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Design and Implementation of a Configurable Multi-rotor UAV

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ABSTRACT

This manuscript details the design process and implementation considerations of a configurable multi-rotor unmanned aerial vehicle (UAV), which is switchable between quadcopter mode and hexacopter mode in easy plug-and-play action. The design includes customized detachable rotor arms, complemented with an altered arrangement of motors to enable the simple switching feature between the two types of platforms. An innovative flight control architecture is formulated to handle both types of platforms using a single control algorithm. Mathematical modelling of the platforms is crucial to the proposed flight control algorithm and it will be briefly discussed in this manuscript. The configurable platform is implemented and actual flying tests have been conducted in both configurations to verify the feasibility of the design.

1 INTRODUCTION

With the advancement of robotic technologies, unmanned aerial vehicles (UAVs) or drones today are recognized to have huge potential in upgrading future transportation network, especially in aerial delivery system [1, 2, 3]. Specifically, the electrical multi-copters characterized by vertical taking-off and landing (VTOL) appear to be the most promising choice for logistics industry [4]. The commercial outlook of UAV delivery has attracted many technology companies to incorporate this fashionable element into their services [5]. One of the most notable products of recent time would be Prime Air, a delivery system designed by Amazon, which promises to safely bring the package to customers' doorstep within 30 minutes [6]. The high efficiency of this solution also projects the possibility of goods delivery in emergency cases, e.g. drug shipment and registered mail consignments [7]. On the other hand, the National Aeronautics and Space Administration (NASA) of America is also looking into the prospect of the drone-aided disaster management. With the speculation drones hovering above the disaster zone and transmitting back the real-time data and visual images of the constant-changing situations, authorities will be able to give faster responses and optimize their disaster relief planning [8].

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However, most UAVs in today's market, with a fixed range of payload capacity and a fixed number of rotor arms, are highly specialized in task execution. In the scenario, for example, where thousands of UAVs are employed for delivery tasks, since requirements on the loading capacity, delivery speed, flight duration and flight distance would vary case by case, the primary demand would be how to customize and deploy them to suit various needs of each delivery. Therefore, the problem with task specialization surfaces: dozens of models designed for different purposes need to be developed and mass produced to create a diverse pool of UAVs.

There are many existing researches seeking to improve the efficiency and flexibility of drone delivery system. On the hardware side, hybrid powering system is developed to meet varying power demands of the UAV. Managing the power from two energy sources into a single output is made possible with the smart *Power Manager* [9]. However, energy is not the only consideration to sustain a highly efficient delivery network. Hardware resources and its resilience are also important concerns for mass delivery. During peak periods, when UAV-network capacity is loading up to a saturation point (i.e. not enough vehicles to meet the service requests), even the optimal allocation of carriers in shipping process is not able to utilize them beyond the physical restrictions of the machines (the number of vehicles and their capacities). Hence, configurable drones will be at advantage to adjust themselves to suit the need of each and every task [10].

With this problem as our main motivation, a solution to enhance the adaptability of multi-rotor UAVs is proposed. Our solution makes use of detachable rotor arms of multi-rotor UAVs to support multi tasks with specific payload or flight duration. This manuscript provides detailed design methodology of an integrated multi-rotor UAV which is reconfigurable between two types of platforms. The paper is divided as follows: Section 1 given as introduction to this work; Section 2 shows a system overview of the solution; Section 3 details the hardware design and construction of the platform; a proposed universal flight controller will be proposed in Section 4; flight results will be shown in Section 5 and concluding remarks will be made in the last Section.

2 SYSTEM OVERVIEW

The proposed integrated system of multiple configurations provides several advantages over conventional multi-rotors:

1. *Versatility* - High power output from fully-loaded rotor arms enables larger loading capacity, faster speed and higher agility. Lower power output from partially-loaded rotor arms enables a longer flight duration.

2. *Usage* - High adaptability maximizes the potential of UAVs in all aspects of real-life applications.

3. *Portability* - The detachable mechanical parts can be disassembled and packed into a small package, saving space and reducing the possible damages to the delicate structure when being carried around.

4. *Cost-effectiveness* - Various multi-rotor models are integrated into one to achieve multiple purposes.

