

A novel hybrid back-stepping and fuzzy logic control strategy for a quadcopter

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ABSTRACT

This article aims to present a novel control strategy for quadrotor helicopter. It is composed of three main parts constituting the system modelling, the integral back-stepping control, and fuzzy logic compensator. In the first part, a non-linear model is presented taking in consideration some non-linearities and variables that are usually neglected. In the second part, a controller based on the integral back-stepping algorithm has been developed for the system in order to make the system follows a desired path. However, due to complexity of paths and to the presence of unknown disturbances, a fuzzy logic compensator is added in parallel to the integral back-stepping controller to improve trajectory tracking in some critical conditions (high wind speed, mass variation, etc.). Simulation results have been presented to show the effectiveness of the proposed approach.

Keywords: Quadrotor modelling; Integral Back-stepping; Fuzzy Logic

1.0 INTRODUCTION

Quadcopter designs have become popular in Unmanned Aerial Vehicle (UAV) research. UAVs are used in military and civil scopes, focusing on tasks such as searching, rescue, vigilance, inspection, and so on. These vehicles are under actuated mechanical systems, which complicates the control design stage. Techniques developed for fully actuated robots cannot be directly applied to the under actuated non-linear mechanical systems⁽¹⁾. Therefore, non-linear modelling techniques and modern non-linear control theory are usually employed to achieve autonomous flight with high performance⁽²⁾.

Many efforts have been made to control the quadrotor helicopter and many strategies have been developed in order to solve the path tracking problem for this type of system⁽³⁻⁷⁾. In Ref. 8, a non-linear model was proposed, presenting the helicopter kinematics and dynamics based on Newton-Euler formalism.

The aerodynamic forces and moments acting on this model were considered. The path tracking problem and state observation were solved using exact linearisation techniques⁽⁹⁾ and non-interacting control via dynamic feedback. In Ref. 10, the same methodology was used to obtain its motion equations, but considering also the rotor dynamics. The system equations were written in state space for the controller design. In Ref. 11, a strategy to control mechanical systems considering the tracking error dynamic equation was proposed. In such strategies, a non-linear H_∞ control, formulated via game theory, was applied. This strategy provides, by an analytical solution, a constant gain similar to the results obtained with the feedback linearisation procedures. In Ref. 12, a nested saturations control to move a quadrotor to a position and stabilise its attitude has been proposed. In Refs 13 and 14, Altug et al. used the back-stepping method to stabilise a quadrotor by keeping the positions and the yaw angle constant and the pitch and the roll angle zero. In Ref. 15, Tayebi et al. proposed a controller based on the compensation of the Coriolis and gyroscopic torques to stabilise the attitude of a quadrotor as it vertically takes off and lands. Bouabdallah et al. mechanically designed, dynamically modelled and used non-linear control techniques in their works^(16,17). Beji et al.⁽¹⁸⁾ presented structure and control of a quadrotor where two rotors are bidirectional. In Ref. 19, an adaptive sliding mode control for quadrotor has been presented. Romero et al.⁽²⁰⁾ used a simple vision system for a quadrotor's local positioning and orientation in indoor flight. Castillo et al.⁽²¹⁻²³⁾ used a Lagrangian model of the quadrotor and the control is based on Lyapunov analysis.

Back-stepping is a technique developed for designing a stabilising controller for a certain class of non-linear systems. It has a recursive structure, in which the existing states of the first-order model are recursively used to stabilise the steady motion of the second-order model. With the back-stepping techniques, we are able to elegantly reject strong disturbances, but stabilisation in hover flight was delicate. Another improvement is now introduced thanks to Integral Back-Stepping (IBS). The idea of using integral action in the back-stepping design was first proposed in Ref. 50 and applied in Ref. 51. In fact, back-stepping is well suited for the cascaded structure of the quadrotor dynamics. Moreover, the controller design process can be straightforward if done properly. In addition, this method guarantees asymptotic stability and has robustness to some uncertainties, while the integral action cancels the steady state errors.

The back-stepping controller is popular for its path tracking abilities, stability and speed. However, in cases of undeterminable disturbances caused by natural and synthetic external unrespectable forces such as wind, loads and inertia calculation error, the back-stepping controller abilities starts to fail as a cause of its high dependency upon the physical model. As

a result, we need a hand, a compensation from a more independent controller, which is in this case the Fuzzy Logic Compensator.

Fuzzy logic^(24–26) is a mathematical method that can be utilised to transform an inexact knowledge into the form of a computer algorithm. The first fuzzy control application belongs to Mamdani and Assilian⁽²⁷⁾. The fuzzy control applications in several domains begin with electrical household industry and consumer electronics up to other industries like mechanical and robotic systems, power plants and systems, telecommunications, transportation systems, automotive systems, chemical processes and nuclear reactors^(28–33). The control approach based on human experience is acting in fuzzy controllers by expressing the control requirements and elaborating the control signal in terms of the natural If-Then rules^(34,35).

Fuzzy Logic Controllers (FLCs) are successfully applied to control quadrotor. In Ref. 36, a Mamdani type of fuzzy inference is used to control quadrotor, and in Ref. 37 the comparison of Mamdani and Takagi-Sugeno-Kang (TSK) fuzzy controllers is conducted. In this paper, fuzzy logic was utilised for building up compensator of uncertainties. The proposed compensator corrects corresponding compensatory force and moment commands provided by the dynamic controller, on the base of trajectory tracking errors.

In this paper, a non-linear model for the quadrotor has been developed to simulate the dynamics of the Quadrotor. This model is based on several bibliographical studies, as presented in Refs 4–7, 21–23, and 38–45, and takes into consideration most of the non-linearities characterising its motion in order to have a simulator as close as possible to the real Quadrotor. In fact, we have identified the coefficients of this model using experimental data presented in references^(46,47). After identifying the coefficients of the model, we have used it to develop the IBS controller in order to ensure that it will track a desired path. The presence of a complex trajectories and unknown disturbances motivated us to propose a fuzzy compensator in parallel with the IBS controller.

