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Improved 3D trajectory tracking by Nonlinear Internal Model-Feedback linearization control strategy for autonomous systems

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Abstract: This paper presents a nonlinear controller for 3D trajectory tracking of an autonomous helicopter. The main idea consists of combining feedback linearization controller together with a novel nonlinear IMC control. This approach allows more robustness, fast and good trajectory tracking. It is applied to a small, eight-rotor, Square-Shaped Octo-Rotor and has shown satisfactory results using adequate control architecture. The controller effectiveness is shown through numerical simulations and confirmed using a software simulator and real tests.

Keywords: Nonlinear control, Autonomous system, Trajectory tracking.

1. INTRODUCTION

Rotorcrafts have many applications because of their vertical landing/take-off capability and payload. Among these rotorcrafts, Octo-Rotor helicopter may usually afford a larger payload than conventional helicopter due to the eight rotors. For these advantages, the Octo-Copter has received much interest from students and researchers where some models have been presented for different shapes (Star-Shaped: Alwi 2013; Stocia et al. 2012 and 4Y-shaped: Adir et al. 2012; ...).

In order to achieve complicated missions, it is necessary to design controller such that the system will be able to follow predefined trajectories, particularly, in the presence of disturbances. This is the reason for why many studies have led to the development of nonlinear control laws. The feedback linearization control law is, as known, one of the most popular nonlinear control methods, which has been the subject of many books (see for example Slotine et al. 2012; Khalil 2002, Isidori 1985). In addition, the nonlinear control results permit a global asymptotic stability provided that no singular points exist. Many controllers allow good set-point tracking. However, for almost all processes control, disturbance rejection is much more significant. Hence, controller design that emphasizes disturbance rejection rather than a good set point tracking is of a great interest and a real design problem. Our focus is consequently pushed on this last point. Among the large variety of control techniques available in the literature, a model based control method, namely the Internal Model Control (IMC), is popular in industrial process control applications (Muhammad et al. 2010) due to its disturbance rejection capability and robustness (Morari et al. 1989). The aim of this research work is to stabilize the helicopter while ensuring the tracking of complex trajectories with a precise way, and also to ensure a given level of robustness with respect to structured and unstructured uncertainties. For this purpose, a novel Nonlinear IMC-Feedback linearization control is herein described by taking care of having an adequate control structure.

This paper is organized as follows: Section 2 introduces the dynamics of the Octo-Rotor and its operating principle. Section 3 presents the synthesis of the so-called nonlinear IMC- feedback linearization control and its application is developed in section 4. In section 5, the controller effectiveness is shown through numerical simulations and confirmed by experimental tests under different operating conditions. Finally conclusions are given.

2. OCTOROTOR DYNAMICS

In this section, we give a brief explanation of the system used to obtain the complete model, and which describes the UAV's behaviour. The Octo-Copter is controlled by the angular speeds of eight electric motors. Each motor produces a thrust and a torque, whose combination creates the main thrust, the yaw, the pitch and the roll torques acting on the UAV. As shown in Fig. 1, the system operates in two coordinate frames: the earth fixed frame $R_0(O_0, X, Y, Z)$ and the body frame R_1 (O_1, X_1, Y_1, Z_1). Let $\chi = (x, y, z)^T \in R^3$ be the absolute position of the system and $\eta = (\varphi, \theta, \Psi)^T \in \left]-\frac{\pi}{2}, +\frac{\pi}{2}\right[\times \left]-\frac{\pi}{2}, +\frac{\pi}{2}\right[\times \left]-\pi, +\pi\right[$ be the Euler angles (roll, pitch, and yaw) that describe the orientation of the aircraft. In order to obtain a usable model for the control synthesis of control laws, it is necessary to make a certain number of approximations and assumptions.

Assumptions:

1) The structure and propellers are rigid and perfectly symmetrical
2) The gyroscopic and ground effects are neglected.

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3) The UAV has very small upper bounds on $|\varphi|$ and $|\theta|$ in such a way that the differences $|\varphi| - sin(\varphi)$ and $|\theta| - tan(\theta)$ are arbitrarily small.

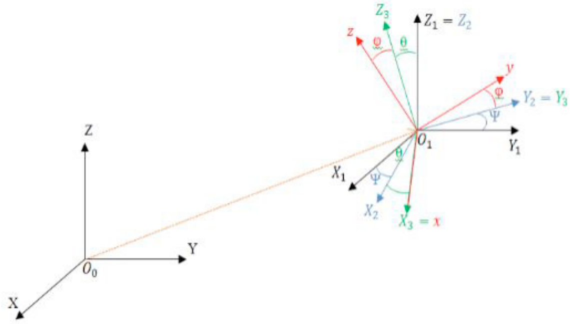

Fig. 1. Frames representation.

