Design and Experimental Verification of a Multirotor Aircraft with fuzzy neural network controller

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Abstract. Conventional multirotor aircrafts are underactuated, while the translational and rotational motions are strongly coupled. These features severely limit the maneuverability of the aircraft. Therefore, a multi-rotor aircraft is designed, which can perform omnidirectional motion, vector thrust control flight and tilt-hovering. In addition, an fuzzy neural network controller is designed. And the aircraft demonstrates a higher fault tolerance than the conventional ones. Finally, the experimental results show that the aircraft has a higher maneuverability than the conventional quadrotors.

1. Introduction

With the rapid development and wide application of multi-rotor UAV [1-5] technology, it has brought great convenience to industrial production and people's life, especially in the fields of film and television aerial photography, express delivery, infrastructure inspection, search and rescue, and industrial maintenance.

The rotor of the traditional multi-rotor aircraft is fixed on a plane, and the thrust direction provided is orthogonal to the plane of the air-frame. It is a kind of strong coupling and under actuated nonlinear system. In the actual scene, the aircraft must use the platform to ensure the stability of the angle of view during the flight. In particular, in the application of tunnel and bridge inspection, the inspection target is a three-dimensional object in three-dimensional space, which requires the aircraft to have a 360° angle of view from top to bottom, to minimize the inspection blind area as much as possible, so as to avoid potential safety hazards when the traditional multi-rotor UAV conducts such inspection. It must be equipped with a double cloud platform to complete such tasks. However, the configuration of the double cloud platform not only increases the weight of the body, but also increases the inspection cost.

In order to solve the above problems, more and more scholars begin to pay attention to the new structure of aircraft. The design concept of over driven multi-rotor aircraft is gradually promoted. Generally speaking, there are two main ways to design the over driven multi-rotor aircraft: (1) spatial three-dimensional structure layout, which provides omnidirectional thrust by increasing the number of rotors and changing the installation position of rotors, so that the driving force and driving direction of the aircraft have enough redundancy; (2) in the tilt rotor mode. The thrust direction of each rotor is changed through the servo mechanism, so that the size and direction of the thrust provided to the aircraft can be changed. The aircraft can follow any trajectory in 3D space and has stronger maneuverability. In conclusion, for the design concept of overdrive aircraft, if the rotor fixed design method is adopted, more than four rotors are bound to be equipped. The rotors pointing in all directions are required. There is a force dissipation effect between the rotors, resulting in energy waste.
The energy loss caused by internal force can be reduced to a certain extent by using the tilt rotor design scheme, but the existing design scheme using the tilt rotor has the singularity problem. That means when the rotor rotates 90° in the air, the aircraft cannot hover stably.

In this paper, an overactuated multi-rotor aircraft [19] is proposed, which combines the advantages of three-dimensional structure and tilt rotor, and makes the aircraft have new functions of omnidirectional motion, tilt hover:

(1) A new overactuated multi-rotor aircraft with three-dimensional structure is designed, and the dynamic characteristics, controllability and stability of the aircraft are analyzed and proved theoretically.

(2) Aiming at the new overactuated multi-rotor structure, a controller which can independently control the position and attitude of the aircraft is designed, so that the aircraft can track any trajectory and direction in 3D space, and has a certain fault tolerance.

And the control strategy is based on Neuro-Fuzzy adaptive controller, Neuro-Fuzzy has been used in a lot of successful applications [6–11]. But which is based on type-I fuzzy sets. With the higher control accuracy requirements, type-II fuzzy neural network [12–18] is developed recently which has better performances than type-I fuzzy neural network. In this paper, an over driven multi-rotor vehicle is proposed. It combines the advantages of three-dimensional space structure layout and tilt rotor, so that the vehicle has new functions of omnidirectional motion, tilt hover and vector flight.

