A Comparison of Optimised, Fixed-Tilt, Fully-Actuated Multirotor UAV Configurations

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ABSTRACT

Multirotor Unmanned Aerial Vehicles (UAVs) that are fully-actuated offer improved dexterity for aerial manipulation tasks by decoupling attitude and translation. There is also potential for improved agility when the airframe design is optimised, which can lead to better disturbance rejection. This paper compares three fixed-tilt configurations by evaluating optimal designs of each as a function of different design requirements: payload, flight time, and horizontal force while in level hover. Three different characteristics are used as objective functions in the optimisation: thrust bandwidth, airframe mass, and airframe diameter. The results highlight the advantages of a heterogeneous rotor configuration, providing the best trade-off between agility and energy efficiency.

1 INTRODUCTION

In recent years, novel multirotor Unmanned Aerial Vehicle (UAV) configurations have been introduced that are fully-actuated [1-9], driven mainly by aerial manipulation of physical interaction tasks [10, 11]. Examples of fully-actuated configurations are shown in Figure 1. Some designs satisfy a specific operational requirement, such as the placement of a tool requiring a large clearance between two sets of rotors [5]. However, in most cases, the rotor configurations are not designed with an application in mind. Across all the possible configurations, it is not clear which has the potential to operate most favourably as design requirements are changed.

Full-actuation in multirotor UAVs can be obtained via use of fixed-tilt rotors [1-3, 12-15], variable-tilt rotors [16-19] or variable-pitch rotors [20, 21]. Fixed-tilt rotors are mechanically the simplest but sacrifice flight endurance and are the focus of this paper. Different configurations of fixed-tilt rotors are possible. The simplest is to tilt all rotors to the same angle about either one [2, 3, 12, 13] or two [1, 14, 15] axes. One of our studies [1] concluded that there is no advantage to tilting rotors about an axis perpendicular to the rotor arm, also known as dihedral. Having symmetry and uniformity of rotor tilt is helpful in creating a structurally simple system. However, having different tilt for each rotor allows for either the use of fewer rotors [9], omnidirectional motion [4], or unequal force capabilities [6]. In these cases, there is a clear link between the configuration and the performance advantages they may provide.

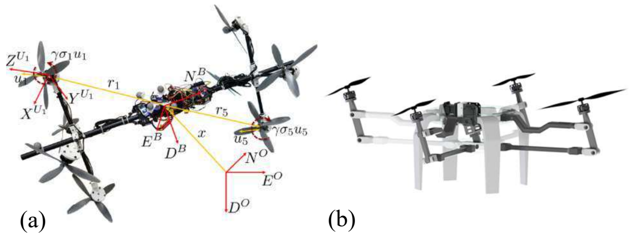

Figure 1: Examples of fully-actuated multirotor UAVs:
(a) fixed-tilt octorotor [5], (b) variable-tilt quadrotor [19].

A clear link between rotor configuration and performance is not always the case. For example, consider heterogeneous configurations, which contain different sets of rotors [1, 7, 23]. In our research group's earlier work, heterogeneous configurations were introduced to solve the problem of the decreased agility of homogenous configurations at high payload mass [2] and, in [1] were shown to have a higher thrust bandwidth at one design condition. This advantage did not hold for other design conditions, especially at lower payload mass, where the homogenous configuration performed well [3]. We explored the use of coaxial and overlapping rotors, involving either all rotors [2] or a subset of the rotors [1]. However, a direct comparison was not made to a configuration with non-coaxial rotors.

Previous studies have attempted to quantify agility. One measure is the bandwidth of the rotor thrust response horizontally [1, 2]. Another is the maximum rotor thrust [4]. In [25], the author introduced nine different experimental ways to measure the agility of a UAV. An example of the introduced methods is the maximum attitude acceleration and time needed to reach a particular attitude. The author in [3] performed an optimisation where horizontal force has a minimum requirement and assumed that after optimisation, the UAV would have a maximum force equal to the required force; thus, rather than using acceleration, the mass of the UAV was used to characterise agility.

The main contributions of this paper are (1) an approach that fairly compares fully-actuated airframes using optimal solutions of each with identical performance requirements, and (2) a thorough comparison of three octorotor configurations. The comparison is performed across different design requirements and three different objective functions to illustrate how the approach can identify the most favourable configuration.