2.0 MODEL

A quadrotor is a helicopter with four rotors. Rotor speeds are controlled to produce the desired lift force. It is an under-actuated system, dynamic vehicle with four input forces and six outputs. Basic motions of a quadrotor can be described as follows. Vertical motion can be achieved by increasing or decreasing the speed of the four rotors. Motion along the x axis and y axis can be obtained through a differential control strategy of the lift force by each rotor. In order to avoid the yaw drift due to the reactive torques, the quadrotor aircraft is configured such that one set of rotors (rotors 1 and 3) rotate clockwise and the other set of rotors (rotors 2 and 4) rotate counter-clockwise. There is no change in the direction of rotation of the all rotors. The yaw motion can be obtained by increasing the speed of one set of rotors and decreasing the speed of other set of rotors. Adding to that, the fact that the total lift force is maintaining unchanged in order to avoid the up-down motion⁽⁴⁸⁾. Let us consider earth-fixed frame E and a body-fixed frame B as shown in the Fig. 1.

From the classical control theory, the rotation matrix from frame B to frame E is given by:

$$R = \begin{pmatrix} c\theta.c\psi & s\phi.s\theta.c\psi - s\psi.c\phi & s\psi.s\phi + s\theta.c\psi.c\phi \\ c\theta.s\psi & c\theta.c\psi + s\theta.s\phi.s\psi & s\theta.s\phi.c\psi - c\psi.s\phi \\ -s\theta & c\theta.s\phi & c\phi.c\theta \end{pmatrix}, \quad \dots (1)$$

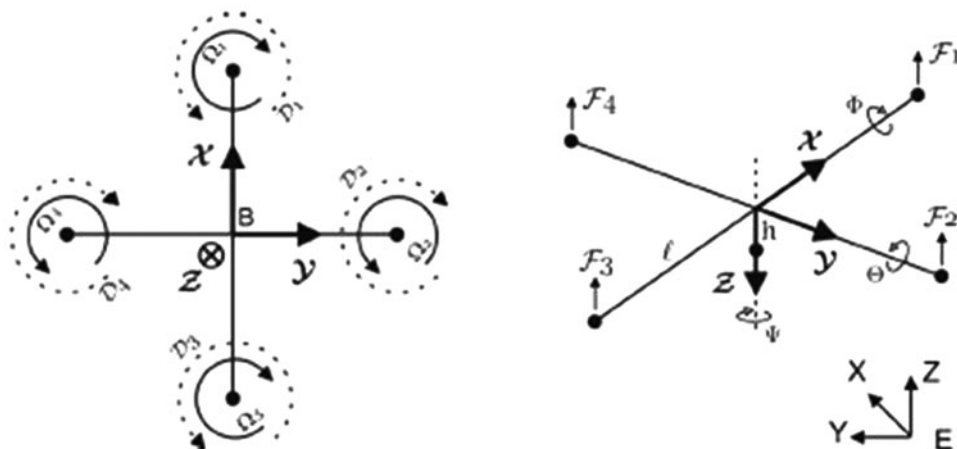


Figure 1. Quadrotor coordinate system.

where $c(\cdot) = \cos(\cdot)$ and $s(\cdot) = \sin(\cdot)$. ϕ is the angular rotation about X axis or roll angle, θ is the angular rotation about the Y axis or pitch angle, and ψ is the angular rotation about Z axis or yaw angle (Fig. 1).

2.1 Aerodynamic forces and moments

The aerodynamic forces and moments are derived using a combination of momentum and blade element theory. For an easier reading of the equations below, we recall some symbols: σ solidity ratio, a lift slope, μ advance ratio, λ inflow ratio, v induced velocity, ρ air density, R_{rad} rotor radius, l distance propeller axis-COG (Centre Of Gravity), θ_0 pitch of incidence, θ_{tw} twist pitch, \bar{C}_d drag coefficient at 70% radial station.

Ω_i is the angular rotation of the blade element. The Thrust force T_i is the resultant of the vertical forces acting on all the blade elements 'i':

$$\begin{cases} T_i = C_T \rho A (\Omega_i R_{\text{rad}})^2 \\ \frac{C_T}{\sigma a} = \left(\frac{1}{6} + \frac{1}{4}\mu^2\right)\theta_0 - (1 + \mu^2)\frac{\theta_{\text{tw}}}{8} - \frac{1}{4}\lambda \end{cases} \quad \dots (2)$$

Hub force H_i is the resultant of the horizontal forces acting on all the blade elements 'i':

$$\begin{cases} H_i = C_H \rho A (\Omega_i R_{\text{rad}})^2 \\ \frac{C_H}{\sigma a} = \frac{1}{4a}\mu\bar{C}_d + \frac{1}{4}\lambda\mu\left(\theta_0 - \frac{\theta_{\text{tw}}}{2}\right) \end{cases} \quad \dots (3)$$

Drag moment Q_i is caused by the aerodynamic forces acting on the blade elements 'i'. It determines the power required to spin the rotor:

$$\begin{cases} Q_i = C_Q \rho A (\Omega_i R_{\text{rad}})^2 R_{\text{rad}} \\ \frac{C_Q}{\sigma a} = \frac{1}{8a}(1 + \mu^2)\bar{C}_d + \lambda\left(\frac{1}{6}\theta_0 - \frac{\theta_{\text{tw}}}{8} - \frac{1}{4}\lambda\right) \end{cases} \quad \dots (4)$$