2. System modeling of the aircraft

According to Newton-Euler’s law, the dynamics model of over driven multi-rotor vehicle is established with the rotor speed \( \sigma_i \) and the angle of servo motor \( (\alpha_i, \beta_i) \) as input which has been proposed in reference [19]. Due to the three-dimensional structure layout of the aircraft and the close layout of the tilt rotor module, the complex aerodynamic effects (such as the mutual interference between the rotors and the rotation of the servo motor in the tilt rotor module) will have a significant impact on the dynamic characteristics of the aircraft. Therefore, the modeling of the overdrive vehicle is a very challenging task.

2.1. definition of coordinate system

The definition of coordinate system is shown in Fig. 1:

1. \( \{F_w: O_w - X_w, Y_w, Z_w\} \) is the geodetic world coordinate system;
2. \( \{F_b: O_b - X_b, Y_b, Z_b\} \) represents the body coordinate system of the aircraft, and the origin \( O_b \) is located at the position of the center of gravity of the aircraft;
3. \( \{F_{pi}: O_{pi} - X_{pi}, Y_{pi}, Z_{pi}\} \) represents the coordinate system of the \( i \) tilt rotor module.
The rotation matrix of the coordinate system $F_B$ relative to the world inertial coordinate system $F_W$ is defined as $^W R_B \in SO(3)$, and $^B R_{pi}$ is defined as the rotation matrix of the $i$ tilt rotor module relative to the air-frame coordinate system.

The state vector is defined as: $X = (x, y, z, \psi, \theta, \phi)\,$ and $\xi = (x, y, z)^T$ for the position vector of the aircraft in the world coordinate system $F_W$, and $\eta = (\psi, \theta, \phi)^T$ for the direction vector of the aircraft relative to the world coordinate system.

Taking $^B O_{pi}$ as the origin of the coordinate system $F_{pi}$ of the tilt rotor module, it can be seen from Figure 4 that the position matrix $P$ meets the following requirements:

$$
    p = l \begin{bmatrix} a & 0 & -a & 0 \\ 0 & a & 0 & -a \\ -b & b & -b & b \end{bmatrix}
$$

(1)

$l$ is the distance between the center of the aircraft and the center of the tilt rotor module, $a = \sqrt{6}/3$, $b = \sqrt{3}/3$.

Since the thrust of tilt rotor module is fixed with respect to $F_{pi}$, it can be expressed as $^p O_{pi} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$. Let $^B O_{pi}$ be the representation of the direction vector of the tilt rotor module in coordinate system $F_B$, and the rotation matrix from coordinate system $F_{pi}$ to $F_B$ can be expressed as

$$
    O = \begin{bmatrix}
        c\alpha_1s\beta_1 & s\alpha_1 & -c\alpha_2s\beta_3 & -s\alpha_4 \\
        s\alpha_1 & c\alpha_2s\beta_2 & s\beta_3 & -c\alpha_2s\beta_4 \\
        c\alpha_1s\beta_1 & c\alpha_2s\beta_2 & c\alpha_2c\beta_3 & c\alpha_2c\beta_4 \\
        c\alpha_1s\beta_1 & s\alpha_2 & -c\alpha_2s\beta_3 & -s\alpha_4 \\
    \end{bmatrix}
$$

(2)

2.2. translation equation

The motion of the aircraft in three-dimensional space includes translation and rotation. The corresponding dynamic equations are also divided into translational and rotational dynamic equations. The power of the aircraft in this paper comes from the fixed pitch propeller on four tilt rotor modules. The thrust $T_i(N)$ and torque $M_i(N \cdot M)$ generated by the propeller driven by the DC brush-less motor can be expressed as

$$
    T_i = k_1 \sigma_i^2 \\
    M_i = k_2 k_1 \sigma_i^2
$$

(3)

(4)

Among them, $k_1$ and $k_2$ are thrust coefficient and torque coefficient respectively, which are determined by the physical characteristics of rotor and determined by experimental test.

