inner and the outer loops by means of a single set of experimental data. More precisely, the pitch attitude degree of freedom of the vehicle is considered, operating the quadrotor indoor on a dedicated test bench. The achieved control performance is compared with the one obtained by applying a model-based structured H_∞ synthesis approach to a black-box model of the pitch dynamics.**

I. INTRODUCTION

The quadrotor platform has gained considerable interest in the last decade for small-scale Unmanned Aerial Vehicle (UAV) commercial and research applications due to great maneuverability, high payload capability and good performance in many flight conditions.

In order to achieve the best possible performance for a quadrotor in terms of pointing and positioning accuracy, the design and tuning of attitude controllers must be carried out in a sensible way. Depending on the specific application, requirements may vary and the set of appropriate modelling and control law design tools may differ quite significantly. As an example, while for aggressive manoeuvering flight nonlinear models and nonlinear control design methods are needed (see, *e.g.*, [12] for a recent survey), if one is mainly concerned with applications such as inspection, surveillance, mapping, video and photography (which, incidentally, cover most of the actual market for this type of vehicles) then linear modelling and control design methods are more suitable, while on the other hand, the expected performance level is significantly higher.

For hover and near-hover operations, typical control laws for attitude regulation are of the PID type. Their tuning can be carried out in may different ways, typically ranging between two extreme solutions. On one hand, if fast deployment has the priority over performance, then manual tuning can be used. If, on the other hand, high performance is seeked, then advanced model-based methods should be considered (see, for example, [15]). Note, in passing, that this is particularly important when considering variable-pitch quadrotors (see, *e.g.*, [4], [16]), which have the potential for much tighter attitude control thanks to the wider achievable bandwidths. Model-based approaches, however, assume that reliable mathematical models of the system are available; unfortunately, while mathematical models for quadrotor dynamics are easy to establish as far the kinematics and dynamics of linear and angular motion are concerned, characterizing additional dynamics such as, *e.g.*, due to aerodynamic effects, actuators and sensors, is far from trivial (see [17] for a detailed discussion of this topic).

Recently, data-driven tuning methods have gained attention from several researchers. The main concept of these methods is to tune the controller parameters directly from experimental input-output data. Thus, this approach can be applied when *a-priori* knowledge about the plant model is limited or when an accurate modeling of the system requires too much effort. Furthermore, these methodologies allow a fast re-tuning of the controller when the plant performance is reduced (*e.g.*, components aging) and/or operating conditions change (*e.g.*, different payloads, environment). Several data-driven control tuning methods have been proposed in the literature, such as the Iterative Feedback Tuning (IFT) [10], the Virtual Reference Feedback Tuning (VRFT) [3] and the Correlation-Based Tuning (CbT) [18], [9].

In view of the above discussion, in this paper the VRFT approach developed in [7] has been adopted to tune the cascade attitude controller of a variable-pitch quadrotor exploiting experiments conducted indoor on a dedicated test-bed. The method has been selected because it has already been successfully applied to the cascade control architecture and it requires only a single set of experimental data to tune either the inner and the outer loops. Results are then compared with those obtained with a manual tuning procedure and the model-based structured H_∞ synthesis presented in [15].

The paper is organized as follows. In Section II the considered quadrotor platform and its controller architecture are presented in detail. Section III provides a brief summary of the considered model-based tuning methodology; subsequently, in Section IV, after a short introduction to the standard VRFT approach, the same methodology applied to the cascade control architecture is outlined. Finally, results and performance comparison are presented in Section V. The last section is devoted to some concluding remarks about the presented method and its applicability.

II. QUADROTOR PLATFORM

The quadrotor studied in this paper is the Aermatica P2-A1 prototype (see Figure 1), a platform having a maximum take-off weight of about 5 kg and an arm length of 0.415 m. The four rotors have a radius of 0.27 m and a teetering articulation with flapping motion partially restrained by rubber elastic

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elements. Unlike most quadrotors, which use variable rotor angular rates as control inputs (with fixed rotors blade pitch), P2-A1's rotors are operated at a fixed angular rate and use variable collective pitch as control variables. While this choice leads to a more complex design of the rotor hub and a slight weight penalty, it has been shown (see, *e.g.*, [4], [16]) that variable pitch control can overcome the limitations on the achievable quadrotor performance associated with the bandwidth of motor dynamics for rate-controlled configurations.