Rolling moment R_{mi} is the integration over the entire rotor of the lift of each section acting at a given radius (not to be confused with the overall rolling moment):

$$\begin{cases} R_{mi} = C_{R_m} \rho A (\Omega_i R_{\text{rad}})^2 R_{\text{rad}} \\ \frac{C_{R_m}}{\sigma a} = -\mu \left(\frac{1}{6} \theta_0 - \frac{\theta_{\text{tw}}}{8} - \frac{1}{8} \lambda \right) \end{cases} \quad \dots (5)$$

Ground effect is related to a reduction of the induced airflow velocity. The principal need is to find a model of this effect for quadrotor to improve the autonomous take-off and landing controllers. A simple way to proceed is to consider that the inflow ratio In Ground Effect (IGE) as: $\lambda_{\text{IGE}} = (v_{i,\text{IGE}} - \delta v_i - \dot{z}) / \Omega_i R_{\text{rad}}$, where the variation of the induced velocity is $\delta v_i = v_i / (4z / R_{\text{rad}})^2$.

We can then rewrite the thrust coefficient IGE as follows:

$$\begin{cases} T_{\text{IGE}} = C_T^{\text{IGE}} \rho A (\Omega_i R_{\text{rad}})^2 \\ \frac{C_T^{\text{IGE}}}{\sigma a} = \frac{C_T^{\text{IGE}}}{\sigma a} + \frac{\delta v_i}{4\Omega_i R_{\text{rad}}} \end{cases} \quad \dots (6)$$

2.2 General moments and forces

Quadrotor motion is obviously caused by a series of forces and moments coming from different physical effects. In this section, moments and forces are presented. J is the inertia matrix of the quadrotor used in the model:

$$J = \begin{pmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{pmatrix}$$

I_{xx} , I_{yy} , I_{zz} are the moments of inertia about X , Y , Z axis, respectively.

The rolling moments have the following components:

1. Body gyro effect:

$$\dot{\theta} \dot{\psi} (I_{yy} - I_{zz})$$

2. Rolling moment due to forward flight:

$$(-1)^{i+1} \sum_{i=1}^4 R_{mxi}$$

3. Propeller gyro effect:

$$J_T p \dot{\theta} \Omega_r$$

4. Hub moment due to sideward flight:

$$h \left(\sum_{i=1}^4 H_{yi} \right)$$

5. Roll actuators action:

$$l(-T_2 + T_4)$$

The pitching moments are as following:

1. Body gyro effect:

$$\dot{\theta}\dot{\psi}(I_{zz} - I_{xx})$$

2. Rolling moment due to forward flight:

$$h \left(\sum_{i=1}^4 H_{xi} \right)$$

3. Propeller gyro effect:

$$J_{TP}\dot{\phi}\Omega_r$$

4. Hub moment due to sideward flight:

$$(-1)^{i+1} \sum_{i=1}^4 R_{myi}$$

5. Roll actuators action:

$$l(T_1 - T_3)$$

The yawing moments are described as follows:

1. Body gyro effect:

$$\dot{\theta}\dot{\phi}(I_{xx} - I_{yy})$$

2. Hub force unbalance in forward flight:

$$l(H_{x2} - H_{x4})$$

3. Inertial counter-torque:

$$J_{TP}\dot{\Omega}_r$$

4. Hub force unbalance in sideward flight:

$$l(-H_{y1} + H_{y3})$$

5. Counter-torque unbalance:

$$(-1)^i \sum_{i=1}^4 Q_i$$

2.3 Equations of motion

The equations of motion are derived from the forces and moments listed above. After some simplifications, we obtain the quadrotor model in the state space form:

$$\dot{X} = f(X, U), \quad \dots (7)$$

where

$$f(X, U) = \begin{pmatrix} \dot{\phi} \\ \dot{\theta}\dot{\psi}a_1 - \dot{\theta}a_2\Omega_r + b_1U_2 \\ \dot{\theta} \\ \dot{\phi}\dot{\psi}a_3 + \dot{\phi}a_4\Omega_r + b_2U_3 \\ \dot{\psi} \\ \dot{\theta}\dot{\phi}a_5 + b_3U_4 \\ \dot{z} \\ -g + (c\phi \cdot c\theta)\frac{1}{m}U_1 \\ \dot{x} \\ u_x\frac{1}{m}U_1 \\ \dot{y} \\ u_y\frac{1}{m}U_1 \end{pmatrix}$$

X is the state vector as follows:

$$X = [\varphi \quad \dot{\phi} \quad \theta \quad \dot{\theta} \quad \psi \quad \dot{\psi} \quad z \quad \dot{z} \quad x \quad \dot{x} \quad y \quad \dot{y}]$$

and

$$a_1 = (I_{yy} - I_{zz})/I_{xx}, a_2 = J_{TP}/I_{xx}, a_3 = (I_{zz} - I_{xx})/I_{yy}, a_4 = J_{TP}/I_{yy}, a_5 = (I_{xx} - I_{yy})/I_{zz}$$

J_{TP} is the rotor total inertia with respect to the rotor main axis.

And

$$b_1 = l/I_{xx}, b_2 = l/I_{yy}, b_3 = l/I_{zz}$$

$$\Omega_r = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4$$

$$\begin{cases} u_x = s\psi \cdot s\phi + s\theta \cdot c\psi \cdot c\phi \\ u_y = s\theta \cdot c\phi \cdot s\psi - c\psi \cdot s\phi \end{cases}$$

The vector $U = [U_1 \ U_2 \ U_3 \ U_4]^T$ is the control vector inputs of the model and is composed of:

1. The vertical thrust U_1 that allows us to control the height z :

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2)$$

2. The virtual torque U_2 around the x axis to control the roll angle:

$$U_2 = bl(-\Omega_2^2 + \Omega_4^2)$$

3. The virtual torque U_3 around the y axis to control the pitch angle:

$$U_3 = bl(\Omega_1^2 - \Omega_3^2)$$

4. The virtual torque U_4 around the z -axis to control the yaw angle ψ :

$$U_4 = d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2)$$

b is the thrust coefficient, and d is the drag coefficient. The differential equations of the quadrotor are implemented in Simulink/Matlab, and this model is validated by different strategies and the following numerical values have been used to run the program: $m = 1 \text{ kg}$, $l = 0.235 \text{ m}$, $I_{xx} = 0.0081 \text{ N.m/rad/s}^2$, $I_{yy} = 0.0081 \text{ N.m/rad/s}^2$, $I_{zz} = 0.0142 \text{ N.m/rad/s}^2$, $J_{TP} = 104 \times 10^{-6} \text{ N.m/rad/s}^2$, $b = 54.2 \times 10^{-6} \text{ N.m/rad/s}$, and $d = 1.1 \times 10^{-6} \text{ N.m/rad/s}$.

