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Nonlinear Dynamic Inversion and Neural Networks for a Tilt Tri-Rotor UAV

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Abstract: A small scale tri-rotor test bed with tilting propellers has been built to test flight control laws in view of the construction of a larger tilt rotor UAV. As a first step to achieve autonomous flight capabilities, a nonlinear dynamic inversion based flight controller is developed. This controller is designed on the basis of a time-scale principle with two levels. A lower level, fast control action, designed to achieve attitude control and stability goals, is driven by a higher level trajectory tracking control law. To achieve robust stability and performance in the presence of parametric variations and modelling uncertainties, an adaptive flight control law correction based on neural networks is investigated. A RBF neural network is implemented to mitigate the effects of imprecise inverse dynamics. The overall proposed flight controller performance are tested via numerical simulations on the mathematical model of the small scale tri-rotor. Preliminary results on the full tilt rotor are also shown.

Keywords: Unmanned Aerial Vehicle, Flight Control, Nonlinear Dynamic Inversion, Neural Networks, Adaptive Control.

1. INTRODUCTION

Tilt rotor aircrafts are versatile platforms capable of operating over a broad flight envelope from hovering conditions to forward flight speeds characteristic of fixed wing airplanes. The design of FCSs (Flight Control Systems) for this kind of UAVs (Unmanned Aerial Vehicles) can be very difficult due to their nonlinear dynamic response, the transition phase between hovering and forward flight, and the large cross coupling effects. Hovering and forward flight typically need a separate control strategy: in hover, only thrust vectoring can be used to control the aircraft acting as a multi rotor with tilting propellers, whereas in forward flight classical aerodynamic surfaces can be also used. During transition tilt rotors need a blending strategy, defining the control allocation to manage redundancies in control effectors.

Several approaches have been proposed in the literature for the flight control of small scale tilt rotors UAVs. Most of them have been tested in simulation with few flying platforms [Kang et al. (2008, 2012), Ta et al. (2012), Chowdhury et al. (2012), Yu et al. (2006), Amiri et al. (2012), Chen et al. (2005), Rysdyk et al. (1999), Wang (2013)].

One of the most promising and popular nonlinear techniques for flight control applications is dynamic inversion, already used for several multi-rotor hovering aircrafts. NDI (Nonlinear Dynamic Inversion) is a control technique which attempts to cancel out the inherent dynamics of a plant and enforce the dynamics of a reference model. The most important benefits of NDI are the ability to linearize systems, decouple controlled variables, separate reference model from dynamic inversion model and compute solution in a closed form. However NDI exhibits strong sensitivity to modelling errors and external disturbances. To reduce this sensitivity and solve the lack of control affinity problem, the technique can be improved using INDI (Incremental NDI) [Sieberling et al. (2010), Di Francesco et al. (2014)]. To face with this problem adaptive control is used in combination with NDI.

Neural Network adaptive control for aircrafts has been extensively studied with different strategies [Calise and Rysdyk (1997), Jonhson et al. (2000), Idan et al. (2001), Calise and Rysdyk (2005), Chowdhary and How (2012)]. In this paper, an adaptive flight control method based on RBF (Radial Basis Function) NN (Neural Network) and NDI is adopted to design attitude and trajectory tracking control actions for tilt rotor UAVs. This method can guarantee the convergence of tracking error also in the presence of modelling errors.

To demonstrate the effectiveness of the proposed control techniques during hovering and low speed flight phases a tri-rotor small scale UAV has been designed and built. This is a testing platform to be used in view of the construction of a large tilt-rotor UAV.

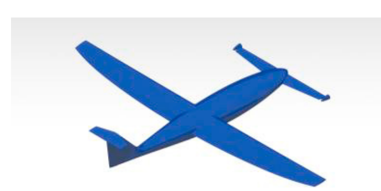

Fig. 1. Schematic view of the tilt rotor UAV.

The paper is organized as follows. In Section 2 the full tilt-rotor aircraft and the small scale testbed are presented. Section 3 describes the design of the nonlinear flight control algorithm. In Section 4 a direct neural network is added to the NDI controller scheme to improve the robustness to parametric and modelling uncertainties in the presence of wind disturbances. Finally in Section 5, simulation results are

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shown to prove the effectiveness of the scheme. Both simulation results on the small scale tri-rotor and preliminary results on the full scale tilt rotor UAV involving also transition from hovering to forward flight are discussed.