To start with the idea, a prototype is developed by adapting the most conventional configurations, quad-copter and hexa-copter, into one integrated system. This lays the foundation for integrating more configurations in the future. To achieve this, two major parts are considered:

1. *Physical structure* - The structure of the multi-rotor UAV needs to support multiple configurations, with specially important easy mount-and-remove characteristic on each of the rotor arms.

2. *Flight controller* - Conventionally, flight controller design for different types of platform will be slightly different. In this work, an all-in-one flight controller for different multi-rotor configurations is proposed.

3 Hardware Design

As both quad-copter and hexa-copter are well developed and designed, the focus of this paper is on the integration of both platforms into one single UAV. The emphasis is thus on the connecting mechanism, which allows user to mount the rotor arms to the UAV body with simple plug-and-play fashion. Following this, an alternate configuration of quad-copter and hexa-copter rotors placement is then proposed.

3.1 Connection Mechanism

The adaptability feature of the designed UAV requires easy restructuring. In design, connection mechanism of the rotor on the UAV body should fulfil two criteria: detachability and stability. In other words, it needs to be easily reconfigured while minimizing vibration during the flight. However, detachability and stability appear to be conflicting goals in conventional mechanical designs. To solve the dilemma of being either locked up or weakly secured, after research and experiments, a new form of connection mechanism is developed.

Shock-absorbing rubber tube clamps are used to minimize vibration during the flight. They provide strong friction to fix the rotor arm position while acting as the cushion on the main platform. Rubber tube clamps also allow the users to freely detach or plug in the rotor arms.

Figure 1: Shock-absorbing rubber tube clamp

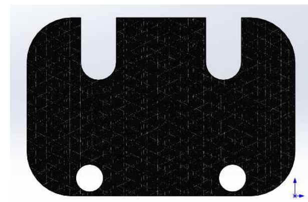

Figure 2: SolidWorks impression of the stabilizer

Since both the rotor arm and rubber tube clamps are circular-shaped, tube rotation is very likely to cause the rotor arm to deviate from its upright position. A stabilizer is specially designed to minimize the rotational shifting of circular-shaped rotor arms. One side of the stabilizer is fixed on top of the tube clamp, while the other side is plugged into the main platform to secure the relative position of the arm and UAV body.

The two additional mechanical designs, rubber tube clamps and stabilizers, take good care of the detachability and stability of rotor arms, allowing convenient installation and restructuring without undermining flying performance.

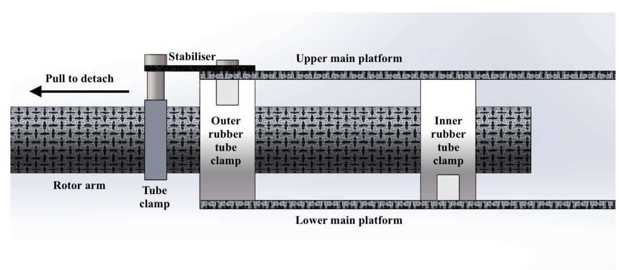

Figure 3: SolidWorks impression of the connection mechanism

3.2 Multi-rotor Configuration

This section describes the special configurations of the UAV in detail. To enhance the adaptability of the reconfigurable UAV, it is designed in such a way that, when users decide to restructure the UAV into a hexa-copter from a quad-copter, they do not have to change positions of any of the 4 rotor arms of the quad-copter. Therefore the 4 rotors on the quad-copter are organized in a non-perpendicular X shape to align with the rotor positions of hexa-copter configuration. To be more precise, the 1st and 2nd rotor arms are 60 degrees from each other while the 1st and 4th are 120 degrees from each other, just as Fig. 4 shows. The 5th and 6th rotor arms can be simply inserted so that the six rotor arms are all 60 degrees apart.

Similar to normal quad-copters, the UAV has two of its rotors rotating clockwise while the other two rotating anti-clockwise in quad-copter mode.

To make the platforms easily interchangeable, the 3rd and 4th rotor arms of the hexa-copter is swapped (from conventional hexa-copter design) so that their rotating directions are consistent of that of the quad-copter platform. It is proved to be dynamically viable in Section 4 of the paper.

