Review of Standard Rotor Configurations for a Micro Aerial Vehicle Application

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***Abstract*— The use of micro aerial vehicles (MAVs) is on the rise with an array of industries finding use for them in a variety of applications. This review hopes to assist potential drone designers on selecting the drone best suited for their application. This paper attempts to first give a better understanding of flight theory and the basics of rotary winged vehicles. Next it builds on that knowledge and applies it to a few important selection parameters. After which it addresses the criteria and links it directly to a few standard configurations of rotorcrafts. A final discussion is had where it addresses a few critical points.**

I. INTRODUCTION

With the increase in computing power making controlling rotorcraft possible, drones are becoming an ever more popular platform for a variety of applications and users. From military personnel to photographers just trying to get the best angle, drones are benefiting an array of industries. The hobbyist now can pick and choose from a warehouse full of different, rotors, motors and even full drone kits.

There is a lot of documentation about rotorcraft, especially since it has recently gained a lot of attention form hobbyists. Unfortunately there are not a lot of comparisons between the different types of configurations, or even what parameters should be looked at. This ends in the majority of people not using a drone type that is the right fit for their application. This paper will summarise a few key points of rotor dynamic theory and then use this information to address a few important parameters and finally applies it to different drone configurations. By the end of this paper the reader should be able to identify the appropriate rotor configuration for their application.

II. FUNDAMENTALS OF FLIGHT THEORY

A. Basic Rotor Theory

The rotor is responsible for all the aspects of flight and generates the lift, forward propulsion and the means to control the orientation of the craft [14]. It is for this reason that an in depth understanding of rotor characteristics and performance is needed. It is important to note that any rotating blade will cause a rotation of the craft in the opposite direction to that motion. This applied moment must be countered by a counter-torque mechanism which is visualised as the tail rotor in a traditional helicopter.

The capability of any part of a rotor to produce lift is influenced by the local blade position and pressure at that point [14]. As the rotor spins, the blade's angle of attack shifts. This angle is defined as an azimuth angle (α) and is measured relative to air flow. The azimuth angle is 0°down stream and sits at 180°when it faces directly upstream. Angular velocity equations state that the speed of any part of the rotor varies along the length of the rotor. With the maximum velocity sitting at the rotor tip.

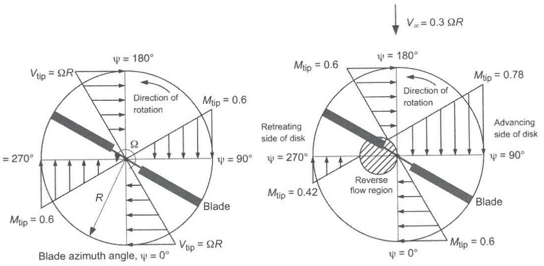

Fig. 1. Velocity components of a rotor (Taken from [14])

As the rotorcraft adds a horizontal component to it's hover or vertical flight, the relative speed of the individual rotor segments now adheres to (1). The relative velocity at the any part of the rotor is affected by the azimuth angle of the blade (α), forward translatory speed of the craft (V_∞), angular speed of the rotor (Ω) and the considered distance along the rotor blade (r) [14], [1].

$$V_r = \Omega r + V_\infty \sin(\alpha) \tag{1}$$

What this relationship shows is that during forward flight the tip velocity, relative to the ground, changes even if the rotor rotates at a constant speed. This complicates the rotor dynamics at higher speeds and limits the top speed of the craft. On the retreating edge ($\alpha = 270° \therefore \sin(\alpha) = -1$) if $\Omega r <= V_\infty$ the rotor would effectively be going backwards and the helicopter is at risk of stalling out, this is known as a stall condition, while the advancing edge is reaching it's maximum speed by approaching Mach conditions and sever instability [14], [1].