3.0 INTEGRAL BACK-STEPPING CONTROLLER DESIGN

Several controllers have been tested and compared in order to stabilise the quadrotor, including the: PID, state feedback, back-stepping, feedback linearisation, the H_∞ , sliding modes, fuzzy logic, IBS and other controllers, and a comparison among several controllers has been done⁽⁴⁹⁾. In this section, we use the IBS controller to stabilise our quadrotor.

3.1 Attitude (angular motions) control

Attitude control is the heart of the control block; it keeps the 3D orientation of the helicopter to the desired value. The first step in IBS control design is to consider the tracking error $e_1 = \varphi_d - \varphi$ and its dynamics $\dot{e}_1 = \dot{\varphi}_d - \omega_x$.

The angular speed ω_x is not our control input and has its own dynamics, so we set for it a desired behaviour and consider it as our virtual control:

$$\omega_{xd} = c_1 e_1 + \dot{\varphi}_d + \lambda_1 \int_0^t e_1(\tau) d\tau \quad \dots (8)$$

We can see that the integral term is now introduced to the virtual control term.

We compute the error e_2 of ω_x and its dynamics as follows:

$$\dot{e}_2 = c_1(\dot{\varphi}_d - \omega_x) + \ddot{\varphi}_d + \lambda_1 e_1 - \ddot{\varphi} \quad \dots (9)$$

We can rewrite roll tracking error dynamics as:

$$\dot{e}_1 = -c_1 e_1 - \lambda_1 \int_0^t e_1(\tau) d\tau + e_2, \quad \dots (10)$$

where $e_2 = \omega_{xd} - \omega_x$

By replacing $\ddot{\varphi}$ by its corresponding expression from the system differential equation, the control input U_2 appears as:

$$\dot{e}_2 = c_1(\dot{\varphi}_d - \omega_x) + \ddot{\varphi}_d + \lambda_1 e_1 - \dot{\theta} \dot{\psi} a_1 + \dot{\theta} a_2 \Omega_r - b_1 U_2 \quad \dots (11)$$

By combining, from the equations treated above, the tracking errors of the position e_1 , of the angular speed e_2 and of the integral position tracking error $\int_0^t e_1(\tau) d\tau$, one obtains:

$$\dot{e}_2 = c_1 \left(-c_1 e_1 - \lambda_1 \int_0^t e_1(\tau) d\tau + e_2 \right) + \ddot{\varphi}_d + \lambda_1 e_1 - \tau_x / I_{xx}, \quad \dots (12)$$

where τ_x is the overall rolling torque.

The desirable dynamics for the angular speed tracking error to ensure stability is:

$$\dot{e}_2 = -c_2 e_2 - e_1 \quad \dots (13)$$

Note that the stability can be proved by choosing a Lyapunov candidate function as follows⁽¹⁶⁾:

$$V = \frac{1}{2} \lambda_1 X_1^2 + \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 \quad \dots (14)$$

$X_1 = \int_0^t e_1(\tau) d\tau$ and λ_1 is a positive constant.

Deriving the Lyapunov Candidate and by using Equations (10) and (13), we get:

$$\dot{V} = -c_1 e_1^2 - c_2 e_2^2 \leq 0 \quad \dots (15)$$

This global stability can be obtained if we choose the control input U_2 as:

$$U_2 = [(1 - c_1^2 + \lambda_1) e_1 + (c_1 + c_2) e_2] / b_1 + \left[-c_1 \lambda_1 \int_0^t e_1(\tau) d\tau + \ddot{\varphi}_d - \dot{\theta} \dot{\psi} a_1 - \dot{\theta} a_2 \Omega_r \right] / b_1 \quad \dots (16)$$

c_1 , c_2 and λ_1 are positive constants that forms the control parameters which determines the convergence speed of the angular speed loop.

Similarly, the pitch controller is:

$$U_3 = [(1 - c_3^2 + \lambda_2)e_3 + (c_3 + c_4)e_4]/b_2 \left[-c_3\lambda_2 \int_0^t e_2(\tau)d\tau + \ddot{\theta}_d - \dot{\phi}\dot{\psi}a_3 + \dot{\phi}a_4\Omega_r \right] / b_2, \quad \dots (17)$$

and the yaw controller is:

$$U_4 = [(1 - c_5^2 + \lambda_3)e_5 + (c_5 + c_6)e_6]/b_3 - \left[c_5\lambda_3 \int_0^t e_3(\tau)d\tau \right] / b_3, \quad \dots (18)$$

where $(c_3, c_4, c_5, c_6, \lambda_2, \lambda_3) > 0$ are the control parameters, where:

$$\begin{cases} c_1 = c_3 = 10 \\ c_2 = c_4 = c_5 = c_6 = 2 \\ \lambda_1 = \lambda_2 = 1000 \\ \lambda_3 = 0.01 \end{cases}$$

3.2 Altitude control

On the control law side, the altitude tracking error is defined as: $e_7 = z_d - z$

