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Control Strategies for Unmanned Aerial Vehicles under Parametric Uncertainty and Disturbances: a Comparative Study.

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Abstract: UAVs within the class of Mini Aerial Vehicles (MAVs) are autonomous aircrafts with low inertias that fly at relatively low speeds. In this sense, MAVs are exposed to high airspeed uncertainties since unexpected changes in wind velocity represent an important percentage of the total airspeed of the vehicle. Moreover, such changes directly modify the aerodynamic forces acting along the vehicle, which leads to important variations on their acceleration owed to their low inertia. Although the structure of the dynamic model of an aircraft is well known, important difficulties arise on the identification of an specific MAV due to its particular characteristics. Thus, modelling errors become an additional source of uncertainty when control algorithms are designed. In this situation, studying the ability that different control strategies present in performing trajectory tracking is of great interest on the development of applications for this type of UAVs. In this paper a comparative study of four control strategies is presented. All algorithms have been implemented in a MAV flight computer. Results from both, Hardware-In-the-Loop (HIL) simulations and real flight experiments, are presented as the main contribution of this work.

Keywords: Aircraft control, Uncertain dynamic systems, LQR control, PID controllers, Predictive control, Multiobjective optimization.

1. INTRODUCTION

MAVs are UAVs with masses between 1 and 15kg on take off and flying altitudes up to 3000m (Maddalon et al., 2013). Those characteristics along with their relative low velocity compared to the wind speed make engineers confront to high uncertainties when system dynamics have to be identified. Although the structure of the dynamic model of an aircraft is well known, important difficulties arise on the particularisation of that structure to an specific MAV. These modelling errors become an important source of uncertainty when control algorithms are designed. Thus, the performance of a given control strategy might decrease significantly when implemented, compared to the observed behaviour by using the identified model.

In this paper a comparative study of four control strategies is presented: PID tuned by root locus, PID tuned by means of multiobjective optimization, a Linear Quadratic Regulator (LQR) and a Model Based Predictive controller (MPC). All algorithms have been implemented in a MAV flight computer. Comparison results between Hardware-In-the-Loop (HIL) simulations and real flight experiments are presented as the main contribution of this work.

This paper is divided in five sections as follows: in section 2 a complete description of the UAV is made, including a dynamic model of the system and its linearization; section 3 presents each of the control strategies implemented. Then, results from simulation and experimentation will be shown in section 4 and some final conclusions will be remarked in section 5.

2. UAV TESTBENCH

Three main points are develop along this section. Firstly, both simulation and flight experiments setups are introduced. Including on one side, the aircraft and its hardware components, and on the other, a HIL platform to previously test the designed control algorithms. HIL simulations, the designing process itself and the final controllers performance are mainly based and hence rely on a first principles model of the platform. Therefore that model structure is derived in the second point of this section. Finally, the last point of this section presents the linearisation of the equations presented in 2.2 which is used inside the MPC controller and in the LQR design.

2.1 Experiments and simulations setups

As the main component of the flight platform, a Kadett 2400 aircraft, manufactured by Graupner, is found. It is a light weight airframe with some features that make it suitable for the purposes of this research. Some of those characteristics are:

- 2.4m wing span.

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Fig. 1. Hardware in the loop simulations setup

- $0.9m^2$ wing area.
- $49g/dm^2$ weight/area ratio.
- $16.5l$ free volume.

It houses all necessary devices for its control, not only manually, but also in autonomous mode. During flight, three control surfaces are provided: tail rudder, elevators and ailerons. As the unit of propulsion a brushless engine of alternating current is integrated, which is fed by two LIPO batteries through a frequency variator. Alike the servomotors, the variator is controlled by sending Pulse Width Modulated (PWM) signals as commanding signals.

There exists a bridge device between the manual and the autonomous states. The Servo Switch Controller (SSC) is able to perform the commutation between different command sources. Moreover, it offers the possibility of measuring the applied deflections in control surfaces and changes in the motor torque.