The remainder of this paper is organised as follows. Section 2 describes the case study undertaken. The results for the different optimisations are presented in sections 3, 4, and 5. Section 6 discusses the implications of the results. The paper is concluded in Section 7.

2 DESCRIPTION OF CASE STUDIES

This section describes the case studies performed, including the different configurations, design requirements and objective functions used. Optimisations use the aerodynamic, electrical, and structural models described in [22] except that the calculation of rotor moment of inertia uses the improved model in [26].

2.1 Configurations

Three different configurations with eight fixed-tilt rotors are considered: *Planetary Hex* [1], *Stacked Octo* [2] and *Planar Octo* [3], illustrated in Figure 2. These configurations are chosen because all were previously optimised for their agility. Both the Planar Octo and Stacked Octo configurations are each considered to be homogenous configurations due to having rotors of the same diameter and tilt angles. The Planetary Hex is a heterogenous configuration, using two different sets of rotors: 'sun' rotors in the centre and 'planet' rotors around the perimeter. The Planetary Hex and Stacked Octo configurations have coaxial or overlapping rotors with a thrust penalty of 20% applied to the lower rotors [24].

2.2 Optimisation Problem

A constrained optimisation problem consists of constraints, referred to here as *design requirements*, and the *objective function*. The design requirements chosen are the payload mass, hover flight time, and desired horizontal force. The payload is defined as all non-flight-critical components, such as sensors, companion computers, and manipulators. The horizontal force is defined as the magnitude of a persistent force that the UAV rotors must produce in a horizontal plane while the aircraft is hovering in level flight. The force requirement could, for example, be dictated by an aerial manipulation task or aerodynamic drag from a steady wind. Table I lists the nominal values of the design requirements and the ranges over which each were varied. Within the case studies, one design requirement is changed at a time. For example, when varying the payload from 1 kg to 20 kg, the required hover time and horizontal force are 10 mins and 2 N, respectively.

For the optimisation objective function, three different airframe characteristics are explored separately: (1) open-loop bandwidth of rotor thrust, (2) airframe mass, and (3) airframe diameter. The importance of each characteristic would depend on what the designer deems the most important performance objective. If the UAV is intended to station-keep while rejecting wind disturbances, the rate at which the rotors can adjust thrust is important, correlated to high thrust bandwidth. If the UAV is required to track a fast-changing trajectory, the airframe mass should be minimised. If the UAV must operate in confined spaces, then a small airframe diameter is required.

Requirement	**Nominal**	**Range**
Payload	1 kg	1 – 20 kg
Hover Time	10 min	5 – 30 min
Horizontal Force	2 N	2 – 20 N

Table I: Design requirements: nominal and sweep range.

2.3 Optimisation Method

In our previous work [22], we describe a two-stage hybrid optimisation method to deal with the continuous variables (such as rotor tilt angles) and discrete variables (motor and propeller components). In the first stage, a surrogate optimisation finds an initial design by using empirical models