As shown in Figure 1, it acts on the aircraft body. The vector thrust generated by the four tilt rotors on the can be expressed as

$$
    ^B f = \sum_{i=1}^{4} T_i \, ^B O_{pi}
$$

(5)

$^B O_{pi}$ represents the thrust direction provided by the $i$ rotor module. The moment received by the multi-rotor aircraft in the air includes the thrust moment generated by the rotor thrust, the reversal moment generated by the rotation of the DC brush-less motor, the gyro moment and the reversal moment generated by the rotation of the servo motor. Compared with the torque generated by rotor
thrust and the reverse torque generated by DC BLDC M, other torques can be ignored. Therefore, the external force moment of the aircraft can be expressed as:

$$\tau = \sum_{i=1}^{4} (P_i - O_i) - (-1)^{i+1} O_{i} M_i$$

Among them, item 1 represents the torque caused by the installation position of the rotor, and item 2 represents the torque caused by the aerodynamic resistance of the propeller.

Since each tilt rotor module has two controllable degrees of freedom, the force acting on the aircraft body also has three directions of component force, specifically expressed as:

$$f = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = \begin{bmatrix} c \alpha_1 s \beta_1 & s \alpha_1 & c \alpha_2 s \beta_2 & s \alpha_2 & c \alpha_3 s \beta_3 & s \alpha_3 & c \alpha_4 s \beta_4 & s \alpha_4 \\ s \alpha_1 & c \alpha_2 s \beta_2 & s \beta_3 & c \alpha_3 s \beta_3 & s \beta_4 & c \alpha_4 s \beta_4 & s \beta_4 & c \alpha_4 s \beta_4 \\ c \alpha_1 c \beta_1 & c \alpha_2 c \beta_2 & c \alpha_3 c \beta_3 & c \alpha_4 c \beta_4 \\ c \alpha_1 c \beta_1 & c \alpha_2 c \beta_2 & c \alpha_3 c \beta_3 & c \alpha_4 c \beta_4 \\ s \alpha_1 & c \alpha_2 s \beta_2 & -s \beta_3 & c \alpha_3 s \beta_3 & s \beta_4 & c \alpha_4 s \beta_4 & s \beta_4 & c \alpha_4 s \beta_4 \\ -s \alpha_1 & -c \alpha_2 s \beta_2 & s \beta_3 & -c \alpha_3 s \beta_3 & -s \beta_4 & -c \alpha_4 s \beta_4 & s \beta_4 & -c \alpha_4 s \beta_4 \\ s \alpha_1 & c \alpha_2 s \beta_2 & -s \beta_3 & -c \alpha_3 s \beta_3 & s \beta_4 & -c \alpha_4 s \beta_4 & s \beta_4 & c \alpha_4 s \beta_4 \\ -s \alpha_1 & -c \alpha_2 s \beta_2 & s \beta_3 & c \alpha_3 s \beta_3 & s \beta_4 & -c \alpha_4 s \beta_4 & s \beta_4 & c \alpha_4 s \beta_4 \end{bmatrix} T = B f \times T$$

$$T = [T_1 \ T_2 \ T_3 \ T_4]^T$$, which is the vector thrust exerted on the aircraft by four tilt rotor modules.

The moment generated by the vector thrust can be expressed as

$$\tau_m = \begin{bmatrix} \tau_{m,x} \\ \tau_{m,y} \\ \tau_{m,z} \end{bmatrix} = \begin{bmatrix} c \alpha_1 s \beta_1 & s \alpha_1 & c \alpha_2 s \beta_2 & s \alpha_2 & c \alpha_3 s \beta_3 & s \alpha_3 & c \alpha_4 s \beta_4 & s \alpha_4 \\ s \alpha_1 & c \alpha_2 s \beta_2 & s \beta_3 & c \alpha_3 s \beta_3 & s \beta_4 & c \alpha_4 s \beta_4 & s \beta_4 & c \alpha_4 s \beta_4 \\ c \alpha_1 c \beta_1 & c \alpha_2 c \beta_2 & c \alpha_3 c \beta_3 & c \alpha_4 c \beta_4 \end{bmatrix} T = B \tau \times T$$

And

$$a = \frac{\sqrt{6}}{3}, b = \frac{\sqrt{3}}{3}$$.