The speed tracking error is:

$$e_8 = c_7e_7 + \dot{z}_d + \lambda_4X_4 - \dot{z}, \quad \dots (19)$$

where $X_4 = \int_0^t e_5(\tau)d\tau$. The control law that ensures global stability of attitude tracking is then:

$$U_1 = m \left[\frac{g + (1 - c_7^2 + \lambda_4)e_7 + (c_7 + c_8)e_8 - c_7\lambda_4X_4}{\cos\varphi\cos\theta} \right], \quad \dots (20)$$

where $(c_7, c_8, \lambda_4) > 0$ are the altitude control parameters defined later, where

$$\begin{cases} c_7 = 3.5 \\ c_8 = 1.5 \\ \lambda_4 = 0.1 \end{cases}$$

3.3 Position control

Position control keeps the helicopter over the desired point. Horizontal motion is achieved by orienting the thrust vector towards the desired direction of motion. We have to remind that the motion along the y axis is related to the angle φ , so in order to control the motion along y , we may control the angle φ . The same applies for the motion along x -axis that is related to the angle θ . According to these two assumptions, if we need the system's $\{x(t), y(t)\}$ position to track $\{x_d(t), y_d(t)\}$, one has to compute the values of the desired angles $\{\theta_d(t), \phi_d(t)\}$, which could give $\{x_d(t), y_d(t)\}$. The control law is then derived using the IBS technique.

The position tracking errors for x and y are defined as:

$$\begin{cases} e_9 = x_d - x \\ e_{11} = y_d - y \end{cases} \quad \dots (21)$$

Accordingly, the speed tracking errors are:

$$\begin{cases} e_{10} = c_9 e_9 + \dot{x}_d + \lambda_5 X_5 - \dot{x} \\ e_{12} = c_{11} e_{11} + \dot{y}_d + \lambda_6 X_6 - \dot{y} \end{cases} \quad \dots (22)$$

The control laws are then:

$$\begin{cases} U_x = m \left[\frac{(1 - c_9^2 + \lambda_5) e_9 + (c_9 + c_{10}) e_{10} - c_9 \lambda_5 X_5}{U_1} \right] = s\psi \cdot s\varphi + s\theta \cdot c\psi \cdot c\varphi \\ U_y = -m \left[\frac{(1 - c_{11}^2 + \lambda_6) e_{11} + (c_{11} + c_{12}) e_{12} - c_{11} \lambda_6 X_6}{U_1} \right] = s\theta \cdot c\varphi \cdot s\psi - c\psi \cdot s\varphi \end{cases}, \quad \dots (23)$$

where $X_5 = \int_0^t e_9(\tau) d\tau$, $X_6 = \int_0^t e_{11}(\tau) d\tau$ and $(c_9, c_{10}, c_{11}, c_{12}, \lambda_5, \lambda_6) > 0$ are the control parameters.

Since to control the motion along the x axis we have to control the θ angle, the other two angles are approximated to be zero. The same concept applies for the motion along y axis, which is done by controlling the φ angle and the other two angles are supposed zero. The desired angles become:

$$\begin{cases} \theta_d = \arcsin(U_x) \\ \varphi_d = \arcsin(-U_y) \end{cases} \quad \dots (24)$$

4.0 FUZZY COMPENSATION DESIGN

4.1 Fuzzy compensation system structure

The fuzzy compensation system (Fig. 2) is composed of 12 gains, 4 derivatives and 4 FLCs: FLC $_x$, FLC $_y$, FLC $_z$ and FLC $_\psi$, where $e_x = x - x_d$, $e_y = y - y_d$, $e_z = z - z_d$, and $e_\psi = \psi - \psi_d$, Δe_x , Δe_y , Δe_z and Δe_ψ are the derivatives of e_x , e_y , e_z , and e_ψ , respectively. The different gains are $G_{1x} = 30$, $G_{1y} = 25$, $G_{1z} = 1$, $G_{1\psi} = 1$, $G_{2x} = 8$, $G_{2y} = 5$, $G_{2z} = 1$, $G_{2\psi} = 1$, $G_{3x} = 0.6$, $G_{3y} = 5$, $G_{3z} = 2$ and $G_{3\psi} = 1$.

4.2 Fuzzy logic controller

The FLC block diagram^(25,26) is given in Fig. 3. This fuzzy controller has four main components:

1. The fuzzification maps numerical values into linguistic variables matched to membership degrees using a membership function.
2. The rule base holds the knowledge, in the form of a set of rules, of how best to control the system. This set of rules consists of linguistic rules with an If-Then structure: If (condition), Then (action).

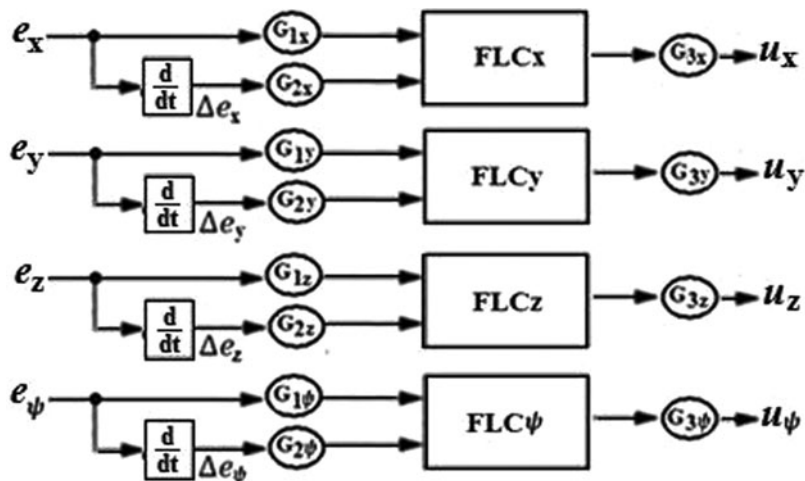


Figure 2. Fuzzy compensation system structure.