All the experiments considered in this work have been conducted operating the quadrotor on a single degree of freedom test-bed (only pitch rotation allowed, see Figure 1): as discussed in [14], this set-up guarantees safer, faster and more repeatable operations with respect to flight while remaining representative of the pitch attitude dynamics in flight for near hovering conditions. Indeed, the test bench brings the vehicle rotors at a height from ground sufficient to assure Out of Ground Effect (OGE , see [11]) aerodynamic conditions. Also, aerodynamic interferences on the rotors caused by the test-bed structure can be considered negligible. Furthermore, identification experiments for the attitude dynamics of P2-A1 have been carried out both on the test bench and in flight. The models obtained from indoor data and flight data have the same structure and nearly identical numerical values of the parameters; in addition they are practically indistinguishable in terms of closed-loop metrics such as the ν-gap (see, again [14] for details).

As for the level of disturbances experienced by the platform on the test bench, it is worth to remark that with respect to an outdoor flight condition, in which the rotor-induced wakes develop free from obstacles, working indoor in a closed volume with limited dimensions implies a complex recirculation of rotor wakes. This, in turn, determines a non-negligible and non-deterministic disturbance on the vehicle during the test, with effects assimilable to free air turbulence. As a result, the platform is subjected to a significant level of aerodynamic disturbance also during indoor tests.

Fig. 1. Aermatica P2-A1 on laboratory test-bed.

Concerning the control architecture, the P2-A1 platform adopts a classical attitude control scheme based on decoupled cascaded PID loops for the pitch, roll and yaw axes (see the block diagram in Figure 2, where the pitch control loop is represented). More precisely, an outer PD loop based on attitude feedback (measured angle θ, set-point θ^o) and an inner PID loop on angular rate feedback (measured angular velocity q, set-point q^o, control variable u). The overall delay of the control loop, from IMU measures, through acquisition and processing, to servo actuation of blade collective pitch, is estimated to be 0.06 s.

III. MODEL-BASED TUNING METHODOLOGY

In order to fully exploit the potential performance of variable-pitch quadrotor platforms, wide bandwidth attitude controllers must be designed. If the design takes place in a model-based framework, this, in turn, calls for accurate dynamic models of the vehicle's response to which advanced controller synthesis approaches can be applied. As was mentioned in the Introduction, previous work on the P2-A1 platform (reported in [15]) has led to the development of a dedicated design procedure for the attitude control laws, combining a black-box model identification step, followed by a robust design step based on a structured H_∞ approach.

The problem of black-box model identification for the attitude dynamics of hovering quadrotors has been studied extensively in the literature (see [1] and the references therein) and for the considered vehicle was tackled in a previous work (see [17]). In particular a LTI state-space SISO model for the dynamics of the pitch angular rate was obtained using a subspace identification method.

The model-based tuning of the P2-A1 pitch attitude control law (see [15] for details) was carried out using a structured H_∞ synthesis approach: for the assigned controller structure and the above-discussed back-box model for pitch dynamics, the procedure finds the (locally) optimal parameters for the two PID controllers so as to satisfy the imposed closed-loop stability and performance requirements (crossover frequency of each loop in a specified bandwidth, attitude angle set-point tracking behavior defined in terms of target response time and maximum steady-state error, process noise disturbance rejection capability specified assigning a maximum gain constraint profile as function of frequency).

It is interesting to point out that the above requirements for H_∞ synthesis were defined in order to obtain an improvement in terms of wind gust rejection compared to the standard tuning obtained through the trial and error empirical procedure done manually, that presently does not guarantee a fully satisfactory performance in flight. On the contrary, as the actual quadrotor performance in terms of set-point tracking is considered adequate, the optimal tuning requirements were defined in order to replicate the standard tuning, as a benchmark. The standard tuning was also used as starting guess for the optimization procedure.