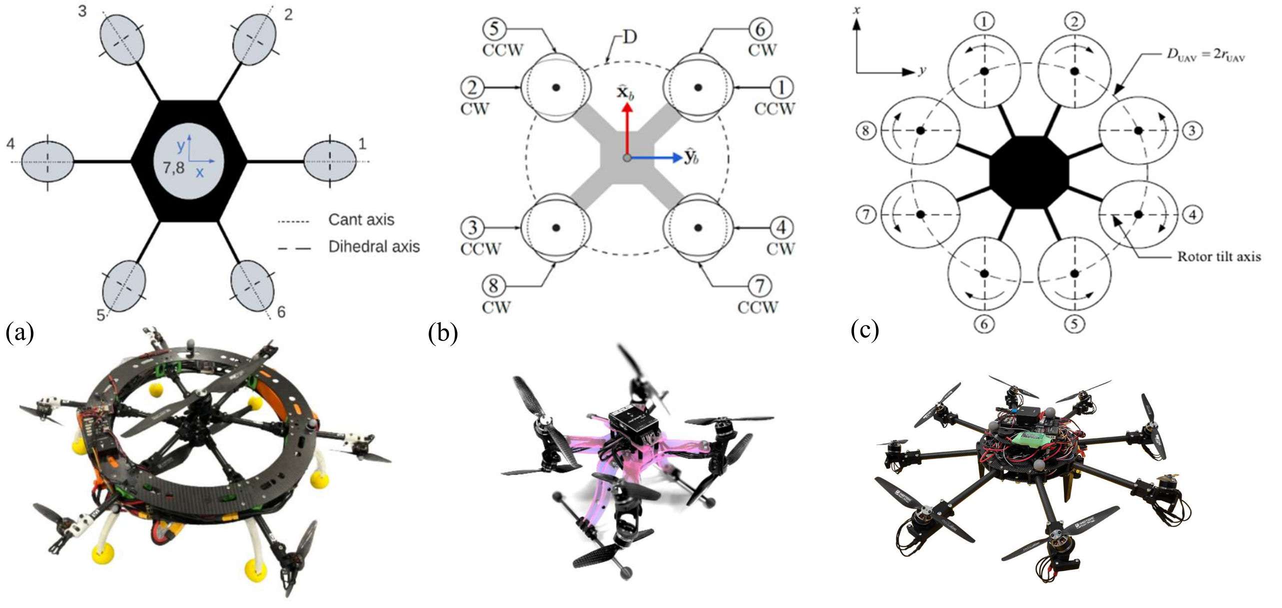

Figure 2: Rotor configurations examined and flight-tested instances of each (not to scale):
(a) Planetary Hex [1], (b) Stacked Octo [2], (c) Planar Octo [3].

for the relationships between the discrete design variables, simplifying the problem to one involving only continuous variables. The empirical models are based on a database of 250 motors and 84 propellers. The second stage is a localised parameter sweep of only discrete design variables, arriving at a design that can be fabricated. In this paper, we examine the optimal solutions after only the initial stage so that trends are not dependent on the discrete components available.

The set of continuous design variables, X, for optimising each configuration are listed in Table II. All other geometric properties are dependent on these variables. The additional variable, *planet hover thrust*, specifies the proportion of the total vertical thrust that is contributed by the planet rotors.

Planetary Hex	**Planar Octo**	**Stacked Octo**
Planet rotor tilt angle	Rotor tilt angle	Rotor tilt angle
Sun rotor diameter Planet rotor diameter	Rotor diameter	Rotor diameter
Planet hover thrust		

Table II: Design variable sets, X, for each configuration.

3 MAXIMUM THRUST BANDWIDTH

This set of case studies considers horizontal thrust bandwidth, f_{HT}, requiring the optimisation objective function

$$\max_X f_{HT}. \qquad (1)$$

3.1 *Effect of Changing the Payload Requirement*

In this subsection, optimal designs are calculated for different payload mass requirements while keeping hover time and horizonal force constant at 10 minutes and 5 N, respectively. The resulting thrust bandwidth is shown in Figure 3. The small trend fluctuations are likely caused by the battery model requiring an integer number of LiPo cells.

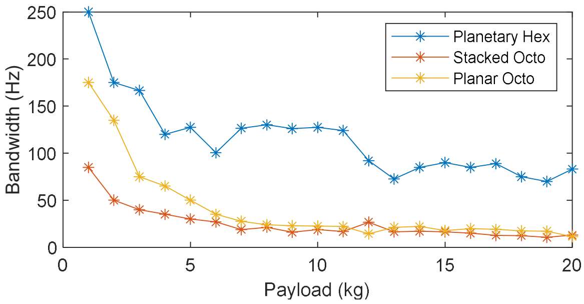

Figure 3: Effect of changing the payload mass on thrust bandwidth.

As payload increases, the thrust bandwidth decreases for each configuration. This is an expected result due to needing larger rotors to lift larger mass UAVs. Larger rotors have a higher thrust bandwidth due to their larger mass moment of inertia. Previous work has demonstrated the superior bandwidth of the Planetary Hex configuration at a single low payload [1]. Figure 3 demonstrates superiority across all payloads, by as much as 5 times for payloads greater than 7 kg. The Planar Octo and Stacked Octo configurations perform similarly at the higher payloads. At lower payloads, the differences in bandwidth are more pronounced due the more significant impact of the shadowed lower rotors on the Stacked Octo.