Considering the influence of the reversal torque produced by the motor rotation on the aircraft body, the torque

$$\tau_c = \begin{bmatrix} \tau_{c,x} \\ \tau_{c,y} \\ \tau_{c,z} \end{bmatrix}$$

can be expressed as

$$\tau_c = \begin{bmatrix} c \alpha_1 s \beta_1 & s \alpha_1 & c \alpha_2 s \beta_2 & s \alpha_2 & c \alpha_3 s \beta_3 & s \alpha_3 & c \alpha_4 s \beta_4 & s \alpha_4 \\ s \alpha_1 & c \alpha_2 s \beta_2 & s \beta_3 & c \alpha_3 s \beta_3 & s \beta_4 & c \alpha_4 s \beta_4 & s \beta_4 & c \alpha_4 s \beta_4 \\ -c \alpha_1 s \beta_1 & c \alpha_2 c \beta_2 & -s \beta_3 & -c \alpha_3 c \beta_3 & s \beta_4 & c \alpha_4 c \beta_4 & s \beta_4 & c \alpha_4 c \beta_4 \end{bmatrix} \Gamma = B \tau \times T$$

$$\Gamma = [\Gamma_1 \ \Gamma_2 \ \Gamma_3 \ \Gamma_4]^T$$ represents the reverse torque generated by the rotation of the propeller motor. Let

$$y = M(\alpha, \beta)^T$$, where

$$y = \begin{bmatrix} \tau \\ f \end{bmatrix}$$,

then the matrix $M(\alpha, \beta)$ is called the control efficiency matrix. The number of rows of the matrix represents the degree of freedom of the aircraft.

The number of columns represents the number of rotors. The rank of the matrix determines the control of the over driven multi-rotor aircraft, which in turn affects the controller design and motion planning of the aircraft. The dynamic equation is described by Newton Euler equation:

$$m p = -g + R_n \tau$$

$$\tau = J \omega + \omega \times J \omega$$

$m$ is the total mass of the vehicle and $g$ is the acceleration of gravity.

2.3. reliability analysis

Thanks to the three-dimensional structure layout of four tilt rotor modules, the hovering of the aircraft can always be realized no matter what attitude it is in in the air. In other words, when any one rotor
module fails, the remaining three rotor modules can achieve stable hovering by adjusting the attitude of the aircraft in the air. That is, when one of the four tilt rotor modules fails, the aircraft loses the ability of omnidirectional flight. But it can still be controlled as a traditional multi rotor aircraft. It should be noted that when one of the tilt rotor modules fails, the control efficiency matrix of the aircraft changes. However, the control law and control allocation strategy are still applicable. Assuming that the fourth tilt rotor module fails, the control efficiency matrix of the aircraft is expressed as:

\[
M_{n3} = \begin{bmatrix}
c_T & c_T & c_T c \alpha_3 \\
-c_T l_2 & c_T l_2 & 0 \\
-c_T l_3 & c_T l_3 & c_T c \alpha_3 l_1 \\
c_M & -c_M & -c_M c \alpha_3 c_T c \alpha_1
\end{bmatrix}
\]  

(11)

\[l_1 = \sqrt{6}/3, \quad l_2 = 1/2l, \quad l_3 = \sqrt{3}/2l\]. It can be seen that this equivalent dynamic vehicle can still effectively control pitch angle, roll angle, yaw angle and altitude. According to [19], if the power of the rotor is increased, the control of the aircraft can be further improved. At this time, the aircraft has no omnidirectional flight function, position control and attitude control are coupled with each other. However, if this mode is applied to the fault emergency handling control, it can ensure that the aircraft can still fly or land safely in the case of the tilt rotor module fault. Therefore, compared with the traditional multi-rotor aircraft, the safety of the multi-rotor aircraft described in this paper has a higher safety fault tolerance capability.