IV. DATA-DRIVEN APPROACH: VRFT TUNING OF CASCADE CONTROL SYSTEMS

Consider a linear time-invariant discrete-time system $G(z)$, where z denotes the forward time-shift unit (*i.e.*, $zx(t) = x(t+$

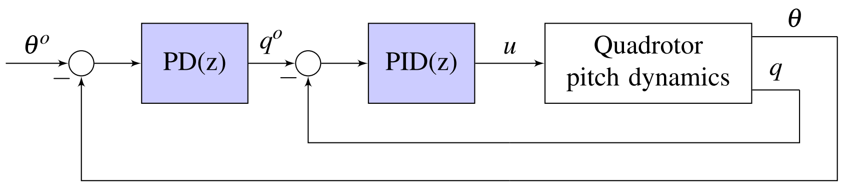

Fig. 2. Aermatica P2-A1 pitch attitude controller structure.

1)), a class of controllers $\mathscr{C}(\theta) = \{C(z,\theta)\ ,\ \theta \in R^n\}$, and a given target closed-loop behaviour $M(z)$. The control aim of VRFT is the minimization of the $\mathscr{L}_2$-norm of the mismatch between M and the actual closed-loop system:

$$J_{MR}(\theta) = \left\| \left(\frac{G(z)C(z,\theta)}{1+G(z)C(z,\theta)} - M(z) \right) W(z) \right\|_2^2 \qquad (1)$$

where $W(z)$ is a weighting function chosen by the user. The main features of VRFT are that the model-reference problem (1) is solved without any knowledge of the system and using only a set of available open-loop measurements $D_N = \{u(t), y(t)\}_{t=1..N}$, where N is the length of the data-set.

The main idea is as follows. Consider the reference signal $r_v(t)$ that would feed the system in closed-loop operation when the closed-loop model is $M(z)$ and the output is the measured $y(t)$. Such a signal is called *virtual reference* and can be computed from the output data (offline) as

$$r_v(t) = M^{-1}(z)y(t).$$

A good controller (making the closed-loop as close as possible to $M(z)$) is then the one that produces the input sequence of the experiment $u(t)$ when it is fed by the error signal $e_v(t) = r_v(t) - y(t)$.

Formally, the cost criterion minimized by the VRFT algorithm is the following:

$$J_{VR}^N(\theta) = \frac{1}{N}\sum_{t=1}^{N} \left(u_L(t) - C(z,\theta)e_L(t)\right)^2, \qquad (2)$$

where $u_L(t)$ and $e_L(t)$ are suitably filtered versions of $u(t)$ and $e_v(t)$. such that the cost function (2) is a local approximation of the criterion (1) in the neighborhood of the minimum point [3]. Recent advances on the VRFT method can be found, *e.g.*, in [2], [8], [5], while application studies are available, *e.g.*, in [13], [6].

In the cascade control framework, it has been shown in [7] that the VRFT rationale can be easily extended to multiple nested loops, by still relying on a single experiment.

Consider the cascade control scheme in Figure 3 (where only two loops are shown without loss of generality). Given two reference models $M_i(z)$ and $M_o(z)$, for the inner loop and the outer loop respectively, consider two families of linear proper controllers $\mathscr{C}_i(\theta_i) = \{C_i(z,\theta_i)\ ,\ \theta_i \in R_i^n\}$ and $\mathscr{C}_o(\theta_o) = \{C_o(z,\theta_o)\ ,\ \theta_o \in R_o^n\}$ and the set of data $D_N = \{u(t), y_i(t), y_o(t)\}_{t=1,\dots,N}$ being $u(t)$ the control variable, $y_i(t)$ the output of the inner loop, $y_o(t)$ the output of the outer loop. The inner controller can be tuned by applying the standard VRFT. For the outer controller, on the other hand, the approach needs to be different, as the input of the system to control is the reference $r_i(t)$ (see again Figure 3), that is not available in the dataset, since measurements are collected during open-loop operation.