Overall, three main modifications are made in hardware design to realize the adaptability of both quad-copter and hexa-copter configurations: connection mechanism, non-perpendicular X configuration of quad-copter and rotor re-arrangement of hexa-copter. The platform is first designed in SolidWorks 3D simulation (Fig. 5 to Fig. 6) then implemented to actual platform.

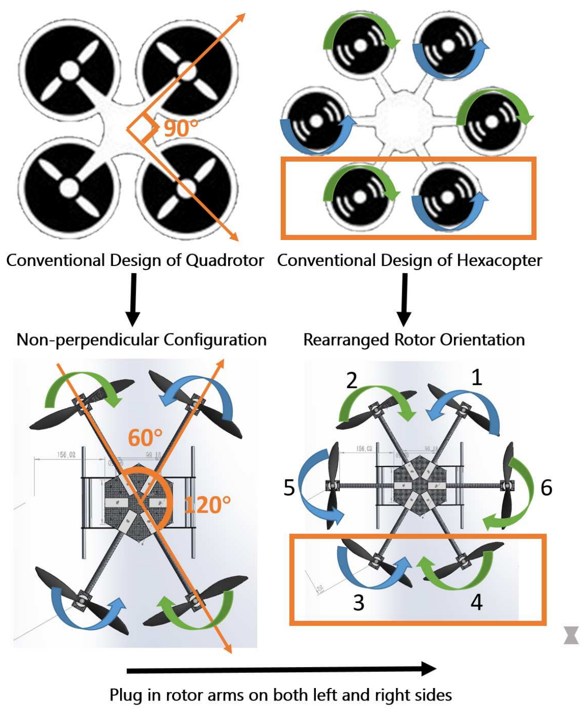

Figure 4: Graphical illustration of hardware modifications

Figure 5: SolidWorks impression of quad-copter configuration

Figure 6: SolidWorks impression of quad-copter configuration

4 2-IN-1 CONTROLLER DESIGN

In literature, mathematical modellings and flight controller designs for both quad-copter and hexa-copter are well derived and documented [11, 12, 13]. The two models are, however, distinct and individual flight controllers were specifically designed for both models. In our integrated system of convertible quad-copter and hexa-copter, a novel idea of controlling both the platforms with a single controller is proposed in this manuscript. It will be discussed extensively in this section.

4.1 Overview

The overview of a typical flight control structure for multi-rotor systems can be visualized in Fig. 7 [14]. The proposed 2-in-1 controller uses the same structure as in Fig. 7, with 2 different Inner Multi-rotor Dynamics blocks: one for quad-copter, and one for hexa-copter. These two sets of inner dynamics will be automatically switched when a different configuration of the multi-rotor is detected.

Translational/rotational kinetics and outer multi-rotor dynamics of all multi-rotor UAVs are similar, and it is governed by the following equations [12]:

$$\begin{aligned} m\dot{V}_b + \omega \times (mV_b) &= F, \\ J\dot{\omega} + \omega \times (J\omega) &= M, \\ \dot{V}_b &= a_b, \\ \ddot{P}_n &= a_n. \end{aligned} \quad (1)$$

Here, m is the mass of the UAV which can be easily measured. J is the moment of inertia of the UAV which can be

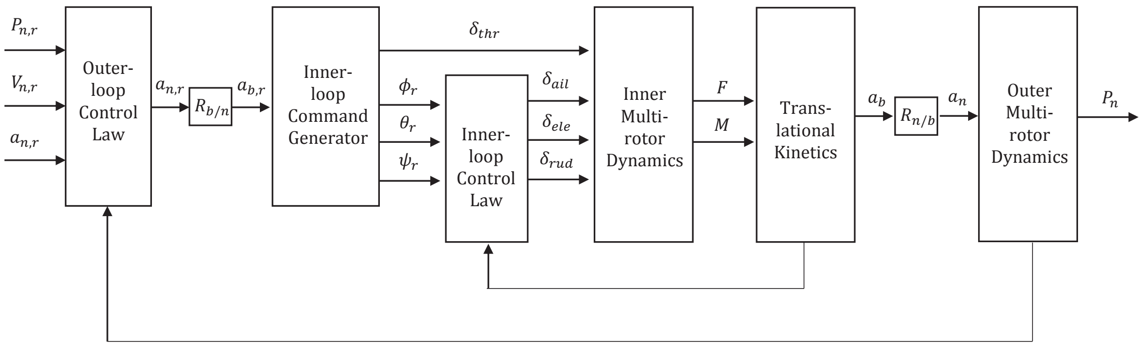

Figure 7: Flight control block diagram

determined from the trifilar pendulum experiment [12]. Both the m and J for quad-copter and hexa-copter configurations will be recorded and used in the unified flight controller.

