Sliding Mode Control Based on Interval Type-2 Fuzzy-Neural Network Controller for an Uav Type Quadrotor

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***Abstract*—In this paper, a robust controller for a Six Degrees of Freedom (6 DOF) quadrotor helicopter control is proposed. Neural Networks (NN), Interval Type-2 Fuzzy Logic Control approach (IT2FLC) and Sliding Mode Control (SMC) technique are used to design a controller, named Neural Network Interval Type-2 Fuzzy Sliding Mode Controller (NNIT2FSMC), for each subsystem of the quadrotor helicopter. The proposed control scheme allows avoiding difficult modeling, attenuating the chattering effect of the SMC, reducing the rules number of the fuzzy controller, and guaranteeing the stability and the robustness of the system. The simulation results show that the NNIT2FSMC can greatly alleviate the chattering effect and is sufficiently robust with respect to the external disturbances.**

***Index Terms*—Quadrotor Helicopter, Neural Network, Type-2 Fuzzy Logic, Sliding Mode Control**

I. INTRODUCTION

Autonomous Unmanned Air vehicles (UAV) are increasingly popular platforms. This is due to their use in military applications, traffic surveillance, environment exploration, structure inspection, mapping and aerial cinematography [1]. The ability of helicopters to take off and land vertically, to perform hover flight, and their agility, make them ideal vehicles.

The idea of using four rotors in helicopters is not new. In fact, a full-scale four rotors helicopter was built by De Bothezat in 1921 [2]. Quadrotor helicopters (Fig.1) have several basic advantages over manned systems including increased maneuverability [3], low cost, reduced radar signatures, and requiring little human intervention from take-off to landing. Nevertheless, this kind of helicopters is one of the most complex flying systems. This is partly due to the number of physical effects, such as: Aerodynamic effects, gravity, gyroscopic, friction and inertial counter torques, acting on the system [4]. Moreover, quadrotor helicopters are dynamically unstable and therefore suitable control methods, such as backstepping and sliding-mode techniques [5], [6], must be used to make them stable.

The main contribution of this paper is to propose an adaptive and a robust control approach using neural networks, interval type-2 fuzzy logic approach and sliding mode control technique. A neural network is used to approximate the equivalent control of the SMC approach. While, in order to eliminate the chattering phenomenon, an interval type-2 fuzzy logic control is used to approximate the corrective control term. This control scheme allows avoiding the nonlinear modeling problems, ensuring the stability of the closed loop system and is robust with respect to external disturbances. To show the effectiveness and the feasibility of the proposed control strategy, the control problem of the quadrotor helicopter dynamical model is considered.

II. QUADROTOR DYNAMIC MODEL

The dynamic model of the quadrotor helicopter can be obtained via the Lagrange approach given as follow [7]:

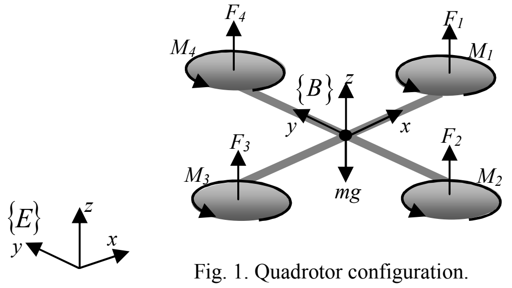

Fig. 1. Quadrotor configuration.

$$\begin{cases} \ddot{x} = \frac{1}{m}\{(Cos\varphi\, Cos\psi\, Sin\theta + Sin\psi\, Sin\varphi)\, U_1 - k_{ftx}\dot{x}\} + \frac{A_x}{m} \\ \ddot{y} = \frac{1}{m}\{(Cos\varphi\, Sin\psi\, Sin\theta - Cos\psi\, Sin\varphi)\, U_1 - k_{fty}\dot{y}\} + \frac{A_y}{m} \\ \ddot{z} = \frac{1}{m}\{(Cos\varphi\, Cos\theta) U_1 - k_{ftz}\dot{z}\} - g + \frac{A_z}{m} \\ \ddot{\varphi} = \frac{1}{I_x}[\dot{\theta}\dot{\psi}(I_y - I_z) + dU_2 - k_{fax}\dot{\varphi}^2] + \frac{A_\varphi}{I_x} \\ \ddot{\theta} = \frac{1}{I_y}[\dot{\varphi}\dot{\psi}(I_z - I_x) + dU_3 - k_{fay}\dot{\theta}^2] + \frac{A_\theta}{I_y} \\ \ddot{\psi} = \frac{1}{I_z}[\dot{\varphi}\dot{\theta}(I_x - I_y) + U_4 - k_{faz}\dot{\psi}^2] + \frac{A_\psi}{I_z} \end{cases} \quad (1)$$

where (x, y, z) are three positions and (φ, ψ, θ) are three Euler angles, representing pitch, roll and yaw respectively. U_i $(i = 1\ldots 4)$ are the virtual control inputs defined as follow [7]:

$$\begin{cases} U_1 = F_1 + F_2 + F_3 + F_4 \\ U_2 = F_4 - F_2 \\ U_3 = F_3 - F_1 \\ U_4 = \dfrac{K_d}{K_p}\left(-F_1 + F_2 - F_3 + F_4\right) \end{cases} \tag{2}$$