B. Momentum Theory and the Basics of Thrust

As mentioned above the rotors of a rotorcraft are responsible for generating all the forces that manoeuvre the vehicle. These forces are induced by pushing air through the rotor disk. With a fixed wing aircraft the analysis of the blades is simplified because the only air flow produced is from the translational velocity of the entire craft. Analysis of blade performance in a rotorcraft can be more challenging as the

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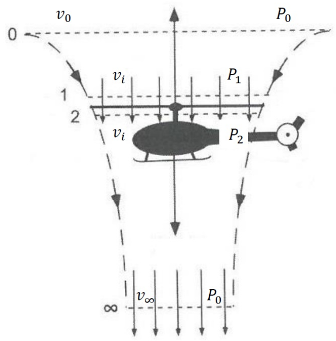

Fig. 2. Momentum Theory in Hover (Adapted From [14])

rotation of the blades must be considered along side the overall speed of the vehicle. As the craft manoeuvres in space, the air flow through the rotor has significant complexities which complicates the analysis. Since the rotorcraft is expected to perform in a variety of flight styles it is important to understand these models, and their flaws.

To simplify, initially consider a helicopter in a hovering state (Weight(W) = Thrust(T)). The rotor 'smooths' out the air as it forces it through the disk area. This more uniform air creates an edge known as the slipstream or wake boundary, with the surrounding air remaining dormant [14]. Inside the wake boundary, the average velocity of the air is tangible and effective, where outside the slipstream edge, the average air velocity is negligible and obsolete. The force required to push that mass of air through the disk space is, by Newton's third law, returned by the air unto the rotor. Thus giving the rotor blades a thrust component.

Rankine-Froude's Momentum Theory looks at this induced velocity as well as the displacement of air through the propeller, and attempts to quantify the induced thrust. The variable naming convention for the equations is shown in figure 2 below and is common to Leishman et al [14] in their naming of the components. Subscripts 0, 1, 2 and ∞ refer to the locations of quiescent flow, inflow directly before the rotor, airflow immediately after the disk and the slipstream[1] or far wake condition respectively. The velocities are shown as the induced velocity in and out the rotor (v_i), the far wake velocity (v_∞) and finally v_0 represents the zone with zero flow rate. There is no velocity jump across the rotor, the energy being fed into the system by the rotor is represented by a pressure change between P2 and P1.

As described above, it is by forcing the air through the disk that lift is generated. The mass flow rate of this air can then be described by (2), where ρ is the density of air and A is the area of one full blade rotation. The rate at which this mass of air is displaced becomes a crucial variable in rotor dynamics and is directly proportional to thrust (T). This relationship can be quantified as shown in (3). Thrust can also be calculated by finding the difference in pressures over the rotor disk as in (4)

$$\dot{m} = \rho A v_i \tag{2}$$
$$T = \dot{m} a \tag{3}$$
$$T = A(P_2 - P_1) \tag{4}$$

Since v_0 is zero during hover and acceleration is the difference in v_∞ and v_0, (5) can be obtained.

$$T = \rho A v_i v_\infty \tag{5}$$

Thrust can now be quantified if the slipstream and induced velocities are known. Then by applying Bernoulli's equation of conservation to both sides of the rotor disk, the change in pressure across the disk can be quantified as shown in (6). That change in pressure fits into one of the initial definitions of thrust (4). Equating both of those definitions yields an important relationship between the three velocities, as shown in (7). The relationship simply states that the induced velocity at the rotor is the average of the quiescent flow above and the far wake velocities. This definition proves useful at a later stage in the rotor theory definitions.

$$P_2 - P_1 = \frac{1}{2}\rho(v_\infty^2 - v_0^2) \tag{6}$$
$$v_i = \frac{1}{2}(v_\infty + v_0) \tag{7}$$

C. Disk and Power Loading

Disk loading (DL) is a term seen often in the world of rotor crafts, it is a simple but important ratio between thrust and the area a rotating disk makes. It is represented in it's simplest form in the beginning of (8). Since the pressure drop across each rotor is considered uniform, the disk loading for each rotor will equate to the pressure drop across that disk. Equation (6) first shows the difference in pressure and by taking v_0 as zero (state of hover), the second half of equation (8) can be formed.

$$DL(\frac{N}{m^2}) = \frac{T}{A} = \frac{1}{2}\rho v_\infty^2 \tag{8}$$

For multi-rotor crafts, the disk loading is assumed uniform across all rotors [14]. The overall disk loading of a single rotor craft such as a traditional helicopter will be lower than