For inner-loop command generator, it relates the body-frame acceleration reference $a_{b,r}$ to the Euler angle references $\{\phi_r, \theta_r\}$ and the normalized input to the throttle channel δ_{thr}, as

$$\begin{bmatrix} \delta_{thr} \\ \phi_r \\ \theta_r \end{bmatrix} = \begin{bmatrix} 0 & 0 & K_{thr} \\ 0 & 1/g & 0 \\ -1/g & 0 & 0 \end{bmatrix} a_{n,r}, \qquad (2)$$

where K_{thr} is a constant gain depending on the thrust coefficient of the motors.

4.2 Inner Multi-rotor Dynamics

As the platform is inter-transformable between a quad-copter and a hexa-copter, the inner multi-rotor dynamics which generates the forces and moments acting on the UAV's body can be divided into 2 portions. The dynamical models of the two configurations will be similar as long as the inputs and outputs to this block remain consistent, namely the four normalized inputs $\{\delta_{thr}, \delta_{ail}, \delta_{ele}, \delta_{rud}\}$ and the forces and moments $\{F, M\}$ acting on the UAV.

By making both the inputs and outputs of this block consistent, it allows us to design a single controller to control both the systems, with just a simple switching of inner multi-rotor dynamics block and the parameters m and J as mentioned above.

By the assumption of fast motor rise time, we can approximate the relationship between the inputs and the outputs of this block to be static. In the other words, only the steady-state is concerned.

According to [14], the relationship between thrust produced by the rotating rotor and the rotating speed is

$$T = C_T \rho D^4 \frac{\Omega^2}{4\pi^2}, \qquad (3)$$

where C_T is the aerodynamic thrust coefficient of the rotor, ρ is the density of air, and D is the diameter of the rotor. As for small fixed-pitch propellers, C_T is constant. We thus can lump the constants together as

$$T = k_T \Omega^2. \qquad (4)$$

Similarly for torque of the rotor, we have

$$Q = k_Q \Omega^2. \qquad (5)$$

4.2.1 Quad-copter

The relationship between the rotating speed of four rotors and the total forces and moments generated by the quad-copter, according to the quad-copter configuration shown in Fig. 4 can be easily derived as

$$\begin{bmatrix} f_z \\ m_x \\ m_y \\ m_z \end{bmatrix} = \mathbf{K_Q} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix}, \qquad (6)$$

where

$$\mathbf{K_Q} = \begin{bmatrix} -k_T & -k_T & -k_T & -k_T \\ -\frac{lk_T}{2} & \frac{lk_T}{2} & \frac{lk_T}{2} & -\frac{lk_T}{2} \\ \frac{lk_T\sqrt{3}}{2} & \frac{lk_T\sqrt{3}}{2} & -\frac{lk_T\sqrt{3}}{2} & -\frac{lk_T\sqrt{3}}{2} \\ k_Q & -k_Q & k_Q & -k_Q \end{bmatrix}. \qquad (7)$$

Each motor of the UAV can be represented by

$$\Omega(s) = \frac{1}{\tau_m s + 1}(C_R \delta + \Omega_{trim}), \qquad (8)$$

where τ_m is the motor time constant, which is generally small enough to be ignored, and C_R is the steady-state gain of the motor rotating speed given the input δ.

Finally, a mapping matrix to map the block's inputs $(\delta_{thr}, \delta_{ail}, \delta_{ele}, \delta_{rud})$ to the motors' input $(\delta_1, \delta_2, \delta_3, \delta_4)$ as follows:

$$\begin{bmatrix}\delta_{thr}\\ \delta_{ail}\\ \delta_{ele}\\ \delta_{rud}\end{bmatrix} = \begin{bmatrix}1 & 1 & 1 & 1\\ -1 & 1 & 1 & -1\\ 1 & 1 & -1 & -1\\ 1 & -1 & 1 & -1\end{bmatrix}\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\\ \delta_4\end{bmatrix}. \quad (9)$$

Note that in order to obtain a unique solution of the inputs $(\delta_{thr}, \delta_{ail}, \delta_{ele}, \delta_{rud})$ given any desired forces and moments (F, M), $\mathbf{K_Q}$ must be invertible.