3.2 *Effect of Changing the Hover Time Requirement*

In this subsection, only the hover time requirement is varied, while payload and required horizontal force are kept constant. Results are shown in 4. The decreasing bandwidth with flight time for all configurations is logical because proportionally larger battery capacities are required, as shown in Figure 5. This leads to increased battery mass, total mass, and larger rotors, consistent with the payload study.

Comparing configurations, there are no unexpected trends with thrust bandwidth. The Planetary Hex is superior, followed by the Stacked Octo and Planar Octo. The Planar Octo requires the lowest battery capacity and consequently the lowest current draw for a given flight time.

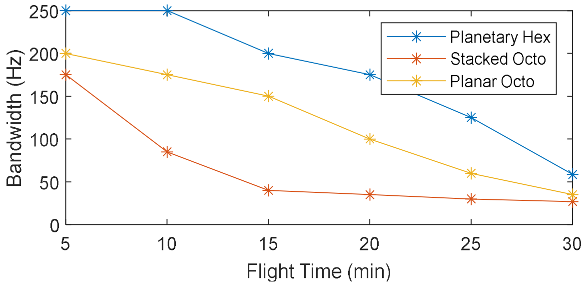

Figure 4: Effect of changing hover time on thrust bandwidth.

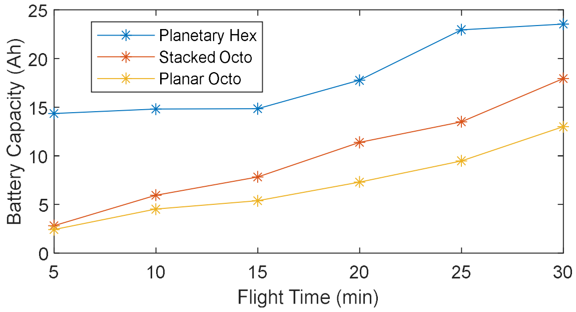

Figure 5: Effect of hover time on required battery capacity.

3.3 *Effect of Changing the Horizontal Force Requirement*

In this subsection, only the horizontal force requirement is varied, while payload and hover time are kept constant. The results are presented in Figure 6. Larger horizontal force is achieved by a combination of larger tilt angles and larger rotor diameters, resulting in lower thrust bandwidth, regardless of the configuration. For example, the trend in planet tilt angles for the Planetary Hex is shown in Figure 7.

The Planetary Hex configuration maintains a higher bandwidth across the entire range of required horizontal force, followed by the Planar Octo and Stacked Octo configurations.

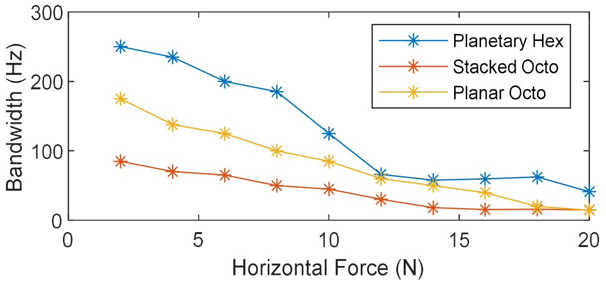

Figure 6: Effect of changing the horizontal force requirement on thrust bandwidth.

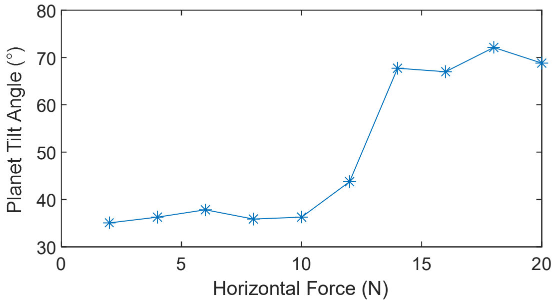

Figure 7: Effect of changing the horizontal force requirement on planet rotor tilt.

4 MINIMUM MASS

This set of case studies considers optimising for lowest mass. The mass of the payload, m_{pay}, is subtracted from the total mass of the UAV, m_{UAV}, to isolate the airframes in the comparisons. The optimisation objective function is thus

$$\min_{X}\left(m_{UAV} - m_{pay}\right) . \tag{2}$$

4.1 Effect of Changing the Payload Requirement

This case study explores the effect of increasing the payload on the bandwidth of the optimal UAV of each of the three configurations. Linear trends can be seen in Figure 8. As expected, with an increase in payload, the mass of the UAV also increases. Higher thrust demands with payload increase the required battery capacity, rotor sizes, and frame sizes, all of which increase UAV mass.