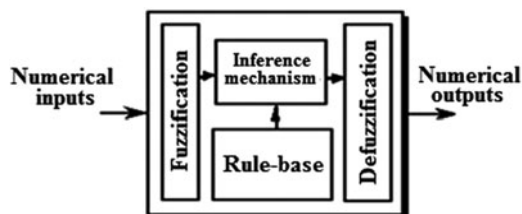


Figure 3. Fuzzy controller architecture.

3. The inference engine is the heart of the FLC operation. The inference mechanism evaluates which control rules are relevant at the current time. This inference system applies the rules to the fuzzified values. For each activated rule, the score of the resulting decision is computed.
4. The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the controlled process. This interface determines the final decision through the intermediate decisions.

4.3 Used fuzzy controller architecture

We will choose two inputs for each FLC (Fig. 4) which significantly affect the performance of the considered system. These two parameters are: $e' = G_1 e$, where $e \in \{e_x, e_y, e_z, e_\psi\}$, and its derivative $\Delta e' = G_2 \Delta e$, where $\Delta e \in \{\Delta e_x, \Delta e_y, \Delta e_z, \Delta e_\psi\}$. The output of this controller is $u' = u/G_3$, where $G_3 \in \{G_{3x}, G_{3y}, G_{3z}, G_{\psi 3}\}$ and $u \in \{u_x, u_y, u_z, u_\psi\}$ is the necessary compensation. The fuzzy controller has a Sugeno-type inference system.

4.4 Membership functions

Figure 5 shows different membership functions of each input and each output of different FLCs. Figures 5(a) and 5(b) show, for each FLC, fuzzy subsets of the first input (e') and the second input ($\Delta e'$), respectively. The fuzzy subsets of the output of FLC ψ (u'), of the output

Table 1
Rule base of each FLC

e'	$\Delta e'$	u'
N	N	N
N	Z	N
N	P	Z
Z	N	N
Z	Z	Z
Z	P	P
P	N	Z
P	Z	P
P	P	P

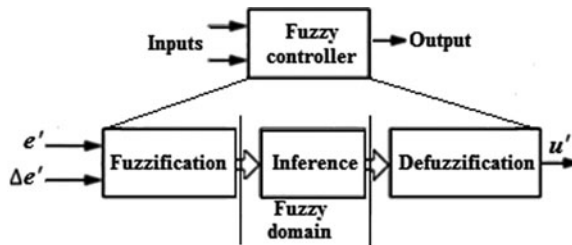


Figure 4. FLC implemented in the compensation system.

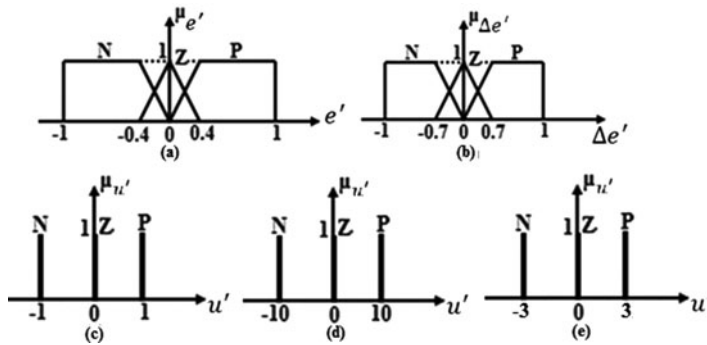


Figure 5. Different membership functions.

of FLCx and FLCz (u'), and of the output of FLCy (u') are shown in Figs 5(c), 5(d) and 5(e), respectively.

4.5 Fuzzy controller's rule base

The rule base of each controller is composed of a set of nine fuzzy If-Then rules $R_i (i = 1, 2, \dots, 9)$ of the form: If (e' is a and $\Delta e'$ is b), Then (u' is c), where a, b, c $\in \{N, Z, P\}$. Table 1 shows the rule base of all controllers.

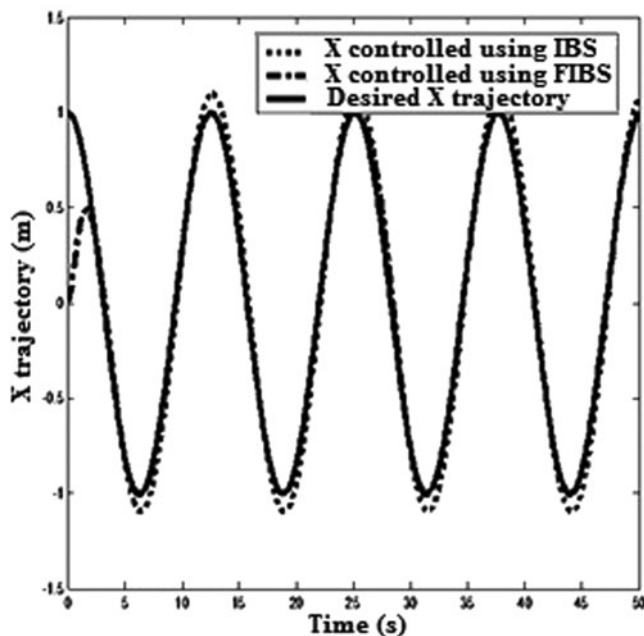


Figure 6. X displacement with the FIBS controller and the IBS controller.

4.6 Simulation results

In fact, the proposed control strategy (Fuzzy Integral Back-Stepping (FIBS) control strategy) is composed of two families of controllers. The first is a model-based controller (IBS controller), and the other family is based on the expert's knowledge on the system (FLC). These controllers are implemented in parallel, and the resulting control signal is sent to the quadrotor system, in which each controller works separately. There is no direct or mathematical coupling between these controllers in order to study the convergence of the global controller. Each controller is derived alone and can work without the need of the other controller.