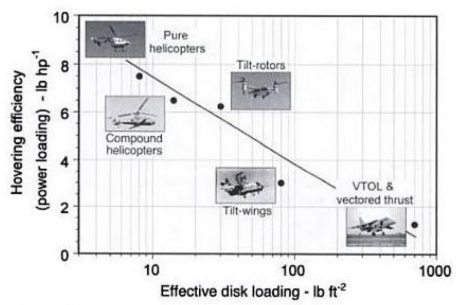

Fig. 3. Image representing, various Disk Loading values for varying rotorcrafts (Taken from [14])

[1]Generally far wake is considered as 1 full rotor diameter distance away [14].

that of a multi-rotor craft of a similar size [1]. Figure 3 shows some examples of disk loading values for a variety of rotor configurations, as shown disk loading is also a measure of hover efficiency. A higher disk loading value results in larger values for induced velocities as well as the required power to hover. This means that the larger the blades, the better the efficiency. More force will be generated by pushing large quantities of air slowly, than forcing small amounts of air through at high speeds [20]. Of course with bigger blades, comes larger rotational inertia and geometry as well as the craft being less immune to gusts and interferences. A larger blade also creates faster tip velocities, which will limit the speed of the craft severely [14].

Power is given by the product of both Thrust and the induced velocity at the blade. It can be written as shown in (9). What this ratio shows is that the ideal power is in cubic proportion to the induced velocity at the rotor. Therefore to reduce required power the rotor's induced velocity must be small, which can be accomplished by a significant increase in disk area [14].

$$P = 2\rho A v_i^3 \tag{9}$$

Another important ratio is between thrust and power, it is called power loading (PL) and is shown in (10). Power loading can be seen as a measure of craft efficiency.

$$PL(\frac{N}{kW}) = \frac{T}{P} \tag{10}$$

From (8) and (10) it can be shown that power loading is inversely proportional to disk loading. Therefore a craft with a lower disk loading ratio will be a more efficient platform.

D. Electrical Power to Thrust

Equation (9) gives a quantitative approach to solving for aerodynamic power (P_i). If electrical power is taken as $P_e = VI$, where V is the applied voltage and I is the sourced current, with an efficiency of η then $P_i = \eta VI$. Noting that $P_i = Tv_i$ and using (9), a relationship between thrust and P_e can be formed and is represented in (11).

$$T = (2\rho A)^{\frac{1}{3}} (\eta P_e)^{\frac{2}{3}} \tag{11}$$

Equation (11) brings to light a very important relationship which states that thrust grows at a slower rate than the electrical input power to the system.

$$T \propto P_e^{\frac{2}{3}}$$

III. SELECTION PARAMETERS

Some of the fundamental theories described above relate to the basics behind various rotor configurations and even varying flight techniques. Each different arrangement of blades introduces certain advantages and disadvantages to the system. Not every configuration will be applicable for all operations and it is important to determine what criteria is critical for the intended application. An analysis of varying rotor configurations is done below and follows a similar trend to that seen in [5], [2] and [21]. The main weighted criterion for the discussion were listed in no particular order as:

1) Flight time, payload capability and efficiency
2) Geometry and size and mechanical complexity
3) Drone manoeuvrability and control algorithms
4) Stability and Disturbance Rejection

A. Efficiency, Payload Capability and Flight Time

Flight time is a by product of efficiency and payload, as a more efficient craft will drain the power source slower, thus producing a longer flight. Where a heavier craft, with a larger payload, will have a shorter flight duration. Most miniature drones these days have a flight time somewhere between 6-12 minutes before they need recharging. This is not conducive for a variety of applications where longer mission durations are pertinent. Of course a larger power source could always be added, but this increases the weight, limiting the payload capability and once again flight time. The relation between hover efficiency and disk loading was mentioned above, what was not discussed was how a potential payload effects these decisions. A single rotor will have a lower disk loading ratio at hover and will not be able to carry as heavy loads as a multi-rotor craft that has a higher disk loading at hover [14], [12], [1].

B. Geometry, Size and Mechanical Complexity

In any aerial vehicle mass is always an important design criterion. Every aspect of the platform must be designed to be the lightest it possibly can. Having a light weight craft is one part of the design criterion, another would be ensuring that the weight is geometrically spread out correctly, as well as functionally distributed appropriately. The table below was adapted from [21] and demonstrates the latter point better. Depending on the different criteria for the craft, different functional blocks will be allocated a certain percentage of weight. For example if the user would like a longer flight time, a higher percentage would be given to the power source and possibly less to the external payload. Generating a good mass model before designing helps better understand the requirements for the craft and could be a deciding factor in the construction.

Component	0.3kg	1.8kg	3.7kg
Rotor System	11.0	11.2	13.9
Tailboom Assembly	8.0	9.1	7.8
Main Rotor Motor	15.4	10.5	8.1
Fuselage/Structure	7.0	15.1	12.0
Main Transmission	2.0	3.4	3.4
Landing Gear	2.3	3.4	2.9
Control System	5.7	18.3	9.3
Avionics	29.4	2.4	1.6
Power Source	19.2	26.6	41.0

TABLE I

MAV WEIGHT DATA (ADAPTED FROM [21])

It was also mentioned that the weight needs to be geometrically positioned correctly, the point of this would be to create as much symmetry in the craft as possible. If this is done correctly the principle axes of inertia will align very closely with the body of the craft. The inertia tensor is a matrix that is a representation of a rigid body's resistance to movements in 3D space, this is obviously crucial since the application is to move a body through 3D space! For the general case the inertia tensor takes the form as shown in (12). The inertia tensor is very dependant on a craft's symmetry, and is symmetric itself. In other words, $I_{xy} = I_{yx}$, $I_{xz} = I_{zx}$ and $I_{zy} = I_{yz}$ and therefore if a craft is symmetric about the y axis (x = 0), then $I_{xy} = I_{yx} = 0 = I_{xz} = I_{zx}$ [16], [6].

$$\mathbf{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \tag{12}$$

Symmetry in a craft can also help reduce the effects of disturbances such as wind. This is due to the disturbance affecting the craft evenly, thus making it easy to counter the effects. More on disturbance rejection is mentioned below.

C. Drone Manoeuvrability and Control Algorithms

In three dimensional space there are effectively six possible degrees of freedom (DOF) three of them are translational (ξ) and three of them rotational (η). The naming scheme used in this paper follows the same form used by Castillo et al in [6], [7]. In mathematics discussions are had regarding rotations around the x, y and z axes, in flight theory they are labelled as roll, pitch and yaw. The three axes change as the aircraft changes since they are labelled relative to the aircraft's position. Pitch relates to how much the vehicle is tipping forward or backward, roll is an influence in the left and right rotation, while yaw is rotation around the z axis. Instead of x, y and z, these axes can be considered as forward, sideways and vertical [14]. Refer to figure 4 for a visual description of the axes.

$$\xi = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} \quad \boldsymbol{q} = \begin{bmatrix} \xi \\ \eta \end{bmatrix} \tag{13}$$

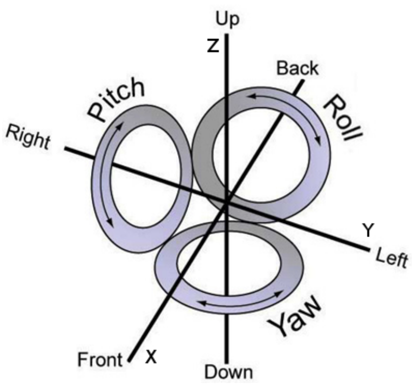

Fig. 4. Control surfaces required for 3 dimensional flight (Taken from [9])

Drone manoeuvrability and control algorithms have been grouped together because they both relate directly to the dynamic model of the craft, as well as the amount of control authority available to the pilot. The same way that the wheels in a car decide which direction the car drives, the rotors provide all the control authority to a standard rotorcraft. Having only a single, fixed pitched rotor allows only for control in the amount the craft flies up or down. There are many different methods to obtain full six degrees of flight freedom.

Typically a rotorcraft will be designed with either fixed pitched, or variable pitched rotors. A fixed pitched rotor is a rotor that has an optimally selected, unchangeable pitch and therefore a fixed angle of attack. This of course means that since the angle of attack is fixed for the blade, an increase in speed will be required for a change in lift. With a variable pitched blade, the pilot can change the angle of attack to increase the forces. As the angle of attack increases, the blade will produce more lift without changing the speed of the motor. However, as the pitch increases, so does the drag of the blade. This then requires more motor power to keep the blade moving through the air [6], [14].

The power requirements for either system are fairly similar, the advantages of a varying pitch is a single rotor has the potential for more dynamic force applications. The downfall however is the high level of complexity in the mechanical design. Both of these facts become pertinent in the final decision making of the platform design. The end goal is to have a craft that can fly stably and accurately in three dimensions. To do this the craft will need more control surfaces to apply forces in those planes. There are many different methods to obtain full six degrees of flight freedom. Some designers have added multiple rotors, ensuring there is always a counter rotating pair, eliminates the anti torque generated by each motor. So ultimately giving the control engineer more control authority will simplify the control algorithms and increase drone manoeuvrability having only a single, fixed pitched rotor, allows only for control in the amount the craft flies up or down.

Most configurations will give the user sufficient control authority, the trade off becomes between number of rotors and mechanical complexity.

D. Stability and Disturbance Rejection

Stability and disturbance rejection are generally considered control problems and a good control law should be able to help the user find stability amongst disturbances. They have been isolated in this case to focus on what can be done before there is an attempt to apply control laws. Stability is a broad term and what is meant by it in this case is the ability to completely control movements in all six DOF. Any rotating member will produce a counter rotating torque to the static body, which means that any system with only one fixed pitched rotor will have inherent instability in the yaw axis and only vertical control [6]. It was mentioned earlier that symmetry in the craft can help eliminate the effects of some disturbances. Multiple blades helps reduce the effects of disturbances just as well, this way if one blade falters or is affected substantially by a disturbance the other rotors can still rectify the error. Some multi-rotor designs can still fly with substantial control even after losing power to one or more of the rotors [17].

IV. DISCUSSION

This discussion looks at the different rotor configurations and attempts to address each parameter mentioned above. It starts with the traditional helicopter which is always seen as a main rotor with a smaller rotor at the tail, even when there are many different types of anti torque tail set ups. The ducted fan approach increases the efficiency of the tail rotor by channelling the air flow of the rotor. The NOTAR design [15] manipulates the airflow generated by the main rotor and directs it to counter act the induced torque. A tip-jet design eliminates the torque applied to the airframe and therefore no tail rotor is required [5]. There have been many attempts at improving the standard helicopter design. These improvements have taken the form of adding rotors, designing hybrid aircrafts and complex mechanical designs to harvest advantages of both the fixed wing and VTOL crafts. Some have even tried to combine multiple features as Flanigan [10] did in his design of a tip-jet, compound, tilt rotor aircraft.

In an attempt at simplification, not all configurations were investigated. The following standard groups of designs were covered:

1) Traditional helicopter
2) Coaxial rotors
3) Tandem rotors
4) Multirotor designs
5) Tilt rotors

A. Traditional Helicopter

When most people think of a rotorcraft they will think of a conventional helicopter, which is still the most widely used configuration for large rotorcrafts [5]. It consists of a single main rotor, coupled with a smaller counter rotating rotor located in the tail to counteract the developed counter torque.

The main rotor of a standard helicopter has a very low disk loading ratio which gives it excellent hover efficiency. To achieve yaw stability this configuration makes use of a small tail rotor to counter act the induced moments of the main rotor. The extended tail rotor requires energy which it will draw from the motor while also adding a significant amount of length to the craft. Since the single rotor only gives the pilot thrust control and the tail rotor gives measurable yaw control, there is need for more control surfaces to do more manoeuvring. To implement this most helicopters use a variable pitched rotor system. Cyclic control of this pitch allows the pilot to adjust the angle of attack of the rotor blades while they rotate, thus more force can be applied on the left by increasing the pitch and the craft will tilt to the right. This set up is extremely mechanically complex but is luckily readily available these days. Custom designing the swash plate for cyclic control will be a mammoth sized task on it's own.

Once the mechanics are set up the control algorithms are still slightly limited and intensive. Only having a single main rotor makes the traditional helicopter extremely susceptible to disturbances and limits the payload capability with the low disk loading factor.

B. Coaxial Rotors

A coaxial configuration consists of two counter rotating blades located about the same centre of rotation that both use the same drive system. This eliminates the need for a tail rotor as the torque applied by both rotors cancel each other out. Functionally the coaxial is very similar to the traditional helicopter [8]. With no modifications and only using fixed pitched rotors, this platform will only give yaw and over all thrust control. Bohorquez et al [2] attempted a number of lateral control methods, eventually settling on aerodynamic flaps to control the flow of the downwash, that and other methods are shown in figure 5. Briod et all also used the same set up in his team's design of the Gimball [4].