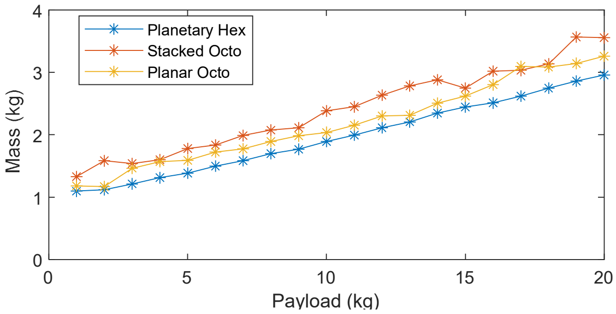

Figure 8: Effect of changing the payload mass on UAV mass (excluding payload).

The Stacked Octo and Planar Octo have very similar mass airframes across all payloads tested. Marginally, the Planetary Hex is consistently the lightest configuration. Examining the mass of the different sets of components that comprise the UAV airframe, Figure 9, reveals that the Planetary Hex can have the lowest mass because of its heterogeneous set of rotors. Effectively, having 2 larger rotors and 6 small rotors is generally lighter than 8 rotors of the same size.

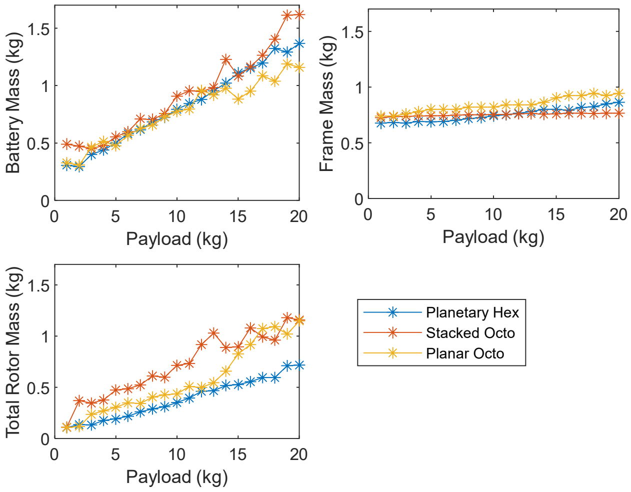

Figure 9: Mass of individual UAV components.

4.2 Effect of Changing the Horizontal Force Requirement

This case study explores the effect of increasing the horizontal force requirements on the mass of the optimal UAV for each of the three configurations. The increase in force requirements is expected to increase the mass for each configuration. This is because the tilt angle will have to be increased, resulting in a larger battery capacity and mass. As seen in Figure 10, the mass of the Planetary Hex configuration is lower across all horizontal force requirements than the other two configurations. In addition, as in the previous case studies, the Stacked Octo is inferior to the other two configurations.

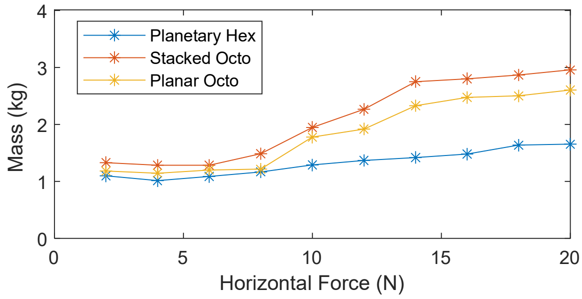

Figure 10: Effect of changing the horizontal force requirement on UAV Mass (excluding payload).

A significant trend in the Planetary Hex design as horizontal force requirement increases is the angle of the planet rotors, as shown in Figure 11. Increasing the tilt angle allows more thrust within the horizontal plane, increasing the horizontal force capabilities. When not required, a low angle is favourable as it means less opposing thrust, i.e. more efficient UAV and lower battery capacity required, resulting in a lower mass.