TABLE I. PHYSICAL PARAMETERS OF THE QUADROTOR.

Symbol	Definition
$I_{x,y,z}$	body inertia
$F_{1,\ldots,4}$	forces generated by four rotors
φ	roll angle
θ	pitch angle
ψ	yaw angle
g	Gravitational acceleration
m	Total weight of the quadrotor
d	Distance from the rotor and the center of mass of the quadrotor
K_p	thrust factor
K_d	drag factor
A_x, A_y, A_y	external disturbances on the aerodynamic forces
A_ψ, A_θ ,A_φ	external disturbances on the aerodynamic moments
K_{ftx}, K_{fty}, K_{ftz}	Translation drag coefficient
K_{fax}, K_{fay}, K_{faz}	Friction aerodynamics coefficients

III. DESIGN OF NEURO TYPE-2 FUZZY SLIDING MODE CONTROL

Fig.5 shows the structure of a general type-2 fuzzy logic system. This structure is similar to type-1 fuzzy logic system except that the output processor which consists of two operations: type-reducer and defuzzifier.

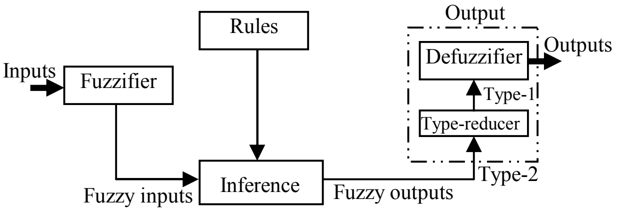

Fig. 2. Structure of type-2 fuzzy logic system [8-9]

In the proposed structure, the equivalent control term of sliding mode control is computed by a neural network. The output of the neural network is summed with the corrective term computed by a type-2 fuzzy controller. The corrective control term is taken as a measure of the error to update the weights of the neural network [10]. The aim of the learning process of the neural network is to minimize the corrective control term used to compensate the deviations from the sliding surface [11]. In fact, when the system states are on the sliding surface, the equivalent control is enough to keep the system states on this surface and the corrective term must be equal to zero. The overall control system, using the proposed controller applied to the quadrotor helicopter model, is given in Fig.2 and Fig.3.

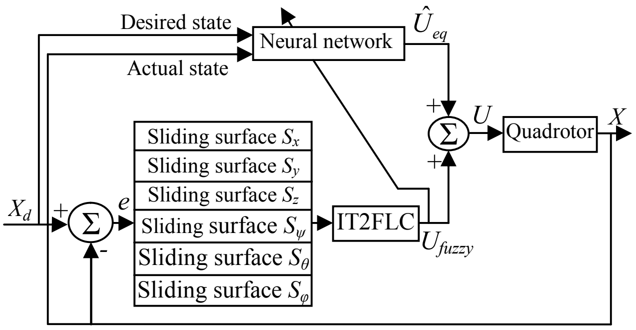

Fig. 3. Structure of the NNIT2FSMC

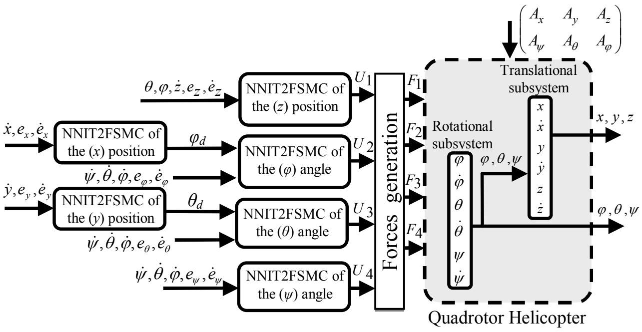

Fig. 4. Synoptic of the proposed control strategy.

A. Computation of the corrective control

In order to attenuate the chattering effect and handle the uncertainty of the quadrotor helicopter, we choose to use a type-2 fuzzy controller with single input and single output for each subsystem. Then, the input of the controller is the sliding surface ($s_i = \dot{e}_i + \lambda_i e_i$) and the output is the corrective control u_{Fuzzy} . All the membership functions of the fuzzy input variable are chosen to be triangular and trapezoidal for all upper and lower membership functions. The used labels of the fuzzy variable (surface) are: {negative medium (NM), negative big (NB), zero (ZE), positive medium (NM), positive big (PB)}.