4.2.2 Hexa-copter

Similar to that of the quad-copter counterpart, the relationship between the rotating speed of six rotors and the total forces and moments generated by the hexa-copter, according to the hexa-copter configuration shown in Fig. 4, can be derived as

$$\begin{bmatrix}f_z\\ m_x\\ m_y\\ m_z\end{bmatrix} = \mathbf{K_H}\begin{bmatrix}\Omega_1^2\\ \Omega_2^2\\ \Omega_3^2\\ \Omega_4^2\\ \Omega_5^2\\ \Omega_6^2\end{bmatrix}, \quad (10)$$

where

$$\mathbf{K_H} = \begin{bmatrix}-k_T & -k_T & -k_T & -k_T & -k_T & -k_T\\ -\frac{lk_T}{2} & \frac{lk_T}{2} & \frac{lk_T}{2} & -\frac{lk_T}{2} & lk_T & -lk_T\\ \frac{lk_T\sqrt{3}}{2} & \frac{lk_T\sqrt{3}}{2} & -\frac{lk_T\sqrt{3}}{2} & -\frac{lk_T\sqrt{3}}{2} & 0 & 0\\ k_Q & -k_Q & k_Q & -k_Q & k_Q & -k_Q\end{bmatrix}.$$

Note that the motor dynamics and mapping matrix are identical to the quad-copter's part.

In order to obtain a unique solution of this hexa-copter system, we need to find an inverse of $\mathbf{K_H}$. As $\mathbf{K_H}$ is rank 4, one solution to the system would be taking the right inverse of $\mathbf{K_H}$, i.e.

$$\mathbf{\Omega} = \mathbf{K_H^T}(\mathbf{K_H}\mathbf{K_H^T})^{-1}\begin{bmatrix}f_z\\ m_x\\ m_y\\ m_z\end{bmatrix}. \quad (11)$$

4.3 Control

Once the control structure of the system is fixed as in Fig. 7, controllers can be designed accordingly. There are two separated controllers in the system, the inner-loop controller and the outer-loop controller.

Inner-loop controller helps stabilize the UAV and orientate the platform to any desired Euler angle reference. As the inner-loop controller runs at a much faster rate as compared to the outer-loop, a position controller can be designed by assuming any desired Euler angle can be achieved within a single control loop on the outer-loop. This control strategy is well established and widely used in UAV control and thus it will not be further elaborated here. Interested reader can refer to [12, 14].

5 PROTOTYPING

Figure 8: Assembled hexa-copter configuration

Figure 9: Assembled quad-copter configuration

A UAV with the transforming capability was constructed according to the SolidWorks impression shown in Fig. 4. Main parts of the UAV's body are made of carbon fiber, while a Pixhawk flight controller is included to implement the proposed 2-in-1 controller. Specification of the UAV of both configurations matched with a 4 cells 5200 mAh battery is shown in Table 1. The design specification is met with actual flying experiment of the UAV in its two different modes.

	Quad-copter	Hexa-copter
Weight	1532 g	1796 g
Payload	100 g	600 g
Flight duration	23 mins	15 mins

Table 1: Specification of the platform

6 Conclusion

The paper elaborates in detail the design and modelling of a configurable multi-rotor UAV. Rotor arms are arranged into the formation adaptable to both quad-copter and hexa-copter flights. Connection mechanism enables easy detachment or installment of arms. Mathematical modelling proves the viability of modified configuration in flight kinematics and forces and moments generation. The configurable multi-rotor UAV performs well in actual flight tests with different payloads. In future, more configurations can be integrated into this UAV platform to further enhance its versatility. Autonomous control law can also be implemented such that the UAV would fly automatically with the assistant from GPS. With this UAV prototype as a foundation, future UAV platforms are able to operate with adjustable loading capacity, flying speed and flight duration over a wider range. When in service among large UAV fleets, each is more energy efficient and adaptable in catering to its specific task; when in private use, configurable UAV is flexible enough to handle personal requests of all sorts.

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