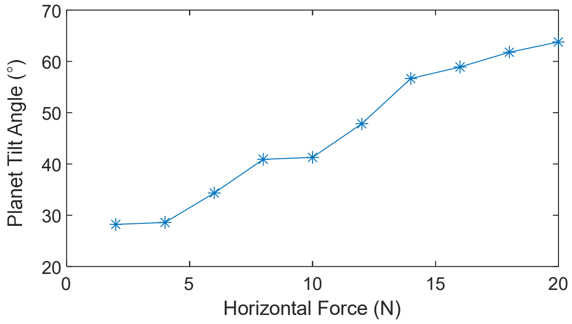

Figure 11: Effect of changing horizontal force requirement on planet rotor tilt.

5 MINIMUM DIAMETER

This case study involves minimising the diameter of the UAV, D_{UAV} and examines the effect of changing only one design requirement, the payload mass. Here, diameter of the UAV is defined as the diameter of the circle passing through the centres of each outer rotor. The diameter is expected to increase with the payload because of the need for larger rotors to produce more lift. The results in Figure 12 confirms this expected trend.

Up to payloads of 5 kg, there is no significant difference between the minimum diameters of all three configurations. Above 5 kg payload, the Planetary Hex is consistently the smallest configuration, followed by the Stacked Octo, and then the Planar Octo. It follows that configurations with rotors that are stacked or coaxial can achieve a smaller diameter. The losses caused by rotor overlap are not significant when diameter is the optimisation objective.

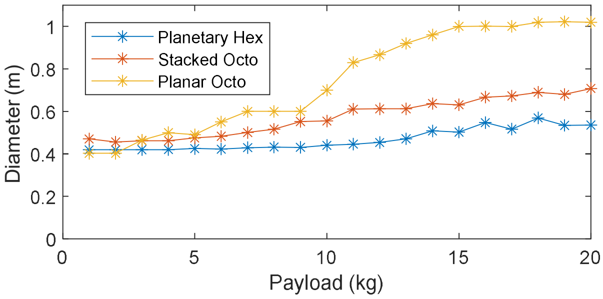

Figure 12: Effect of changing payload mass on UAV diameter.

6 DISCUSSION

Some common findings are observed across the different case studies. Firstly, the heterogeneity of the Planetary Hex was a significant reason behind the configuration being superior compared to the other two under all situations. Heterogeneity contributes to this improvement through two main methods. The first aspect is evident when the two rotor sets are responsible for different design requirements. An example is the bandwidth case study with the payload requirement change. For a significant range of the payloads tested, it was found that the planet rotors, which are responsible for the thrust bandwidth, did not change, but the sun rotors adjusted to produce a UAV that could satisfy the requirements.

The other method in which heterogeneity contributes to improved design is the ability to reduce UAV capabilities without affecting the requirements. In some instances, using the same eight rotors compared to 2 different rotor sets totalling eight rotors is not advantageous as both achieve the same design requirements. The heterogeneous UAV can use a lower-performing rotor as it does not contribute; it will only require a low contribution to achieve the UAV's design requirements. This condition is demonstrated in the mass case study with the horizontal force requirement change. It was found that the sun rotor used was selected within certain design regions for its light mass, as it only needed to contribute a small amount of the total thrust for hover. Similarly, this effect is clear when looking at the change in planet rotors.

The other modification is the use of overlapping rotors, either coaxial or stacked. Using overlapping rotors was consistently unfavourable except when optimising for smallest diameter. In a case where a UAV hovers far away from obstacles, size would not be a major factor.

7 CONCLUSIONS

The paper presented an approach to fairly compare design characteristics of different UAV configurations by ensuring each design is optimised with the same design constraints. Using this approach, studies were presented to evaluate the thrust bandwidth, mass, and diameter by comparing three UAV configurations: Planetary Hex, Planar Octo, and Stacked Octo. The Planetary Hex proved superior in all cases due to its heterogeneous rotor design. Of the homogeneous configurations, the Stacked Octo was inferior when optimising for bandwidth or mass but superior to the Planar Octo when optimising for minimum diameter.

The results are based on empirical models and make several simplifying assumptions. Experimental work is required to validate the comparisons, such as by building and bench-testing a sample of the optimal designs. This study could be further expanded by including other fully-actuated UAV configurations.

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