The corrective control is decomposed into five levels represented by a set of linguistic variables: negative big (NB), negative medium (NM), zero (ZE), positive medium (PM) and positive big (PB). Fig.4 presents the input/output membership functions distributed on discourse universes and Table.2 presents the rules base:

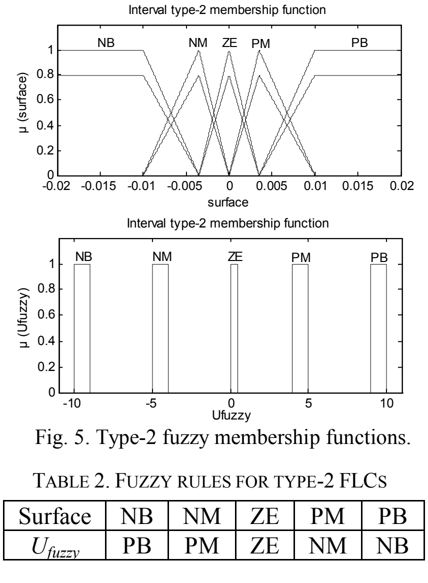

Fig. 5. Type-2 fuzzy membership functions.

TABLE 2. FUZZY RULES FOR TYPE-2 FLCS

Surface	NB	NM	ZE	PM	PB
U_{fuzzy}	PB	PM	ZE	NM	NB

B. Computation of the equivalent control of the altitude

Denoting the desired altitude by (z_d), we define the tracking error and the sliding surfaces by:

$$\begin{cases} e_z = z - z_d \\ S_z = \dot{e}_z + \lambda_z e_z \end{cases} \text{with } \lambda_z > 0 \tag{3}$$

The neural network is chosen to be a three – layer feed – forward neural network which has an input layer, an output layer and one hidden layer. The structure of the inputs and the output of the network are established by the equivalent control equation [12, 13]. The structure of the neural network used to generate U_{eqz} is presented in Fig.5.

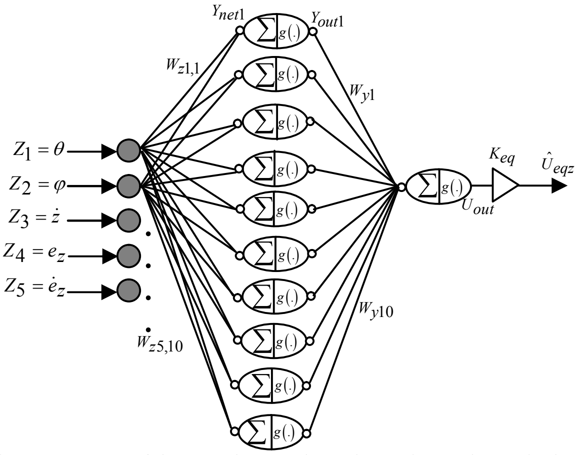

Fig. 6. Structure of the neural network used to estimate the equivalent control in Z axis.

The activation function $g(x)$ of the net is selected as a sigmoid transfer function, defined by (5):

$$g(x) = \frac{2}{1 + e^{-x}} - 1 \tag{4}$$

The equivalent control is computed by using the iterative gradient algorithm to minimize the mean square error between the desired and actual states [13].

$$E = \frac{1}{2}\left(U_{eqz}(t) - \hat{U}_{eqz}(t)\right) \tag{5}$$

The gradient descent method is used to update the weights of the NN. The weights are then updated by using the following two equations:

$$Wy_i(t+1) = Wy_i(t) - \alpha \frac{\partial E}{\partial Wy_i} \tag{6}$$

$$Wz_{i,j}(t+1) = Wz_{i,j} - \alpha \frac{\partial E}{\partial Wz_{i,j}} \tag{7}$$

Where α is the learning-rate parameter of the backpropagation algorithm and it is a constant, the update terms in (5) and (6) can be derived as follows:

$$\frac{\partial E}{\partial Wy_i} = -\frac{1}{2}\left[\left(U_{fuzzy}\right) K_{eq}\left(1 - U_{out}{}^2\right)\right] Y_{outj} \tag{8}$$

$$\frac{\partial E}{\partial Wz_{i,j}} = -\frac{1}{4}\left[\left(U_{fuzzy}\right) K_{eq}\left(1 - U_{out}{}^2\right) W_{yi}\left(1 - Y_{outj}{}^2\right) Z_i\right] \tag{9}$$