2. UAVs DESCRIPTION AND DYNAMIC MODEL

2.1 Full scale Tilt-rotor UAV

The final object of the research is the flight control of a tactical uninhabited vehicle capable of VTOL and primarily intended for medium endurance and short range surveillance, reconnaissance and patrolling missions. The aircraft is powered by two propellers located at the tips of a canard and a central ducted fan with dual counter–rotating rotors. The two front nacelles can be continuously tilted to independently change the thrust line of the two front propellers. Such propulsive configuration has been adopted to minimize the flow interaction between tilt rotors and aerodynamic surfaces, while maximizing propulsive efficiency. The central ducted dual fan, located near the CoG (Center of Gravity), provides most of the thrust required for hover and is optimized for such regime. The aircraft configuration is tricycle fixed gear with high aspect ratio canard and with high aspect ratio, straight leading edge, tapered, untwisted, high mounted wing with no dihedral.

2.2 Mini tri-rotor UAV

A tri-rotor with tilting propellers testbed has been designed and built. Mimicking the full tilt rotor describe in Section 2.1, this mini-UAV is powered by two front propellers and a rear one, at the tips of a T-shaped structure. The main difference with the full scale UAV is the lack of the central ducted fan replaced with a third rotor. All propellers are fixed pitch and powered by electrical brushless motors. The tilting of front propellers is provided by two position controlled angular servos. Electrical power is provided by Lithium-Polymer (Li–Po) batteries. An Inertial Measuring Unit (including three accelerometers, three gyros, GPS, magnetometer, barometer) feeds information to the FCS. Thanks to oversized motors, shifts of the CoG position can be tolerated. These can be obtained moving the Li-Po battery pack, in order to test the robustness of the controller to parametric variations of the system dynamics.

Fig. 2. Tilt tri-rotor experimental platform.

2.3 Tilt tri-rotor dynamic model

The mathematical model of UAVs is readily derived from the nonlinear six degree of freedom model of an aircraft. Two reference frames are used to study the system motion: an inertial earth frame E, and a body fixed frame B, where the origin O_B of body axis is assumed to be located in the CoG of the vehicle. The position in the earth frame E is defined as $\zeta = [x_E, y_E, z_E]^T$. The attitude such as roll, pitch, and yaw is denoted as $\Theta = [\phi, \vartheta, \psi]^T$ with respect to the frame B.

Table 1. Tilt-tri-rotor geometric and inertial parameters.

Name	Description	Value
m	Mass	2.3 kg
l_f	Distance of front props from CoG along x axis	0.3 m
l_r	Distance of rear prop from CoG along x axis	0.3 m
b	Distance of front props from CoG along y axis	0.3 m
I_{xx}	Body inertia of x axis	$8.04 \cdot 10^{-3} kgm^2$
I_{yy}	Body inertia of y axis	$8.46 \cdot 10^{-3} kgm^2$
I_{zz}	Body inertia of z axis	$14.68 \cdot 10^{-3} kgm^2$
τ_r	Time costant of rotor dynamics	0.01 s
k_f	Force coefficient	$5 \cdot 10^{-2}\ Ns^2$
k_t	Torque coefficient	$5 \cdot 10^{-4}\ Nms^2$
τ_s	Time costant of servo dynamics	0.01 s

Considering a rigid body UAV, its dynamic model in the body frame B can be written as:

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \frac{1}{m}\left(-\begin{bmatrix}p\\ q\\ r\end{bmatrix} \times \mathrm{m}\begin{bmatrix}u\\ v\\ w\end{bmatrix} + F(V_B, \Omega, \Theta, \zeta, \overline{\omega}, \gamma)\right) \quad (1)$$

$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} = I^{-1}\left(-\begin{bmatrix}p\\ q\\ r\end{bmatrix} \times I\begin{bmatrix}p\\ q\\ r\end{bmatrix} + T(V_B, \Omega, \Theta, \zeta, \overline{\omega}, \gamma)\right) \quad (2)$$

where m is the mass of aircraft, I is the inertia matrix, $V_B = [u, v, w]^T$ and $\Omega = [p, q, r]^T$ are the velocity and angular velocity vector in the B frame respectively.

The attitude dynamics can be expressed as a function of Ω as:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & sin\phi \cdot tan\theta & cos\phi \cdot tan\theta\\ 0 & cos\phi & -sin\phi\\ 0 & \dfrac{sin\phi}{cos\theta} & \dfrac{cos\phi}{cos\theta}\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (3)$$

In order to obtain the inertial position we also can write:

$$\begin{bmatrix}\dot{x}_E\\ \dot{y}_E\\ \dot{z}_E\end{bmatrix} = R_{BE}^{-1}(\phi, \theta, \psi)\begin{bmatrix}u\\ v\\ w\end{bmatrix} \quad (4)$$

where R_{BE} is the rotation matrix from the earth reference frame to body axis.

The external forces and moments in (1) and (2) depend on V_B, Ω, Θ, ζ, rotational speed of the propellers $\overline{\omega} = [\omega_1, \omega_2, \omega_3]^T$, and tilting angles of two front rotors $\gamma = [\gamma_1, \gamma_2]^T$.

The force vector F and the moment vector T are sums of different terms: