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# Towards A More Efficient Quadrotor Configuration

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***Abstract*— The small rotor sizes of quadrotors and multirotors makes them intrinsically less energy efficient than a traditional helicopter with a large single rotor. However, the quadrotor configuration's innate simplicity and inexpensive construction recommends its use in many aerial robotics applications. We present a four-rotor configuration that merges the simplicity of a quadrotor with the energy efficiency of a helicopter, while improving manoeuvering rotor bandwidth. This class of aircraft, called a 'Y4' or 'triangular quadrotor', consists of a single fixed-pitch main rotor with three smaller rotors on booms that provide both counter-torque and manoeuvering control. Our analysis indicates that a Y4 may provide a 20 per cent reduction in hovering power required, compared with a similarly sized conventional quadrotor. Using a matched pair of quadrotor/triangular quadrotor aircraft, our preliminary experiments show that the test-bed Y4 used 15 per cent less power, without optimisation. We present a dynamic model and demonstrate experimentally that the aircraft can be stabilised in flight with PID control.**

## I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have stepped out of the realm of academic research and military operations and are rapidly becoming useful in civilian applications. Advances in integrated avionics have driven the cost and complexity of UAVs down, and into the hands of commercial users. There is increasing demand for reliable UAV platforms that can carry large equipment payloads, and have longer flight times and range — particularly for indoor applications.

The utility of hovering UAV systems is bounded by available power sources, and the efficiency of transferring that energy to the air via rotors. This restricts the achievable payload, flight time and speed performance, typically to payloads of less than 1 kg or flight times of less than 20 minutes for vehicles small enough to fly through doorways and around human spaces [1]. Increasing available energy stores correspondingly requires heavier (and thus larger) aircraft that would not fit in small spaces. The energy density of power sources improves slowly — thus, we focus on improving energetic performance of aircraft but maximising the power efficiency of lifting systems.

The power a rotorcraft requires to hover scales with the mass being lifted and the area of the rotor [2, p 63]. For this reason, skycranes and cargo helicopters have particularly large diameter rotors [3] or multiple rotors [4] to reduce disc-loading. In contrast, the smaller rotors employed by quadrotors and multirotors are more energy intensive [5]. However a trade-off of helicopters lies in the complex

Fig. 1: 'Y4' Triangular Quadrotor Configuration.

rotorhead mechanics, which are maintenance intensive — quadrotors, conversely, are simple and robust.

Our approach is to combine the energetic benefits of a helicopter's single large rotor with the simplicity of a quadrotor. This is achieved by employing a single large main rotor with three smaller manoeuvering rotors. The small rotors are canted to provide counter-torque like the tail-rotor of a traditional helicopter. By placing the manoeuvering rotors beneath the main rotor, the largest rotor disc area may be realised for a given maximum footprint diameter. Furthermore, the low rotational inertias of the smaller rotors increase the available attitude control bandwidth, but at the cost of increased gyroscopics of the larger rotor [6]. We call this configuration a 'triangular quadrotor' or 'Y4'.

Similar multirotor arrangements have been previously developed with an eye towards increasing payload. The SkySapience Hovermast [7] employs a single larger central rotor with smaller outboard rotors, as does the CLQ16 Aerial Platform [8]. These designs are aimed at increasing lift by employing rotors matched to a chemical fuel drive system; they rely on the drag torque of co-linear outboard rotors to provide counter-torque. Their use of numerous outboard rotors (four or more), which require a larger footprint for a given main rotor diameter, reduces the expected achievable efficiency compared with the proposed configuration.

To test the anticipated performance improvement of the triangular quadrotor, we developed a matched quadrotor and Y4 pair. These aircraft are of identical gross mass, motor mass, footprint diameter, flight controllers, batteries and central airframe. They differ only in the number of boom arms, and the rotor-motor-speed controller combinations being tested. By comparing their performance directly, we can assess the relative merits of the proposed approach.

In this paper we describe the improved rotor configuration for hovering multi-rotor robots and compare its energetics to

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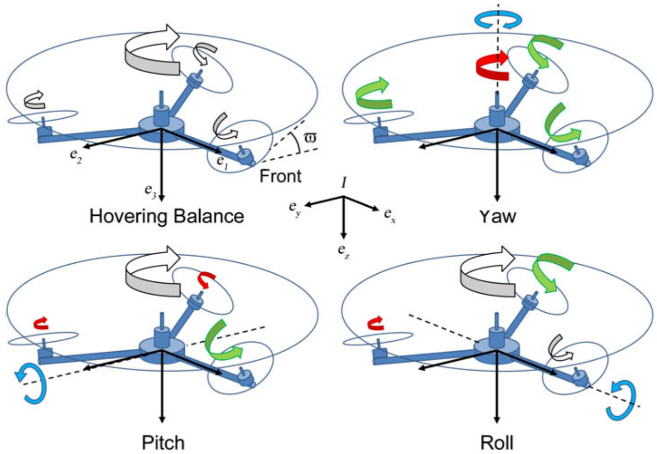

Fig. 2: Triangular Quadrotor Manoeuvering Controls. Arrow sizes indicate relative rotor velocities (white arrows are constant).

a 'matched pair' conventional quadrotor. In Section III we analyse the theoretical performance of rotor configurations for flight indoors, and consider the effect of rotor size and gyroscopics on control bandwidth. In Section IV we present a comparative dynamic model and control schema for the Y4 configuration with respect to a standard quadrotor. Section V presents preliminary power experiments. A brief conclusion completes the paper.

## II. The Triangular Quadrotor

The proposed configuration is a hybrid between traditional helicopters and quadrotors. The configuration uses a single large fixed-pitch rotor at the centre of the craft to provide the majority of lift. Three smaller rotors spaced around the central point on booms, each slightly canted sideways at a fixed angle, provide lateral thrust (see Fig. 1). Like the traditional helicopter, the boom-mounted rotors provide active counter-torque; like a quadrotor, the rotors provide control torques. Unlike a quadrotor, these three smaller devices are not intended to provide significant lifting thrust.

The manoeuvering moment produced by the counter-torque rotors is derived from their vertical thrust component. Control torques are applied much like standard quadrotors — the speed of one rotor is increased while the other two is decreased. This maintains the total counter-torque produced in the plane, whilst producing an asymmetry in the vertical thrust components (see Fig. 2). This causes the rotorcraft to pitch or roll in the air in an identical fashion to standard quadrotors. Yaw control is derived akin to traditional helicopters — the combined counter-torque of the boom-mounted rotors is increased or decreased to affect azimuthal rotation.

As a rotorcraft with four fixed-pitch rotors, the Y4 configuration technically remains a quadrotor and preserves its mechanical simplicity, while also delivering the full area of lifting surface provided by a helicopter. The counter-torque rotors can be mounted outboard of the main rotor or above or below it. Outboard motors provide more effective torque for lower thrust (but with longer boom arms), while under or over mounted rotors allow the design to be made maximally compact. Furthermore, the counter-torque rotors all spin the same direction, reducing the limitation of requiring matched forward and contra-rotating pairs and increasing flexibility when designing with commercial off-the-shelf parts.

## III. Rotor Energetics and Inertia

There are two broad areas of interest in the performance of quadrotors: energetic performance and control performance. Energetics determines the achievable flight time, range and payload weight an aircraft can carry, while control determines its ability to manoeuver and reject disturbances. This paper predominantly considers the energetics of the triangular quadrotor configuration, but a control model is also presented with references to conventional quadrotor design.

### A. Quadrotors vs Traditional Helicopter

From momentum theory, the power required by a rotor, $P$, is linked to the desired thrust [9, p22]:

$$P = \frac{T^{3/2}}{\sqrt{2\rho A}} \tag{1}$$

where $T$ is the hover thrust, $\rho$ is the density of air, and $A$ is the rotor disc area. For a traditional helicopter, $T$ is weight force of the aircraft and the effective area of the rotor will be the region swept by the rotor disc, less the region obscured by the fuselage and tail boom. A traditional helicopter also pays a 5 to 30 per cent power overhead for its tail rotor to provide counter-torque that offsets the drag torque of the main rotor [10].

In contrast, for a quadrotor, the thrust force on each rotor is one quarter of the whole. For a given footprint diameter, the area of the rotors is that of four discs inscribed in the bounding circle. However, interactions of the blade vortices generated by rotors require greater spacing between them; a rule of thumb is $\sqrt{2}$ times rotor radius [11], [12]. Consequently, there is substantially less lifting area available to a conventional quadrotor than a helicopter[1].

Consider a traditional helicopter and a quadrotor, with equal mass, each designed to fit within a unit diameter circular footprint. Assume both have equal fuselage cross-section, such that the entirety of the fuselage exists outside of the quadrotor rotor discs — which are spaced to avoid vortex interaction (see Fig. 3) — but which negates an equal area under the helicopter rotor. The effective rotor disc area available to the helicopter will be 0.732 units$^2$; the total rotor disc area available to the quadrotor will be 0.428 units$^2$.

Consequently, from (1), the total lifting power required by the quadrotor will be 1.31 times that of the traditional helicopter — almost a third more. Adding 15 per cent parasitic power overhead required for a traditional tailrotor, the power saved is approximately 25 per cent. Thus, a quadrotor may be expected to fly only 80 per cent as far or as long as a traditional helicopter UAV.

[1]Not all rotorcraft follow this rule; some tandem helicopters space their rotors closer, or even overlapping, at the expense of higher power requirements [2, p 108]

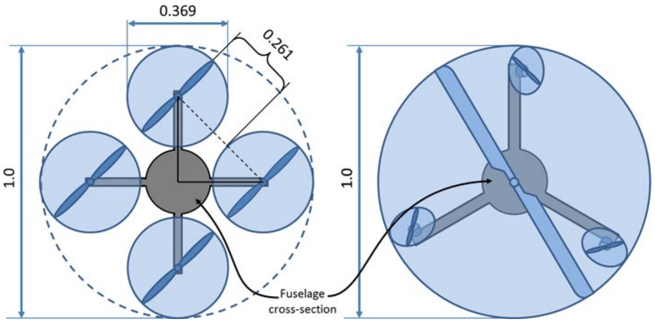


Fig. 3: Conventional Quadrotor and Triangular Quadrotor Rotor Spacing and Lifting Area Comparison — Unit Diameter Footprint.

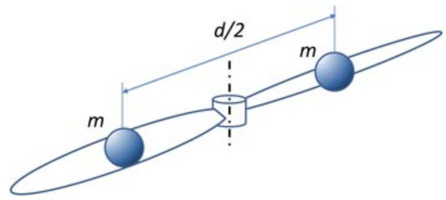


Fig. 4: Two-Point Mass Rotor Inertia Model.

### B. Y4 Configuration

In a simple analysis, the energetics of the main rotor is identical to that of a helicopter, albeit with the option of including the smaller rotors in the inflow or outflow. In comparison with a traditional helicopter, the three smaller motors provide only one-third the counter-torque thrust of an equivalent tail boom. Obviously, as cant angle $\varpi$ is increased to 90 degrees, the thrust (and thus power) required diminishes to a minimum — but this comes at the cost of greatly increasing the power required to affect manoeuvering thrust changes. Cant angle must be chosen to balance control bandwidth and hover power.

From (1), the simple case of three counter-torque tail rotors with 45 degree cant would require 97 per cent of the power of an equivalent single tail rotor of the same size. Each generates $\sqrt{2}/3$ times as much thrust as the single tail rotor, but together produce an equivalent counter-torque. However, the drag torques produced by the boom rotors can themselves be used to provide counter-torque (much like a quadrotor), allowing lower cant angles and further reducing the power required. In this way, the efficiency of a Y4 may be comparable to that of a conventional helicopter.

Given reduced main rotor power and boom rotor requirements, in total, it is expected that a correctly tuned triangular quadrotor may require 20 per cent less power than a conventional quadrotor for the same diameter footprint.

### C. Rotor Inertial Effects

An additional feature of the Y4 arrangement is the lower rotational inertia of its manoeuvering rotors, at the expense of slower rise time and more gyroscopics of the main rotor.

The dynamics benefit derived from even small reductions in rotor size are significant. Consider a simple two-point mass rotational inertia model:

$$\mathrm{I}_{zz} = m\frac{d^2}{4} \tag{2}$$

where I is the axial rotational inertia, $m$ is the rotor mass, and $d$ is the rotor diameter. With mass scaling with the cube of linear dimension, halving the diameter of rotor would reduce the mass of the rotor by a factor of eight (assuming no other geometry changes). These scalings taken together mean a rotor half the size of that of a conventional quadrotor would have only 3 per cent of the rotational inertia. Consequently, this configuration promises to provide substantially higher pitch and roll control bandwidth than achievable with a standard quadrotor. This is particularly important when considering larger quadrotors, where changing rotor speed rapidly is essential to stability of the aircraft [5].

The trade-off is that increasing the main rotor size correspondingly increases the influence of the gyroscopic effect. Unlike a quadrotor, triangular quadrotors have an asymmetry in rotational velocities; the total rotational inertia does not sum to zero and the gyroscopic moments of rotors do not balance. The gyroscopic force applied by a rotor is related to the pitch/roll velocity of the rotor and the rotor's angular momentum [13]:

$$\boldsymbol{\tau} = \boldsymbol{\omega} \times \mathrm{I}_R \boldsymbol{\omega} \tag{3}$$

where $\mathrm{I}_R$ is the inertia matrix of the rotor, $\boldsymbol{\omega}$ is the rotor angular velocity vector and $\boldsymbol{\tau}$ is the resultant torque vector. A Y4 may have a main rotor 2.7 times the diameter of a single quadrotor rotor — resulting in 146 times the rotational inertia, and thus 146 times the developed gyroscopic moment. Without the torque cancelation from a contra-rotating opposite pair, gyroscopic forces are a substantial influence that must be accounted for in the flight control. In general, the angular momentum of the rotor about its driven axis is several orders of magnitude above its roll or pitch momentums. Thus, the simplification can be made:

$$\boldsymbol{\tau} = \mathrm{I}_{zz}\omega_z \boldsymbol{\omega}_\times \tag{4}$$

where $\mathrm{I}_{zz}$ and $\omega_z$ are the rotational inertia and angular velocity of the rotor about its driven axis, respectively, and $\times$ is the skew-symmetric matrix cross-product operator.

### D. Rotor Performance Considerations

The triangular quadrotor configuration both removes and adds aerodynamic complexities to the standard quadrotor design. A consideration in the design of quadrotors is the interaction of vortices of closely-spaced rotors. These vortices arise from the recirculation of high pressure air beneath the rotor, to mix with the low pressure air above. This creates a trailing spiral of entrained air that dissipates energy from the flow, called 'tip loss' [9, p 33]. The interaction of vortices from closely spaced rotors can induce vibration and makes analytical computation of aircraft performance difficult [9], [12, p 57].

By limiting lift production to a single rotor, the effect of these vortex interactions can be greatly reduced. The main rotor is the strongest vortex generator; if placed upstream of the smaller rotors, it will not experience interference from the shed wake of smaller rotors. Likewise, the relatively high disc-loadings and outflow velocities of smaller manoeuvering rotors reduce the influence of a non-uniform shed vortex sheet in the outflow of a large rotor. Placing these smaller rotors around the vena contracta of the main rotor would further insulate them still, but require substantial vertical spacing [2, p 101].

## IV. Dynamic Modeling and Control

With two key exceptions, the flight control and stabilisation of a Y4 quadrotor is identical to that of a standard quadrotor. Both types of aircraft can be considered as rigid body systems with rotors acting as force-torque generators. We first present a model for a standard quadrotor, and then describe how that of the triangular quadrotor differs.

### A. A Standard Quadrotor Model

A common quadrotor dynamic model expressed in the body-fixed frame is [14][2]:

$$\begin{aligned} \dot{\boldsymbol{\xi}} &= R\boldsymbol{v} & (5)\\ m\dot{\boldsymbol{v}} &= -m\boldsymbol{\Omega}_\times \boldsymbol{v} + mgR'\boldsymbol{e}_3 + T\boldsymbol{e}_3 & (6)\\ \dot{R} &= R\boldsymbol{\Omega}_\times & (7)\\ \mathrm{I}\dot{\boldsymbol{\Omega}} &= -\boldsymbol{\Omega}_\times \mathrm{I}\boldsymbol{\Omega} + \boldsymbol{\Gamma} & (8) \end{aligned}$$

where $\xi$ is the vehicle position, $R$ is the attitude rotation matrix, $\boldsymbol{v}$ is the body velocity, $\boldsymbol{\Omega}$ is the rigid body rotational velocity vector, $m$ and I are the mass and rotational inertia matrix of the flyer, $g$ is acceleration due to gravity and $T$ and $\boldsymbol{\Gamma}$ are the total rotor thrust and torque vectors.

The thrust and torque of each individual rotor is modeled using the Blade Element Method thrust and torque equations [9, p 17]. For the $ith$ rotor:

$$\begin{aligned} T_i &= \frac{1}{4} C_T \rho A (d\omega_i)^2 & (9)\\ Q_i &= \frac{1}{8} C_Q \rho A d^3 \omega_i |\omega_i| & (10)\\ P_i &= \frac{1}{8} C_Q \rho A (d\omega_i)^3 & (11) \end{aligned}$$

where $T_i$, $Q_i$ and $P_i$ are the thrust, drag torque and power of the rotor, respectively, $\rho$ is the density of air (taken as 1.184 kg/m$^3$), $A$ is the planform area of the rotor disc, $d$ is the rotor diameter, and $\omega_i$ is the axial rotational velocity of the rotor. Here $C_T$ and $C_Q$ are rotor non-dimensionalised thrust and drag coefficients, properties that relate the rotational velocity of the rotor to the thrust and torque produced; the torque coefficient also relates the power required by the rotor at a given speed. In equation 11, $\omega$ is multiplied by its magnitude to preserve the sign of rotation for counter-rotating rotors.

In these equations, only the rotor velocity is non-constant — they can be simplified to $T_i = \alpha\omega_i^2$ and $Q_i = \kappa\omega_i^2$. Thus, the force-torque mapping of a standard quadrotor can be summarised by a single matrix relating rotor speed to forces [15]:

$$\begin{bmatrix} T \\ \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \end{bmatrix} = \begin{pmatrix} \alpha & \alpha & \alpha & \alpha \\ 0 & -r\alpha & 0 & r\alpha \\ r\alpha & 0 & -r\alpha & 0 \\ \kappa & -\kappa & \kappa & -\kappa \end{pmatrix} \begin{bmatrix} {\omega_1}^2 \\ {\omega_2}^2 \\ {\omega_3}^2 \\ {\omega_4}^2 \end{bmatrix} \qquad (12)$$

[2]These dynamics can be likewise expressed in the inertial frame [15].

where are rotors are indexed 1–4, clockwise, starting at the front, and $r$ is the boom arm distance from the centre of gravity to each rotor centre.

### B. Triangular Quadrotor Adaptation

With reference to the above model, the changes made for the triangular quadrotor are small. Firstly, the rigid body angular velocity dynamics must explicitly incorporate the unbalanced gyroscopic contribution $\tau_i$ of each of the rotors according to (4).

$$\mathrm{I}\dot{\boldsymbol{\Omega}} = -\boldsymbol{\Omega}_\times \mathrm{I}\boldsymbol{\Omega} + \sum \boldsymbol{\tau} + \boldsymbol{\Gamma} \qquad (13)$$

The gyroscopic torques are almost entirely concentrated in the main rotor — we explicitly ignore the contribution of the smaller rotor gyroscopics. Also explicitly ignored are the small side forces produced by the boom rotors; $T$ considers only vertical force contributions.

Secondly, the force-torque mappings of the rotors are quite different and are dependent on $\varpi$:

$$\begin{bmatrix} T \\ \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \end{bmatrix} = \begin{pmatrix} \alpha C_\varpi & \alpha C_\varpi & \alpha C_\varpi & \alpha_M \\ 0 & -\frac{\sqrt{3}}{2} r\alpha C_\varpi & \frac{\sqrt{3}}{2} r\alpha C_\varpi & 0 \\ r\alpha C_\varpi & -\frac{1}{2} r\alpha C_\varpi & -\frac{1}{2} r\alpha C_\varpi & 0 \\ r\alpha S_\varpi & r\alpha S_\varpi & r\alpha S_\varpi & -\kappa_M \end{pmatrix} \begin{bmatrix} {\omega_1}^2 \\ {\omega_2}^2 \\ {\omega_3}^2 \\ {\omega_M}^2 \end{bmatrix} \qquad (14)$$

where $\alpha$ and $\kappa$ and $\alpha_M$ and $\kappa_M$ are the boom rotor and main rotor proportional thrust and drag coefficients, respectively. The shorthands $S_x$ and $C_x$ stand for $\sin(x)$ and $\cos(x)$, respectively.

### C. Controllability and Stabilisation

It is well-known that quadrotors perform well in hover under linear PID control [16]. The control mapping matrices of quadrotors given in (12) is full rank and invertible, as is the case for triangular quadrotors in (14), given non-singular boom rotor cant angles ($0 < \varpi < \pi/2$). This allows for full independent control of roll, pitch and yaw torques and thrust. The control structure of a Y4 could therefore be expected to be very similar to that of a standard quadrotor, barring the effect of the main rotor gyroscopics.

Conveniently, the variables on which the gyroscopic forces depend — rotor inertia, rotor velocity and roll-pitch rate — are constant physical parameters easily measured offline, or aircraft states sensed online by most flight controllers. This, combined with a well-understood gyroscopic model, recommends a feedback linearisation approach to stabilising triangular quadrotors.

A proposed simple control law takes the form of a modified linear PID control with gyroscopic correction:

$$\Gamma = \left(k_p + k_i \frac{1}{s} + k_d s\right) \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} - \omega_M \mathrm{I}_{Mzz} \begin{bmatrix} 0 & s & 0 \\ -s & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} \qquad (15)$$

where $\phi$, $\theta$ and $\psi$ are the roll, pitch and yaw angles of the craft, and $k_p$, $k_i$ and $k_d$ are control gains identical to those of a standard quadrotor of the same size and weight.

An additional advantage of the triangular configuration is improved yaw performance. The value of $\kappa$ for a standard quadrotor is typically very small, and the near cancellation of rotor drag forces in hover results in low yaw control authority. In contrast, the magnitude of $r\alpha \cos \varpi$ for the Y4 are larger and work together, rather than cancel; they may provide as similar degree of yaw control as a conventional helicopter.

## V. Experiments

We have undertaken preliminary analysis of the predictions of the energetic and control performance of the triangular quadrotor configuration. The large number of variables involved in the design of a quadrotor of either configuration makes a direct comparison difficult. To explore the relative merits of the proposed design, two quadrotors were constructed to be as similar as possible, within the limits of their differing rotor configurations — a standard 'control'[3] quadrotor and Y4 testbed. These were then tested in static tests to compare their thrust performance and energy consumption. The triangular quadrotor was also flown to ascertain the stability of simple PID flight control. Detailed comparative control response tests of the triangular quadrotor and standard quadrotor are ongoing, and not presented in this paper.

### A. Comparative Test-Beds

To make as meaningful a comparison as possible between two dissimilar aircraft, both vehicles must be structured along common lines where possible. Both aircraft are designed to be small sub-kilogram vehicles with 30 per cent thrust margin and fit through a conventional doorway ($\tilde{5}0$ cm diameter). The two test-bed aircraft were specifically designed to keep the following common parameters identical:

- 850 g gross mass
- 480 mm footprint diameter
- 300 g actuator mass
- Chassis hub and arm units
- Battery type and capacity
- Flight controller

Aside from the motor and rotor size and placement being tested, the following design parameters were unavoidably different:

- Rotor geometry
- Motor manufacturers
- Electronic speed controller model

Of these non-idealities, the greatest scope for miscomparison lies in the inability to find performance-matched rotors in the various sizes needed. To ameliorate this potential problem, we elected to use a stock rotor tuned for the standard quadrotor configuration and choose an off-the-shelf variable-pitch conventional rotor for the Y4. The variable-pitch rotor was then adjusted to optimise thrust performance. In this way, the 'control' will derive the most benefit from rotors matched to its aerodynamic requirements, while the performance of the Y4 will be conservative. However, it was not possible to obtain a 250-series rotor with 480 mm rotor diameter; the closest match available was 460 mm. Thus, the control quadrotor will have a small relative power (approximately 9 per cent) advantage due to greater lift area.

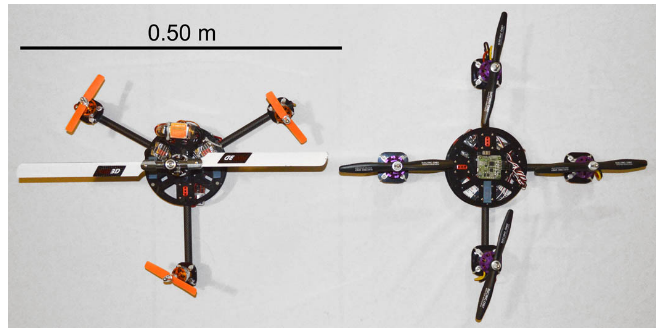


Fig. 5: Y4 Triangular Quadrotor and 'Control' Standard Quadrotor.

The standard quadrotor and Y4 test-beds use identical manufacturers for their manoeuvering thruster motors. These parts were chosen to provide suitable rotor power while maintaining the actuator mass-fraction of the vehicle. The same manufacturer was used to reduce potential variation introduced by different fabrication technology from different makers. However, this could not be maintained for the main rotor of the Y4, as no manufacturer could be found that produced both fast, small motors for flight control and also large motors with low flux-linkage coefficient[4]. Thus, the main rotor motor is of a slightly different design. For similar reasons, it was not possible to entirely use motor controllers the same manufacturer. However, it is expected that variation in the performance of electronic speed controllers will be small.

A mass-budget breakdown for the two aircraft is given in Table I.

### B. Test-Bed Power Performance

The expected power requirements of the aircraft can be predicted using (10–11). The non-dimensionalised coefficients for each rotor were determined empirically using a fixed thrust test rig (see Fig. 6), and are given in Table II — rotor velocity in hover conditions is denoted $\omega_0$ and hover power is $P_0$. A sample static thrust test comparing the low-end performance of the standard quadrotor rotors and the Y4 main rotor, both powered by 3-cell Lithium Polymer packs.Current was measured with a Watts-up meter and thrust was measured with a digital scale. These tests indicate that the Y4's lift rotor produces greater lift thrust per Amp, at the low end of the rotor performance range.

The hover power requirement for the Y4 boom motors is based on a 30 degree rotor cant; this was determined through trial and error to provide good manoeuvering authority but also effective low-power counter-torque. In hover, it is expected that the Y4 will use 77.6 W, while the standard quadrotor test-bed will require 92.8 W of continuous power — almost 20 per cent more.

[3]Used in the sense of 'experimental control' — an unmodified baseline.

[4]Also referred to as the motor's 'KV' — RPM per volt

TABLE I: Quadrotor Test-Bed Weight Budgets.