Nevertheless, in [7] it has been shown that the reference signal $r_i(t)$ can be derived from the available data by exploiting the fact that the inner controller is designed independently of the outer one. In detail, once $C_i(z,\theta_i)$ is fixed, the input of the inner loop can be calculated as

$$r_i(t) = e_i(t) + y_i(t),$$

where the tracking error comes from the result of the inner design as

$$e_i(t) = C_i^{-1}(z,\theta_i)u(t).$$

With such a choice, $r_i(t)$ is exactly the signal that would feed the inner loop in closed-loop working conditions when the output is $y_i(t)$. Then, the outer controller can be easily found as result of VRFT synthesis, by using the set of I/O data $D_N^o = \{r_i(t), y_o(t)\}_{t=1,\dots,N}$. More specifically, θ_o comes as the minimizer of

$$J_{VR}(\theta_o) = \frac{1}{N}\sum_{t=1}^{N} (r_{iL}(t) - C_o(z,\theta_o)e_{oL}(t))^2 \qquad (3)$$

where $r_{iL}(t)$ and $e_{oL}(t)$ are suitably filtered versions of $r_i(t)$ and $e_{oV}(t)$, the latter being the virtual error of the outer loop:

$$e_{oV}(t) = (M_o^{-1}(z) - 1)y_o(t).$$

The optimal filters for the inner and outer loop are discussed in [7], following the rationale of [3].

V. EXPERIMENTAL RESULTS

A. *Tuning experiments*

The identification experiments have been carried out indoor, operating the quadrotor on the test-bed depicted in Figure 1, which constrains all translational and rotational degrees of freedom, except for pitch rotation, applying as excitation signal a PRBS (Pseudo Random Binary Sequence) in quasi open-loop conditions: while the nominal attitude and position controllers were disabled, a supervision task enforcing attitude limits during the experiment was left active (maximum attitude excursion guaranteed from adopted test-bed is $\pm 20°$). The parameters of the PRBS sequence (signal amplitude and min/max switching interval) were tuned to obtain an excitation spectrum consistent with the expected dominant attitude dynamics. During the tests, the pitch

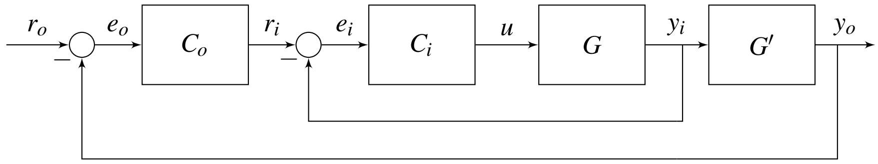

Fig. 3. Cascade control scheme with two nested loops.

angular velocity and the pitch angle, measured by the on-board IMU, were logged with sampling time equal to 0.02 s, together with the control variable (see Figure 4).

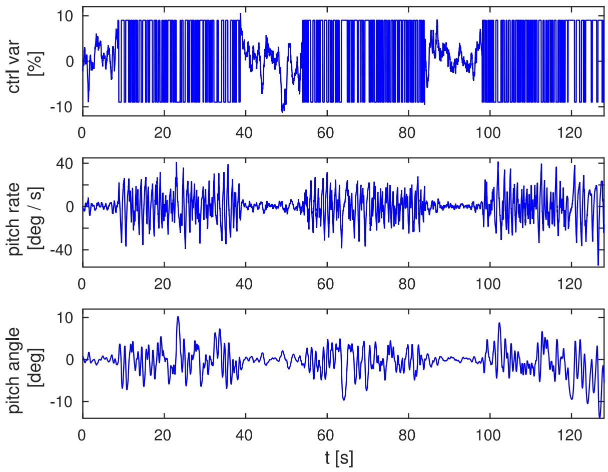

Fig. 4. Open-loop experimental dataset used for VRFT controller tuning.