The main goal of this proposition is to benefit from the advantages of the two controllers which can be resumed as:

- The IBS controller is a model-based controller which is characterised by its robustness and good trajectory tracking if the conditions of stability are well respected.
- The FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Experience shows that the FLC yields results superior to those obtained by conventional control algorithms. In particular, the methodology of the FLC appears very useful when the processes are too complex for analysis by conventional quantitative techniques or when the available sources of information are interpreted qualitatively, inexactly or uncertainly. Thus, FLC may be viewed as a step towards a rapprochement between conventional precise mathematical control and human-like decision making. The comparison in the frequency domain of classical linear and non-linear controllers is clearly done in Ref. 52. Therefore, the used strategy is to compensate the trajectory tracking error issued due to the model-based controller by a fuzzy compensator. Several simulations have been made to validate

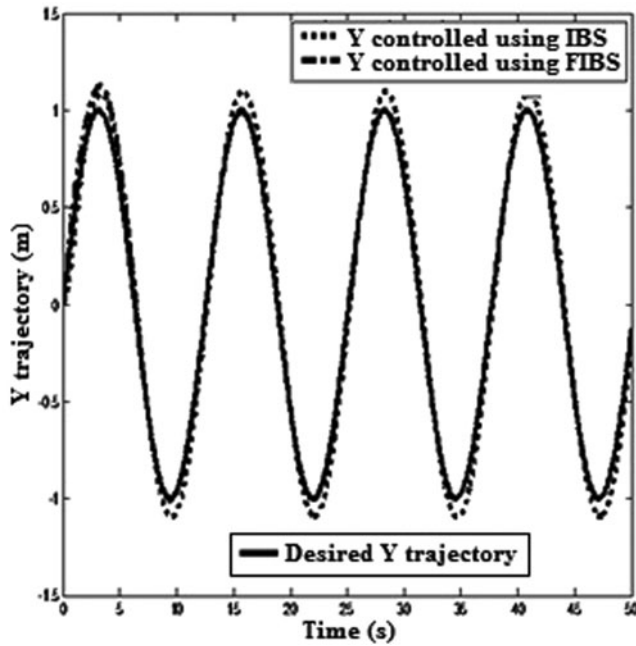


Figure 7. Y displacement with the FIBS controller and the IBS controller.

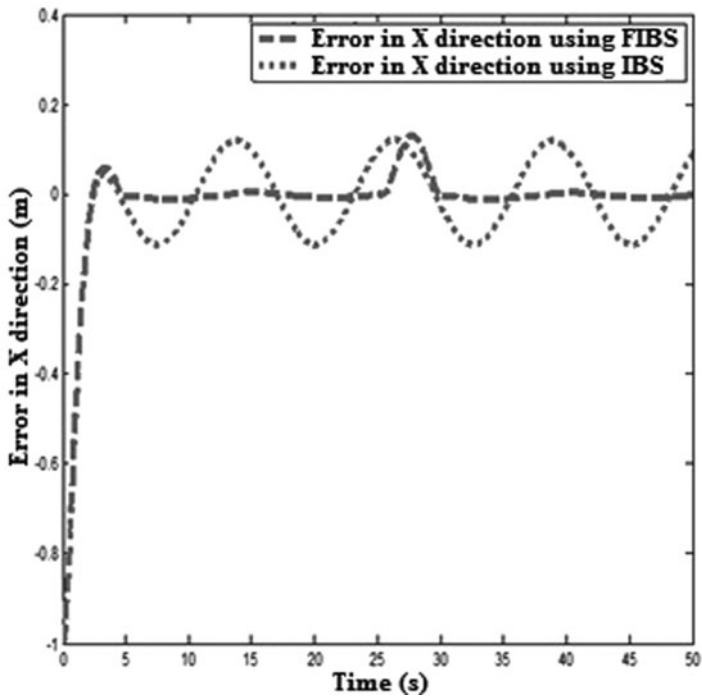


Figure 8. Errors in the X direction.

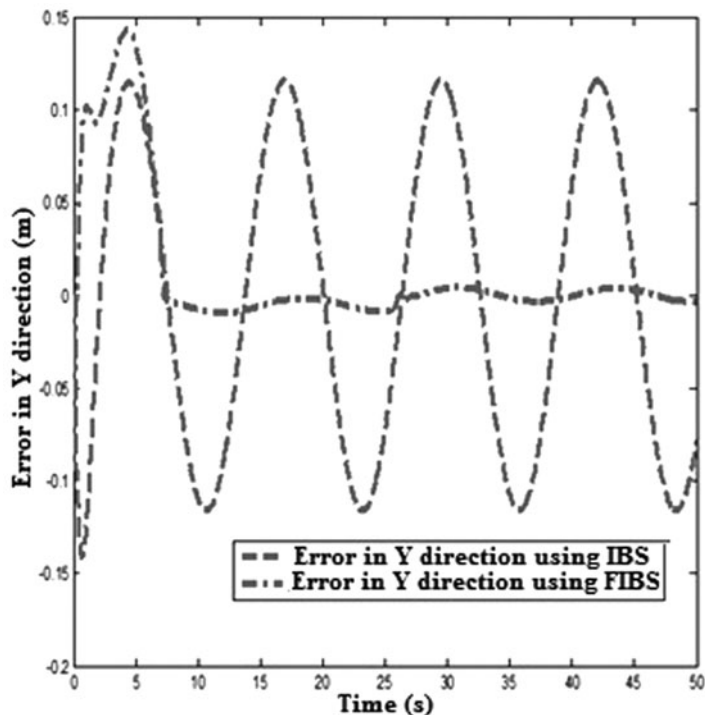


Figure 9. Errors in the Y direction.

our proposed strategy. Different trajectories have been tested, and different types of uncertainties have been added to the simulations. One of the trajectories that we have tested is the following: $x_d = \cos(0.5t)$, $y_d = \sin(0.5t)$, $\psi_d = 0$, $z_d = \begin{cases} \cos(0.5t) + 5 & \text{if } t \leq 25 \\ \cos(0.5t) + 15 & \text{if } t > 25 \end{cases}$. The idea of choosing this trajectory is to analyse the behaviour of the controller due to step function and then to a sinusoidal function on z , and a sinusoidal function of x and y . So, the trajectory may be considered as a good candidate to test our controller.