Control actions are sent from the Flight Control Station (FCS), constituted by a Beagle Bone Black (BBB) [1] board. This unit houses the control algorithms and performs all necessary tasks at each phase of the flight. The loop is closed by the GPS-AHRS IG500N [2] unit. It is a all-in-one device, which joins the efforts of a wide range of sensors, such as accelerometers, gyroscopes and magnetometers. Its Kalman filter is capable of mixing the information coming from those sensors in order to offer precise measurements of position, orientation, linear and angular speeds and accelerations, in the three aircraft body-axes. In Velasco et al. (2012); Velasco et al. (2013); Velasco (2013); Velasco and García-Nieto (2014) is presented this platform with more details together with the results of the first flight tests.

Regarding the HIL simulation setup (Fig. 1), a National Instruments PXI with a real time running model substitutes most of the hardware components, with the exception of the FCS. In this way, the control algorithms are implemented in the BBB and executed exactly as they will be during real flight experiments. This strategy of simulation increases the confidence on the designed controllers by assuring a higher level of safety in the hop from simulation to experimentation.

2.2 Aircraft Dynamic Model

Its particularization to our aircraft is the result of previous works published by the authors and has proved to accurately describe the vehicle dynamics.

The dynamic model will not only be used for simulations in the design stage of control algorithms, but also part of the control algorithm in the MPC strategy. Hence the expressions that relate the input variables, deflection in the control surfaces and motor load, to a series of output signals such as linear and angular velocities and acceleration, and position in a 3D space, will have a direct impact in some of the controllers developed.

Linear and angular momentum conservation principles conform the starting point to derive such model (Klein and Morelli, 2006):

$$\sum_{ext} \overrightarrow{F} = \frac{d}{dt}(m\overrightarrow{V}) \tag{1}$$

$$\sum_{ext} \overrightarrow{M} = \frac{d}{dt}(I\overrightarrow{\omega}) \tag{2}$$

where (1) and (2) deal with the sum of external forces and moments respectively; m and I are the mass and the inertia tensor of the aircraft, and $\overrightarrow{V}$ and $\overrightarrow{\omega}$ are linear and angular velocity vectors. In particular three are the types of external forces that affect to the behaviour of the vehicle: aerodynamic force (F_A), force applied by the motor (F_T) and the gravitational force (F_G). At the same time, two different sources can be counted as torque generators: the air flow -generating aerodynamic torque (M_A) and the motor moment (M_T). Thereby, the equations (1) and (2) can be rewritten as:

$$\overrightarrow{F_A} + \overrightarrow{F_T} + \overrightarrow{F_G} = m\dot{\overrightarrow{V}} + \overrightarrow{\omega} \times m\overrightarrow{V} \tag{3}$$

$$\overrightarrow{M_A} + \overrightarrow{M_T} = I\dot{\overrightarrow{\omega}} + \overrightarrow{\omega} \times I\overrightarrow{\omega} \tag{4}$$

The two previous equations are actually vectorial equations, so that, there is a total of 6 equations that correspond to the 6 degrees of freedom of a rigid body in the space. Deriving (3) and (4) the following expressions are obtained:

$$\begin{aligned} \bar{q}S \begin{bmatrix} C_X \\ C_Y \\ C_Z \end{bmatrix} + \begin{bmatrix} -g\sin\theta \\ g\sin\phi\cos\theta \\ g\cos\phi\cos\theta \end{bmatrix} + \begin{bmatrix} T \\ 0 \\ 0 \end{bmatrix} \\ = m \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times m \begin{bmatrix} u \\ v \\ w \end{bmatrix} \end{aligned} \tag{5}$$

$$\begin{aligned} \bar{q}S \begin{bmatrix} bC_l \\ \bar{c}C_m \\ bC_n \end{bmatrix} + \begin{bmatrix} 0 \\ I_p\Omega_p r \\ -I_p\Omega_p q \end{bmatrix} = \begin{bmatrix} I_x & 0 & -I_{xz} \\ 0 & I_y & 0 \\ -I_{zx} & 0 & I_z \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \\ + \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} I_x & 0 & -I_{xz} \\ 0 & I_y & 0 \\ -I_{zx} & 0 & I_z \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \end{aligned} \tag{6}$$

[1] http://www.beagleboard.org/

[2] http://www.sbg-systems.com/products/ig500n-miniature-ins-gps