B. Controller design

The input-output data collected in the above-described experiments have been then used to tune the cascade pitch attitude control loop via the VRFT approach. As discussed in Section IV, VRFT is essentially a model-reference approach, so from the user's perspective the main degree of freedom in the design procedure is the selection of the reference model. The design of $M_i(z)$ and $M_o(z)$ requires some prior knowledge about the system to be controlled (such as, *e.g.*, achievable closed-loop bandwidth, dominant dynamics, presence of time-delays). Without this information, obtaining a satisfactory tuning can be challenging, as the choice of an unattainable closed-loop reference model can lead to poor performance (not unlike erroneous structure selection in model identification problems). As a consequence, some level of interaction in the definition of the reference models has to be anticipated. Note that the amount of prior information needed to apply this approach is significantly smaller than the one needed in a model-based framework and is usually available from the plant manufacturer or can be obtained with simple open-loop or closed-loop tests. In the present study, the results of previous work on model identification for the P2-A1 platform (see [17]) provided significant insight in the definition of the structure for the reference models. In particular, the reference models $M_i(z)$ and $M_o(z)$ for, respectively, the inner and the outer control loop, have been defined on the basis of available requirements for the desired bandwidth and damping factor of the inner and outer complementary sensitivity functions. More precisely, the desired bandwidth of the inner loop is set to 25 Hz while the one of the ideal outer loop is of 20 Hz. $M_i(z)$ and $M_o(z)$ have been defined as second order systems with a damping ratio of 0.7 and a time delay of 3 samples (corresponding to 0.06 s and representing the overall delay of the control loop, as mentioned in Section II).

The reference models of the two control loops used to compute the virtual reference signals are:

$$M_i(z) = \frac{0.09833z + 0.07778}{z^2 - 1.32z + 0.4966}\frac{1}{z^3}$$
$$M_o(z) = \frac{0.06609z + 0.05481}{z^2 - 1.45z + 0.5712}\frac{1}{z^3}$$

As for the weighting functions $W_i(z)$ and $W_o(z)$ defining, respectively, the model reference cost function (1) for the inner and the outer loops, they have been chosen as $W_i(z) = 1$ and $W_o(z) = 1$.

Since the experimental data are affected by noise, as already mentioned, the VRFT algorithm used in this work implements an instrumental variable method to counteract the effect of noise (see [3]). The instrumental variable is constructed through the identification of simple ARX models for the inner and the outer loops. It is important to note that the estimated plant is used only to generate the instrumental variable and good performance can be achieved also considering inaccurate models of low order (this is instead not the case if such models are used for control design).

C. Validation experiments

To make the obtained results as representative as possible, during the experiments all four rotors are working, with a base collective pitch command of 60% that guarantees a total thrust equal to the vehicle weight (hovering), and only the pitch attitude controller is enabled. Two types of tests have been performed:

- set-point tracking evaluation: a desired pitch angle command history was assigned manually by the operator, with step amplitudes of 5 deg and 10 deg;
- load disturbance rejection evaluation: in order to simulate on the test-bed the effect of a wind gust, a rope was fixed at the tip of the front (or back) vehicle arm, with a weight of 0.7 kg at the end. The operator can act manually on the weight in order to engage/disengage its effect, applying and maintaining the disturbance torque for about 10 s and then suddenly releasing it. A null angular set-point is required throughout the operations.

Concerning the control variable allocation, the 60% of maximum thrust on all rotors is used to maintain hovering flight, then the remaining 40% is shared between the DoFs controllers for maneuvering as follows: 10% increment/decrement equal on each rotor for climb/descent, 15% used differentially (plus and minus) on opposite rotors for roll/pitch control and 15% used differentially on clockwise and counterclockwise pairs of rotors for yaw control. This determines that the nominal saturation limit for pitch control variable is equal to 30%. It is worth to observe that in load disturbance test results (see Figures 8, 9 and 10), for all the considered tuning set, the control variable overcomes the saturation limit: the control allocation routine gives priority to roll/pitch attitude degrees of freedom, allowing an enlarged margin on demand by subtracting it from the yaw and vertical degrees of freedom (in this order). Hence the applied load disturbance is representative of an heavy wind gust, testing the limit of vehicle capabilities.

D. Results and comparison

In Table I the resulting parameters for both the outer loop PD and the inner loop PID controllers (proportional K_p, derivative K_d, integral K_i gains and first-order derivative filter time constant T_f in seconds) are listed, as obtained with the VRFT approach[1]. The standard tuning obtained through the manual procedure and the one from structured H_∞ synthesis are also reported.