It is clearly seen that the FIBS controller in Figs 6 and 7 reduces the trajectory tracking error. Therefore, the first improvement appears when there is no external disturbances. When an external disturbance is added and represented by the wind effect in the three directions and in magnitude equal to 10 N, excellent improvements can be seen by using the FIBS controller. Figures 6 and 7 show three trajectories: the desired trajectory, the trajectory obtained by using the IBS control and the trajectory obtained by using the FIBS controller. It is seen how the FIBS controller improves the trajectory tracking. It can be seen in a more clear view by regarding the errors in Figs 8 and 9. These figures show a good tracking in a short time of convergence.

Figure 10 shows the desired trajectory in the z direction, and the trajectory obtained by using the IBS control and the trajectory obtained by using the FIBS controller. It is seen how the FIBS controller improves the trajectory tracking. It can be seen in a more clear view by regarding the errors in Fig. 11.

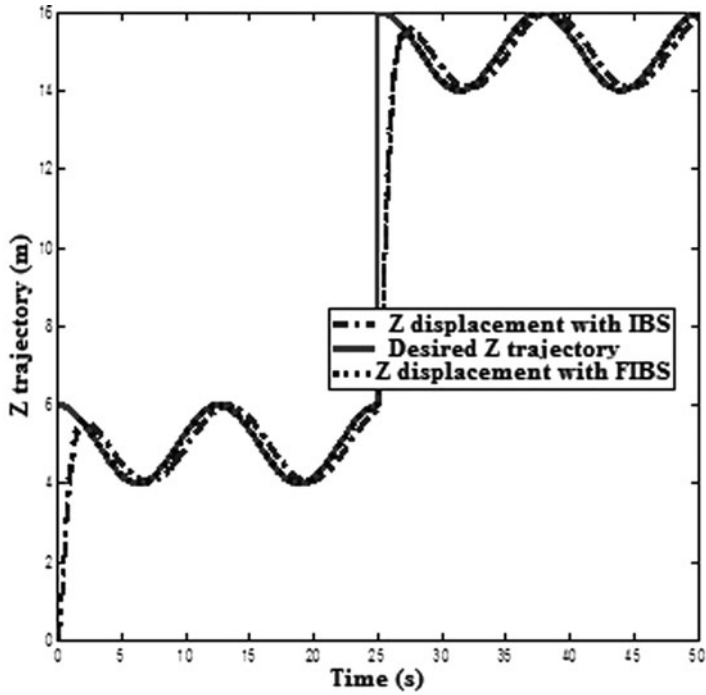


Figure 10. Z displacement with the FIBS controller and the IBS controller.

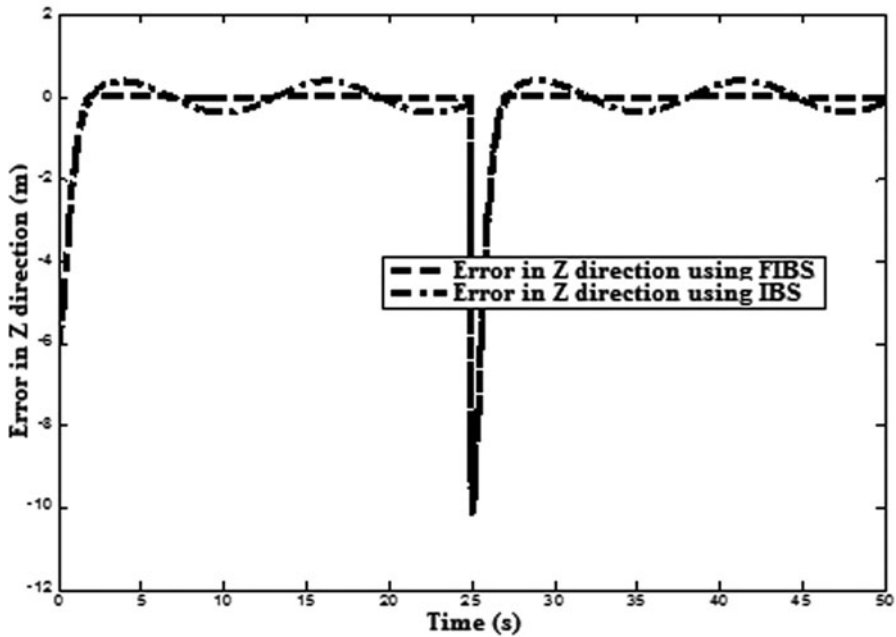


Figure 11. Errors in the Z direction.

5.0 CONCLUSION

In this paper, a novel control strategy has been proposed for a quadrotor helicopter. This novel strategy is based on a non-linear based model controller compensated by a fuzzy controller. The back-stepping controller was able to track the trajectory of the well-designed model, and the integral action ensures the minimisation of the steady state error. The unperfectness of the model and the uncertainties have been compensated by the FLC. The importance of this work resides in the fact that even if the model is not perfect, and in the presence of uncertainties and non-exactness of physical parameters values, the model can track the desired trajectory using a smooth controller. Different trajectories and different conditions such as variation in the wind velocities (and parameters variations) have been tested, and excellent results and excellent improvements regarding classical control theories used have been shown.

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