'Control' Quadrotor

| Description | Mass/g | Qty | Total/g |
|---|---|---|---|
| Delrin centre frame | 21 | 2 | 42 |
| Delrin motor mount | 5 | 4 | 20 |
| Chassis arm | 12 | 4 | 48 |
| Arm root mounts | 19 | 4 | 76 |
| Master Airscrew 7"×4" propeller | 12 | 4 | 48 |
| RCTimer BC3530-10 1400KV motor | 74 | 4 | 296 |
| 18A Turnigy speed controller | 19 | 4 | 76 |
| Afroflight Naze flight controller | 25 | 1 | 25 |
| Radio receiver | 18 | 1 | 18 |
| 3S 1000 mAh 30c lipo battery | 84 | 2 | 168 |
| Mounting hardware | 50 | 1 | 50 |
| 18 AWG silicone wire (metre) | 31 | 2.4 | 74 |
| TOTAL | | | 941 |

Y4 Quadrotor

| Description | Mass/g | Qty | Total/g |
|---|---|---|---|
| Delrin centre frame | 21 | 2 | 42 |
| Delrin motor mount | 5 | 3 | 20 |
| Chassis arm | 12 | 3 | 48 |
| Arm root mounts | 19 | 3 | 76 |
| 250-series rotor blade | 20 | 2 | 40 |
| 250-series main rotor head | 50 | 1 | 50 |
| 4"×2.5" mini propeller | 12 | 3 | 36 |
| Tiger Motor MT2826-10 380KV motor | 187 | 1 | 187 |
| RCTimer A2208 2600KV motor | 38 | 3 | 114 |
| 40A T-Motor speed controller | 35 | 1 | 35 |
| 12A Turnigy speed controller | 10 | 3 | 30 |
| Afroflight Naze flight controller | 25 | 1 | 25 |
| Radio receiver | 18 | 1 | 18 |
| 3S 1000 mAh 30c lipo battery | 84 | 2 | 168 |
| Mounting hardware | 50 | 1 | 50 |
| 18 AWG silicone wire (metre) | 31 | 1.8 | 56 |
| TOTAL | | | 953 |

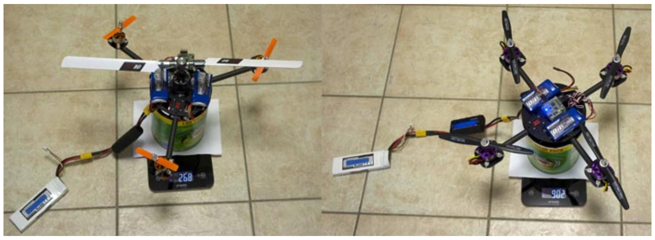

Fig. 6: Rotor Characterisation Thrust Test Configuration.

To compare the power performance of the aircraft under actual hover conditions, two instrumented test flights were carried out. The aircraft used an Attopilot current and voltage sensor calibrated to 45 A to record battery condition and instantaneous current draw (see Figs. 7 and 8). Each aircraft was autonomously stabilised and flown at a constant height out of ground effect for 180 seconds. To avoid start-up and shutdown transients, current data points from $t$ = 11s and $t$ = 168s (157 seconds duration) were averaged to find the constant current requirement. Starting at $t$ = 130s, the Y4 underwent an aerodynamic transient due to wind, which resulted in slightly higher current draw until $t$ = 135s. Average current draw was 19.75 A for the Y4, and 22.77 A for the standard quadrotor — 15.29 per cent more. As the two aircraft are powered by identical batteries of given Amp-hour capacity, this translates into a 15 per cent increase in flight time.

TABLE II: Test-bed Rotor Parameters.

| Rotor | $d$/m | $C_T$ | $C_Q$ | $\omega_0$/rads$^{-1}$ | $P_0$/W |
|---|---|---|---|---|---|
| 'Control' rotors | 0.178 | 0.0587 | 0.0023 | 782 | 23.2 |
| Y4 main rotor | 0.460 | 0.0230 | $3.36\times10^{-4}$ | 441 | 68.9 |
| Y4 boom rotors | 0.101 | 0.0302 | $3.62\times10^{-4}$ | 1872 | 2.9 |

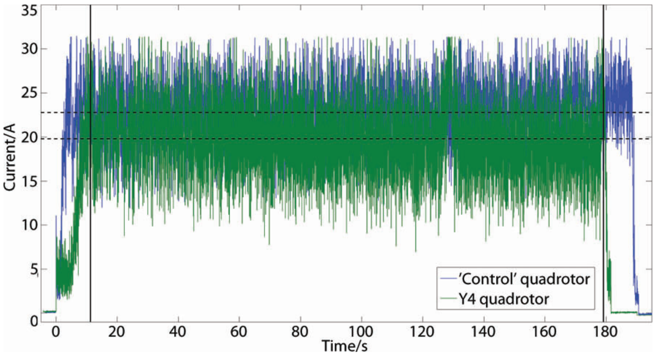


Fig. 7: 'Control' and Triangular Quadrotor Current Draw in Flight.

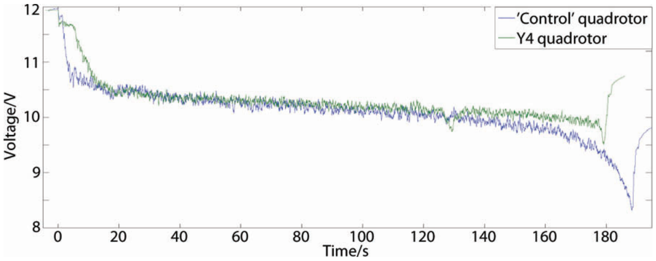


Fig. 8: 'Control' and Triangular Quadrotor Battery Voltage in Flight.

## C. Flight Control

The Y4 has been successfully flown outdoors under autonomous control (see Fig. 9). Early results indicate that simple PID control results in a precession effect. A PID flight controller tuned on the 'control' quadrotor was directly implemented on the Y4 quadrotor. During the power characterisation flights reported in Section V-B the conventional quadrotor kept level attitude within 5 degrees of level, while the Y4 quadrotor had an 8 degree pitch bias and a constant yaw drift (see Fig. 10).

The causes for the degraded hover attitude control performance are not certain. In particular, the unbounded yaw drift is unexpected. It is thought that vibrations set up due to slight imbalances in the main rotor of the Y4 test-bed may be causing the IMU to drift. Flight tests to determine the relative control performance of the triangular quadrotor configuration are ongoing.

Fig. 9: Triangular Quadrotor Hovering Outdoors.

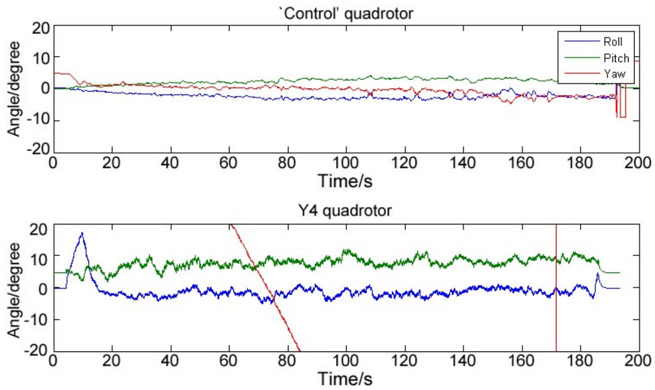


Fig. 10: Quadrotor Outdoor Flight Roll, Pitch and Yaw Angles.

## VI. Non-idealities and Future Work

Despite the 15 per cent power improvement in flight performance, the analytical figures suggest that more gains can be realised. Non-idealities identified include features particular to the development test-bed, and unmodeled aspects of the aeromechanics. Reducing these effects will allow a better comparison to be drawn between the two configurations, and also lead to better Y4 efficiency:

- Foremost, the Y4 uses a smaller main rotor footprint than the 'control'. This can be fixed by fabricating longer rotor blades that precisely match the standard quadrotor.
- Better rotor balancing and vibration isolation for the main rotor will clarify whether the degraded attitude control performance of the Y4 is related to the rotor configuration or a side-effect.
- The stock boom rotors and 250-series rotor assembly of the Y4 can be replaced with custom rotors correctly optimised for their flow regimes, such as hyperbolic twist and chord, to maximise lift efficiency and reduce parasitic drag [1].
- It is not known whether interference effects may be arising in the boom rotors due to their location in the main rotor outflow. This can be tested by changing the inter-rotor spacing and comparing efficiency and attitude control performance.
- Tests must be undertaken to measure and compare the relative attitude control performance of the two test-beds, and the response bandwidth of the Y4 given its main rotor gyroscopics.

With these improvements, it is expected that the relative performance of the Y4 compared to the 'control' will improve to be closer to the analytical prediction.

## VII. Conclusion

We have proposed a configuration of a four-rotor aerial robot — a quadrotor — that is substantially different from the standard quadrotor configuration. This approach employs a triangular configuration of manoeuvering rotors with a single large lifting rotor at the centre. It has been shown analytically this the large central rotor of the triangular quadrotor configuration offers up to 25 per cent power improvement over the smaller rotors of a standard quadrotor with the same footprint diameter (comparable to the benchmark power efficiency of a conventional helicopter). The smaller manoeuvering rotors of the Y4 also have the potential to provide faster response times and higher control bandwidth at the expense of stronger gyroscopics of the main rotor.

Using a matched-pair of standard and Y4 quadrotor test-beds, we found that the Y4 could deliver a 15 per cent power improvement in autonomous hover power tests, even with a slight disadvantage in main rotor size and without aerodynamic rotor optimisation. The triangular quadrotor was able to be stabilised using simple PID flight control, but with degraded attitude tracking performance and unbounded yaw drift. Future work will examine the control issues with the current Y4 test-bed and attempt to resolve non-idealities in the design and this is expected to lead to further gains over the conventional quadrotor configuration.

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