Controller parameter	Standard tuning	H_∞ tuning	VRFT tuning
K_p PD	9.26	4.7314	5.6364
K_d PD	1.11	0.8453	0.3683
T_f PD	0.03	0.0364	0.038
K_p PID	0.257	0.3297	0.4979
K_i PID	0.643	1.6186	2.0685
K_d PID	0.0231	0.0079	0.0111
T_f PID	0.0225	0.0510	0.043

TABLE I

TUNING PARAMETERS FOR OUTER LOOP PD AN INNER LOOP PID CONTROLLERS FROM CONSIDERED TECHNIQUES.

Figures 5, 6 and 7 show the set-point tracking test of the manual, the model-based H_∞ and the VRFT tuning. As can be seen from the figures, the H_∞ approach provides the best performance whereas the VRFT method performs better than manual approach. This confirms that the VRFT approach can lead to a satisfactory closed-loop performance level starting from a limited prior knowledge about the plant. When considering the load disturbance rejection test (Figures 8, 9 and 10), the performance of the H_∞ and VRFT controllers are similar and represent a significant improvement with respect to the one of the manually tuned controller. As can be seen from the figures, however, this comes with a cost in terms of increased control effort with respect to the standard method.

[1]The time constant T_f for the derivative filters has not been tuned via the VRFT approach but its value has been fixed considering the results of the model-based approach.

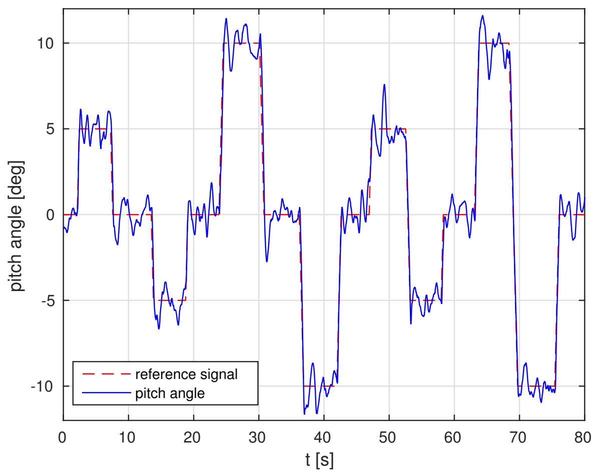

Fig. 5. Set-point tracking with manual tuning.

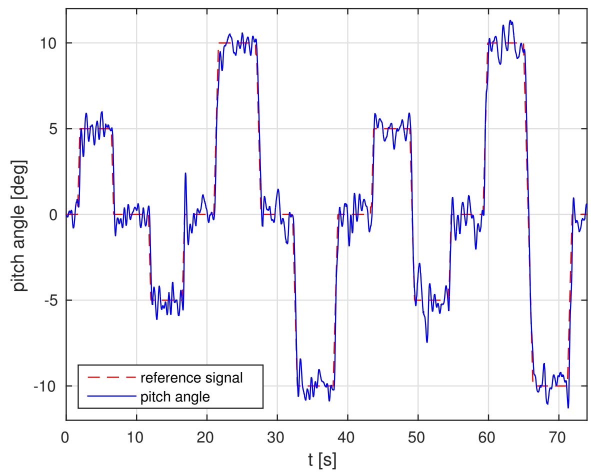

Fig. 6. Set-point tracking with model-based H_∞ tuning.

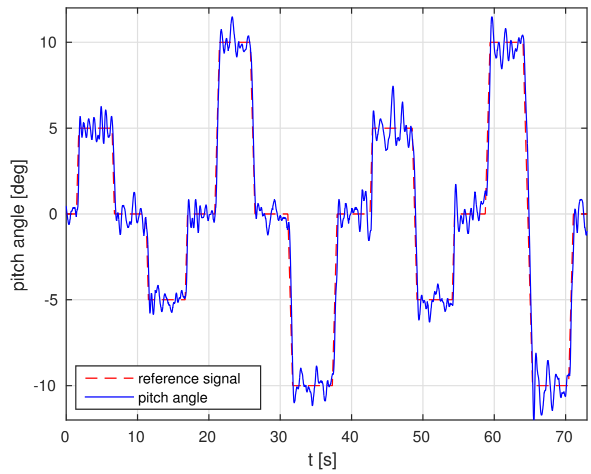

Fig. 7. Set-point tracking with VRFT tuning.

