Feasibility study and development analysis of fully actuated multi-rotor UAVs

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Abstract. Fully actuated multi-rotor UAVs have gone through development in the last decades. This article collects studies on different UAV modelling design and feedback control to prove the feasibility of its full actuation. First, the structure design and model construction of fully actuated multi-rotor UAV are discussed and analyzed. Then, the types of fully actuated multi-rotor are classified and analyzed in combination with relevant papers in recent years. Then, the feedback control method is analyzed on the basis of mathematical modeling. Finally, he feasibility of design and control of fully driven UAV has been confirmed, and the future development trend is expected.

Keywords: UAV, actuated, modelling, feedback control.

1. Introduction

Unmanned aerial vehicles (UAVs) is a special type of aircraft without depending on pilot driving, which is now widely used in many fields. Originally the UAVs were invented for high-risks military missions, including infiltration, reconnaissance, and precise destruction. But with technology development in 21st century, lower cost and reduced design difficulty make the UAVs gradually applied in the civilian field [1].

In terms of information collection, UAVs supply effective and ideal solution in meteorology, search and rescue, exploration, and mapping. In terms of economize on manpower, UAVs could take the responsibility of pesticide spraying, delivery, and firefighting [2-4]. The unmanned property give UAVs great flexibility compared to manned craft. With the integration of more sensors and the compact body, the functionality and potential of UAVs are increased, which establishes it as an important position in various professional fields.

Generally, UAVs can be divided into two large categories: rotor wing and fixed wing. Fixed-wing UAVs have the characteristics of high speed and high energy consumption, which will not be explored due to its efficient but complex aerodynamics layout [5]. Nowadays, civilian multi-rotor UAVs are developing rapidly. The rotors in the same plane supply stable and adjustable lift force to complete functions such as take-off, hover, pan and turn. Civilian market favours it precisely for its mechanical simplicity and relative ease of operation. If more detailed division, multi-rotor UAVs can be classified by the number of rotors, like the quadcopter UAV commonly seen in mainstream market or the hexadecopter UAV with higher stability [2].

Talking about actuated control, the UAVs industry adopts several feedback control methods to reduce error and track the target state. As for the multi-rotor UAVs, the four-rotor and six-rotor have different feedback control methods due to their different dynamic structures. Proper flight control methods can help drones control attitude and altitude, thus achieving better performance. However, conventional multi-rotor UAVs have its disadvantages. The unactuated dynamics generated by unwanted coupling between the horizontal and rotational dynamics cause that drone need to tilt the fuselage first and then lift for translation, which reduces flexibility to some extent. Therefore, in recent years, fully actuated multi-rotor UAVs are developed with inclined rotors, which bring lift in the inclined direction. More freedom degrees due to tilting force increase flexibility, equipping drones the ability to maneuver in smaller space and in shorter time. The installation of inclined rotors brings not only more possibilities, but also more challenges. The change of the original aerodynamic layout requires a new structure design and modelling. The increase of variable also needs the improvement of feedback control methods.

In this article, the above two points will be studied separately to verify the feasibility of fully actuated multi-rotor UAV. First, the structure design and model construction of fully actuated multi-rotor UAV are discussed and analyzed. Then, the types of fully actuated multi-rotor are classified and analyzed in combination with relevant papers in recent years. Then, the feedback control method is analyzed on the basis of mathematical modeling. Finally, the full text is summarized and prospected.

2. Structure design and modelling

In this section, fully actuated UAVs will be analyzed from the perspective of rotor mounting type, transfer matrix, full actuated architecture classification. *Rotor mounting type*

Nowadays there are two main tilt-rotor installation ways to achieve full actuation. One is applying fixed propellers with different tilting angles, another is applying moveable propellers can rotate within a certain range. Here these two concepts are referred as fixed-tilt and variable-tilt [2], As shown in Figure 1 and Figure 2.

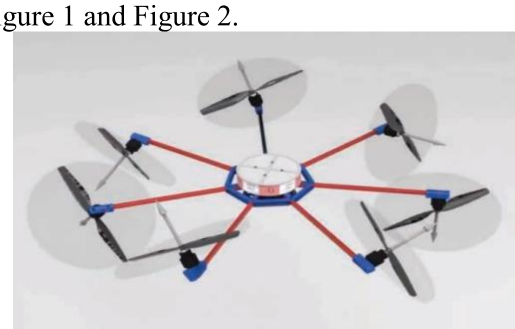

Figure 1. Fixed-tilt multi-rotor UAV [6].