The dynamic model of the Octo-Rotor is classically derived from the Newton-Euler law. Gravity force acts on the center of mass in the negative Z direction in the earth frame. The global thrust is in the positive Z direction of the body frame. Therefore, the translational dynamic equations of the Octo-Copter can be expressed in earth frame as follows,

$$m\ddot{\chi} = (-mg + u_T R)e_z \tag{1}$$

, using the rotation matrix R ∈ SO(3):

$$R(\varphi,\theta,\Psi) = \begin{bmatrix} c_\Psi c_\theta & c_\Psi s_\theta s_\varphi - s_\Psi c_\varphi & c_\Psi s_\theta c_\varphi + s_\Psi s_\varphi \\ s_\Psi c_\theta & s_\Psi s_\theta s_\varphi + c_\Psi c_\varphi & s_\Psi s_\theta c_\varphi - c_\Psi s_\varphi \\ -s_\theta & c_\theta s_\varphi & c_\theta c_\varphi \end{bmatrix}$$

$s_{()}$ and $c_{()}$ are abbreviations for sin(.) and cos(.) respectively. Where g denotes the gravity acceleration, m the mass, $e_z = (0,0,1)^T$ the unit vector expressed in the earth frame, and u_T the global thrust produced by the eight rotors of speeds Ω_i. Each motor M_i (for $i = 1, \dots, 8$) produces the thrust force T_i , so that

$$u_T = \sum_{i=1}^{i=8} T_i = b \sum_{i=1}^{i=8} \Omega_i^2 \tag{2}$$

Where b is the thrust factor.

Yaw motion is generated by the differential drag forces D_i. Pitch and Roll motions, are created as the difference in combined thrust for opposite sides of the vehicle,

$$D_i = d\Omega_i^2 \quad i = 1, \dots, 8 \tag{3}$$

Where d is the drag factor.

The rotational dynamic equation of an Octo-Rotor can be written as follows:

$$I\dot{\varpi} = -\varpi \times I\varpi - G_a + \tau \tag{4}$$

Where $\varpi = (\varpi_x, \varpi_y, \varpi_z)^T$ is the angular velocity vector, $I = diag(I_x, I_y, I_z)$ is the diagonal inertia matrix and G_a is the gyroscopic effect, while τ is the control torque obtained by varying the rotor speeds. $\tau = (\tau_\varphi, \tau_\theta, \tau_\Psi)^T$ is defined for square shaped Octo-Copter as

$$\begin{pmatrix} \tau_\varphi \\ \tau_\theta \\ \tau_\Psi \end{pmatrix} = \begin{pmatrix} L(T_7 - T_3) + l\frac{\sqrt{2}}{2}(T_6 + T_8 - T_2 - T_4) \\ l\frac{\sqrt{2}}{2}(T_6 + T_4 - T_2 - T_8) - L(T_1 - T_5) \\ l(D_2 + D_4 + D_6 + D_8) - L(D_1 + D_3 + D_5 + D_7) \end{pmatrix} \tag{5}$$

Where L represents the distance from the motors placed on the long arms to the center of mass and l the distance from the motors placed on the short arms (see Fig. 2). The gyroscopic effects G_a are neglected according to assumption (2) considered above. Also, translational velocity and acceleration are defined in the earth fixed frame R_0, and angular velocity and acceleration are defined in the body fixed frame R_1.

$$\dot{\varpi} = I^{-1}(-\varpi \times I\varpi + \tau) \tag{6}$$

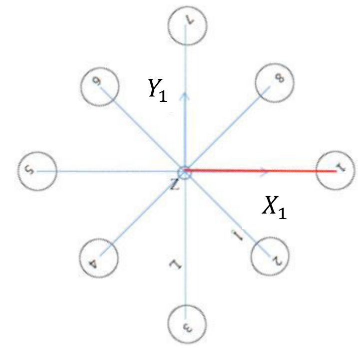

Fig. 2. Simplified diagram of the drone with 8 propellers.

Regarding the angular dynamics, the angular velocities of the drone ϖ are transformed into Euler angular speeds $\dot{\eta}$. This yields

$$\begin{pmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\Psi} \end{pmatrix} = \begin{bmatrix} 1 & s_\varphi \tan\theta & c_\varphi \tan\theta \\ 0 & c_\varphi & -s_\varphi \\ 0 & s_\varphi / c_\theta & c_\varphi / c_\theta \end{bmatrix} \begin{pmatrix} \varpi_x \\ \varpi_y \\ \varpi_z \end{pmatrix} \tag{7}$$

Then, by using equations (1-7) and accepting assumption (3), the dynamic model of the vehicle in terms of position χ and rotation η is finally written as

$$\ddot{\chi} = \begin{cases} \dfrac{c_\Psi s_\theta c_\varphi + s_\Psi s_\varphi}{m} u_T \\ \dfrac{s_\Psi s_\theta c_\varphi - c_\Psi s_\varphi}{m} u_T \\ -g + \dfrac{c_\theta c_\varphi}{m} u_T \end{cases} \tag{8}$$

$$\ddot{\eta} = \begin{cases} \dot{\theta}\dot{\Psi}\left(\dfrac{I_y - I_z}{I_x}\right) + \dfrac{\tau_\varphi}{I_x} \\ \dot{\varphi}\dot{\Psi}\left(\dfrac{I_z - I_x}{I_y}\right) + \dfrac{\tau_\theta}{I_y} \\ \dot{\varphi}\dot{\theta}\left(\dfrac{I_x - I_y}{I_z}\right) + \dfrac{\tau_\Psi}{I_z} \end{cases} \tag{9}$$

3. NON LINEAR CONTROLLER DESIGN

3.1 Nonlinear IMC design procedure

Let us recall, for a linear system, quite briefly the IMC basic principle: if the control system, contains partial or complete representation of the process to be controlled, then accurate control can be achieved. In Fig. 3, $U(s)$ is the input of both process $G(s)$ and its model $\tilde{G}(s)$. $D(s)$ is an unknown disturbance acting on the system. The output $Y(s)$ is compared with the output of the model $Y_m(s)$, resulting in a signal $\tilde{Y}(s)$, that is,

$$\tilde{Y}(s) = \left(G(s) - \tilde{G}(s)\right)U(s) + D(s) \tag{10}$$