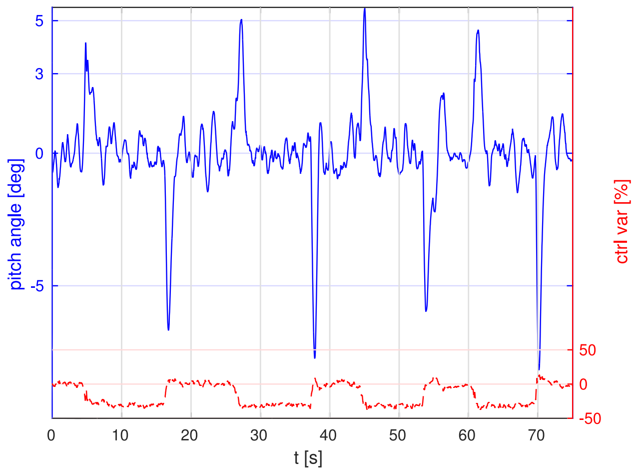

Fig. 8. Load disturbance rejection with manual tuning. Blue solid line: pitch angle, red dashed line: control variable.

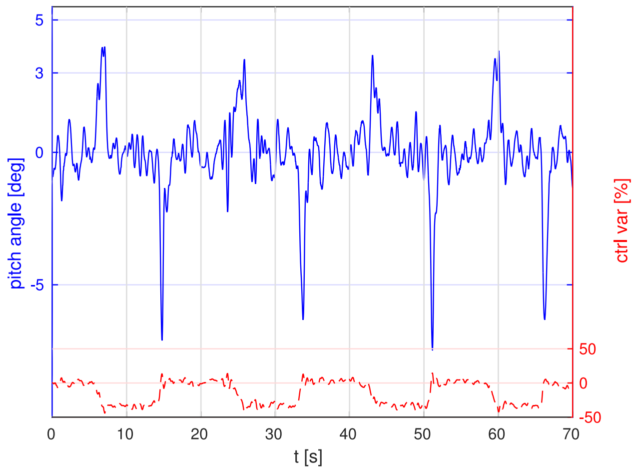

Fig. 9. Load disturbance rejection with model-based H_∞ tuning. Blue solid line: pitch angle, red dashed line: control variable.

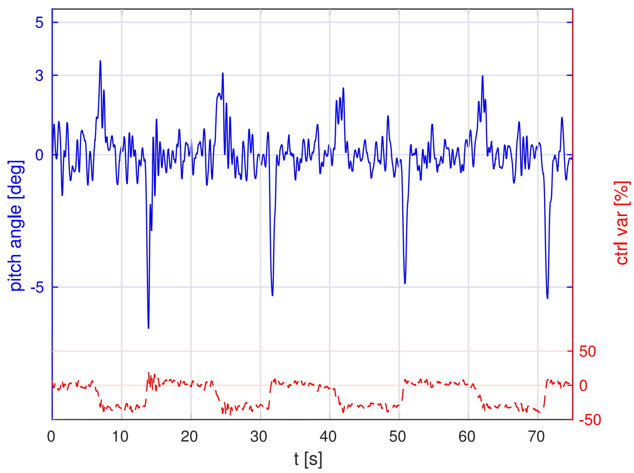

Fig. 10. Load disturbance rejection with VRFT tuning. Blue solid line: pitch angle, red dashed line: control variable.

VI. CONCLUSIONS

The problem of tuning the attitude controller of a variable-pitch quadrotor has been considered and a data-driven approach based on the VRFT method has been proposed. It has been shown that the VRFT algorithm can be successfully applied to tune a cascade control system and that the designed controller provides a performance level comparable with the one of a model-based H_∞ controller. In particular, the data-driven controller presents good tracking and disturbance rejection capabilities and therefore represents a viable solution for the fast deployment of high performance attitude controllers for this platform.

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