C. Computation of the equivalent control of the angles (ψ,θ,φ) and positions (x,y)

The same steps are followed to estimate $\hat{U}_{eq\psi}$, $\hat{U}_{eq\theta}$, $\hat{U}_{eq\varphi}$ $\hat{U}_{eqx}$, $\hat{U}_{eqy}$ the desired roll and pitch angles are given by (9):

$$\begin{cases} \varphi_d = \hat{U}_{eqy} + U_{fuzzy} \\ \theta_d = \hat{U}_{eqx} + U_{fuzzy} \end{cases} \tag{10}$$

The different tracking errors and sliding surfaces are presented by (10):

$$\begin{cases} e_\psi = \psi - \psi_d \\ S_\psi = \dot{e}_\psi + \lambda_\psi e_\psi \\ e_\theta = \theta - \theta_d \\ S\theta = \dot{e}_\theta + \lambda_\theta e_\theta \\ e_\varphi = \varphi - \varphi_d \\ S_\varphi = \dot{e}_\varphi + \lambda_\varphi e_\varphi \\ e_x = x - x_d \\ S_x = \dot{e}_x + \lambda_x e_x \\ e_y = y - y_d \\ S_y = \dot{e}_y + \lambda_y e_y \end{cases} \text{with } \left(\lambda_\psi, \lambda_\theta, \lambda_\varphi, \lambda_x, \lambda_y\right) > 0 \tag{11}$$

IV. SIMULATION RESULTS

In this section, the proposed control algorithm is used to control the full quadrotor helicopter model in presence of the following external disturbances on the aerodynamic forces and moments:

$A_x = A_y = A_z = 0.126$, $A_\psi = 0.008\sin(0.1t)$

$A_\theta = A_\varphi = 0.004\sin(0.1t)$.

The obtained results are given in Fig.6, Fig.7, and Fig.8. It can be seen that the controller ensures a good tracking performance and a good robustness with respect to the external disturbances, and allows overcoming the chattering problem. It can be seen, in Fig.7, that the control signals are quite smooth; this is mainly due to the chattering phenomenon attenuation.

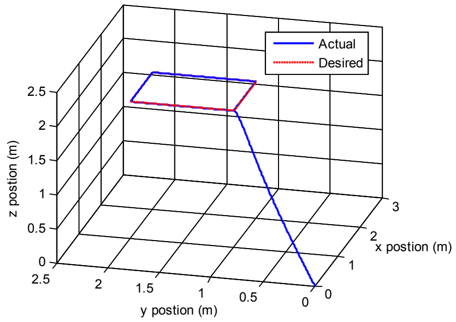

Fig. 7. Global trajectory of the quadrotor in 3D.

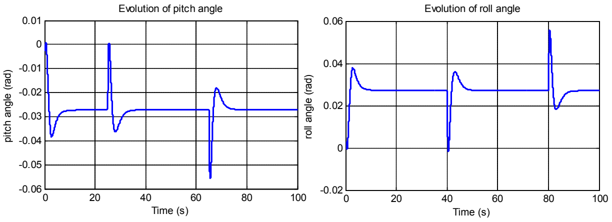

Fig. 8. Simulation results of the desired trajectory tracking.

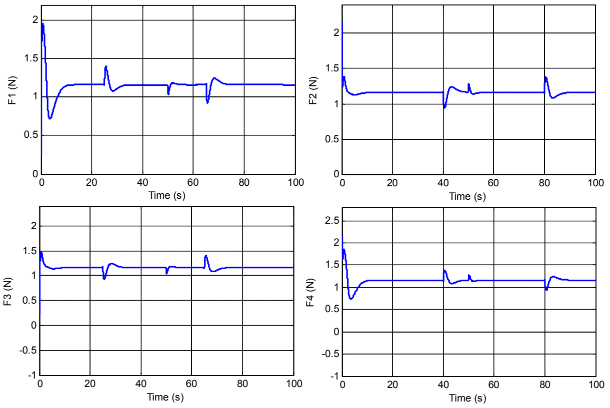

Fig. 9. Control signals.

V. CONCLUSION

In this work, a robust control approach called Neural Network Interval Type-2 Fuzzy Sliding Mode Control (NNIT2FSMC) has been proposed for a 6 DOF quadrotor helicopter control. The sliding mode control allowed to ensure the stability of the helicopter, and the neural network allowed the estimation of the unknown equivalent control of the SMC. The IT2FC with a minimal number of rules was used to attenuate the chattering phenomenon and to handle the uncertainties of the helicopter model. The simulation results have showed the efficiency, the good tracking performance and the high robustness to the external disturbances of the proposed control scheme.

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