3. Optimal type II Fuzzy neural adaptive controller

For the control purpose, it is more convenient to use the dynamic model in earth-fixed coordinate frame like below:

\[
M_\eta(\eta)  \ddot{\eta} + C_\eta(\eta, \dot{\eta}) \dot{\eta} + g_\eta(\eta) = \tau_\eta + \tau_d
\]

(12)

Where \( \dot{\eta} = J(\eta) v, \dot{\eta} = J(\eta) \dot{v} + \dot{J}(\eta) v \), and \( \tau_d \) represents the external disturbance, the system matrices are defined as following:

\[
M_\eta(\eta) = J^{-T}(\eta) M J^{-1}(\eta);
\]

\[
C_\eta(\eta, \dot{\eta}) = 1/2M_\eta(\eta);
\]

\[
g_\eta(\eta) = J^{-T}(\eta) g(\eta);
\]

\[
\tau_\eta(\eta) = J^{-T}(\eta) \tau;
\]

(13)

Where

\[
J(\eta) = \begin{bmatrix}
sin \theta & -c_p \sin \phi + c_s \cos \phi & c_p \cos \phi & c_p \sin \phi & \cos \theta & 0 & 0 & 0 \\
sin \phi \cos \theta & -c_p \sin \phi + c_s \cos \phi & c_p \cos \phi & c_p \sin \phi & c_p \sin \phi & 0 & 0 & 0 \\
-c_p & c_p \phi & c_\phi \phi & c_\phi \phi & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & c_\phi \phi & c_\phi \phi & 0 \\
0 & 0 & 0 & 0 & c_\phi & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & c_\phi / c_\theta & c_\phi / c_\theta & 0
\end{bmatrix}
\]

(14)

The proposed control architecture on the target system based on Neuro-Fuzzy controller is shown in Fig.2. The controller used here is dynamic type II fuzzy neural networks (T-IIIFNN) [16,17] which have dynamic self-organizing structure, fast learning speed, good generalization, and better performance than type-I fuzzy neural network.
From the Fig.2, it can be seen that the control strategy is composed of two T-IIFNNs and one PD controller: the PD controller is used to control the attitude angles; the T-IIFNNs are employed to learn the inverse model of the Eight-Rotor and compensated for the model errors, external disturbance. The proposed control law is given by:

$$
\tau_\eta (\overline{\eta}) = \tau_{T-IIFNN} (\overline{\eta} | W) + \tau_{PD} = W^T \Phi(\overline{\eta}) + K_e e
$$

Where $\tau_\eta$ is the required control torque, $K_e e$ is the torque generated by the PD controller and $\tau_{T-IIFNN}$ is the torque generated by T-IIFNNs. The inverse Eight-Rotor model is obtained by T-IIFNNs. With online learning, one of T-IIFNNs is trained during real-time control of the manipulator. The other one is a duplicate copy of the former one, but its structure and parameters will be further adjusted by the error signal $\tau_{PD}$ as the controller is in operation, which is to compensate for modeling errors and external disturbances $\tau_d$.

**4. Experiment**

The aircraft is respectively controlled to hover at the positions with pitch angles of 0 degree, 30 degree, and 70 degree, and the aircraft is controlled to rise to a height of 1m above the ground in the initial state through the ground station, input the target attitude and hover the aircraft in the target attitude position 30 s.
The results show that the roll angular displacement and roll angular displacement are within 0.05g and 0.05g, respectively. The control task can be realized. The error is caused by environmental factors, model error, controller hysteresis and other factors, but the error is within the allowable range for the
actual system.
It can be seen from the above three experiments that the aircraft can realize tilting hover in a large angle range, which is a new function that the traditional aircraft does not have, and it can bring great convenience for practical application.

5. Conclusion
This paper introduces a new type of multi rotor aircraft which combines the tilt rotor technology and space three-dimensional structure layout. Through the construction of the prototype, it is verified that the aircraft can realize the tilt hover, vector flight, omnidirectional motion and other new motion modes. In the future work, the first is to solve the limitation of the servo motor on the performance of the aircraft, and achieve more refined control objectives. Further, the research on fault diagnosis and fault-tolerant control of aircraft will be carried out.

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