Figure 2. Variable-tilt multi-rotor UAV [7].

1.2. Modelling

The addition of inclined rotor changes the original transmission layout of UAV and complicates it. Based on the principle of dynamic vector form rotor to fuselage, the extra degrees of freedom will change the control allocation matrix. Models of UAV with different rotor allocation modes can be established by the following expression.

$$W_c^B = M\lambda \tag{1}$$

Where $\lambda = (\lambda_1, ..., \lambda_{N_p})^T \in \Lambda$ is the rotor's thrust vector and $M \in R^{6*N_p}$ is the control allocation matrix. As shown in Eq. (1), the mapping matrix M is defined in order to match the allowable propeller-thrust space Λ to the allowable aerodynamic-control wrench space W. For fixed-tilt UAVs, M is a constant matrix, but for variable-tilt UAVs, it is a function of angles related to extra rotors [8]. Thus, in mathematical modelling, models of UAV with different rotor allocation modes can be established by virtue of the master of Eq. (1).

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1.3. Classification
Compared to underactuated concepts, the difference on assembly of fully actuated tilting rotor leads to wide range of possible configurations. Therefore, it is necessary to classify the full actuation types. Table attached below to be detailed.

Table 1. Full actuation classification

Inclination setting	Definition
Fixed-Tilt	Quadrotor with four horizontal rotors (Quad4Hor)
	Hexarotor with canted rotors (HexC)
	Hexarotor with canted and dihedral rotors (HexCD)
	Coaxial hexagon with 12 canted rotors (CoHexC)
	Double tetrahedron hexarotor (HexDTet)
	Heptarotor with minimized frame (HeptF)
	Heptarotor with maximized wrench (HeptW)
	Octarotor cube (OctCu)
	Octarotor beam (OctB)
Variable-Tilt	Quadrotor with variable cant rotors (QuadvC)
	Quadrotor with variable dihedral rotors (QuadvD)
	Quadrotor with variable cant and dihedral rotors (QuadvCD)
	Quadrotor with coupled variable cant and dihedral rotors (QuadvCDc)
	Hexarotor with variable cant rotors (HexvC)
	Hexarotor with coupled variable cant rotors (HexvCc)

It can be seen from literature survey that the HexC and HexCD concept have been extensively studied in recent years, which is due to their mechanical simplicity and less workload of transforming from conventional hexarotor to full actuation structure, as shown in Figure 3 and Figure 4 [2]. Moreover, the HexC structure got better performance on disturbance-rejection against lateral wind gusts compared with conventional hexarotor [9]. The concept of omnidirectional versions have been proposed and developed, the aim of which is to optimize the wrench to achieve the optimal solution of dynamic conversion [10,11].

Figure 3. HexC structure [12].

Figure 4. HexCD structure [13].

3. Feedback control method
In the practical application of UAV, the design of flight model needs to be equipped with feedback control system, to achieve the tracking of expected attitude, hover, throttle condition. Taking the drone as the control object, the speed of each motor is the control input and the flight state is the control output. On the basis of mathematical modelling, the setting and adjustment of parameters between them will directly affect the attitude adjustment and error correction capability of UAV in actual flight.

When it comes to fully actuated UAVs, traditional controllers such as PID control will not be effective in providing stable state tracking due to extra tilting dynamic vector of inclined rotors. Although PID control method has an important position in UAV control field due to its simple and efficient properties, it's not good at handling complex structures with too many variables and disturbance-rejection problem especially under the condition of nonlinear mathematical models of variable-tilt full actuation. Thus new feedback control methods need to be developed to solve and improve fully actuated UAVs control. Many experts and scholars have proposed many novel methods. For example, a kind of robust adaptive control method on fully actuated octocopter UAV was proposed to handle effect of parametric uncertainties and external disturbance in [9]. A robust pose tracking control method for a fully actuated hexarotor UAV based on Gaussian process was developed to tack position and attitude of drone in [14].

4. Conclusion

This article proves that both the design and control of fully driven UAVs are feasible enough. Through the above demonstration, its higher possibility can be proved to have better performance in urban traffic management, debris search and rescue, geological exploration and other conditions that demand work in extreme environments. Moreover, fully actuated multi-rotor UAVs are still in the development phase, it requires industry norms in structural design and a general approach to feedback control. The author believes it has a broader future and rapid progress.

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