The control flaps are the most common used form of lateral control for small coaxial MAVs. They introduce little mechanical complexity and do not require excessive power to use. The flaps do however decrease efficiency of the system, but if designed correctly should only influence the system while being used. For hover and vertical flight the impact will be negligible. As a control surface the flap is quite rudimentary and will require some more advanced control methods as well as in depth testing to obtain smooth flight transitions. Due to it's compactness the design can have considerable manoeuvrability if the control algorithms are designed effectively. Each flap will require an actuator, this will increase total weight, power consumption and required mechanics.

Since half of the bottom blade is working in the top blades slip stream it will have a higher v_0 and therefore a larger v_i, which according to equation 3 will induce a larger thrust. This relates to high values of efficiency and lower values of disk loading, decreasing the payload capability. Coleman in [8] did an extensive survey of coaxial rotors and also found that they produce more drag than the conventional rotor set up, which becomes more pertinent at higher speeds.

Localising the blades around a single point also helps with the geometry of the craft as it is a more compact design. Briod et al [4], [13], [3] used this to their advantage when they were designing a collision resistant robot, the compact design allowed them to surround the entire craft in a rolling

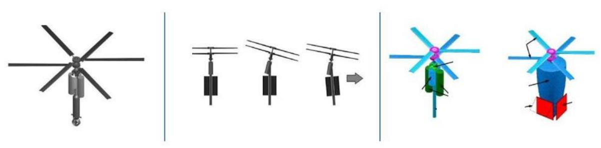

Fig. 5. Different methods of lateral control in a Coaxial MAV (Adapted from [2])

protective cage. Although the coaxial main rotors does make the craft vulnerable to disturbances [8].

C. Tandem Rotors

A tandem rotorcraft is sometimes referred to as a dual rotor, as it consists of two blades to generate lift and to decrease disk loading and increase the payload lift capacity. In a tandem configuration the blades sit in the front and the rear of the craft, sometimes slightly overlapping. Tandems are often used in applications that require heavier loads than the traditional rotorcraft can effectively offer. In a tandem configuration the blades spin in opposite directions to counteract the other one's rotational torque. Pitch and Yaw control are readily available through manipulation of the rotor speeds, while roll control and left and right movements are not easily accomplished with this design [19]. Using two smaller blades also decreases the effects of interferences such as gusts on the craft, although a tandem helicopter has the problem of it's rear rotor being influenced by the wake of the front rotor[2] [12].

As described in (11) the thrust of the system increases slower than the electrical power input into the system. In a standard configuration, doubling the electrical power would only increase the thrust by a factor of ≈ 1.587. Where as doubling the amount of rotors being driven will double both the thrust and the electrical power. This gives the tandem arrangement the capability of lifting heavier loads with relatively low power consumption, as well as demonstrating low power consumption for hover and slow translatory flight. Having twin blades does increase the size of the craft, but the elimination of the tail rotor sees the size being similar to that of a classic helicopter. With no modifications the lack of roll control does limit the craft, although the drone will still be able to move left and right[3] by completing a yaw shift and then a forward movement. The control behind a tandem set up is by no means easy, but compared to it's traditional and co axial counterparts, adjustment of the rotor speeds can account for most of the desired control movements. When the two rotors have an overlap the mechanical couplings required to negate the chance of a collision can become difficult, however if the rotors do not overlap and each blade is coupled to it's own driving mechanism the need for complex mechanical designs is avoided.

D. Multirotor Designs

Drones have joined other remote controlled vehicles in the world of hobbyists. Of all the different designs the multirotor is the most popular. Through discussions with drone designers and aerial photographers, the four rotor design is generally chosen due to it's incredible stability and manoeuvrability. Similar to the tandem, the quad has a very high disk loading ratio and thus can be used to lift heavy loads, there are even products that have 8 rotors to seriously increase the payload capability. This does however relate to a more power hungry system and a less efficient hover.

[2]In the case where the rotors overlap
[3]Relative to original direction of motion

As shown in figure 6 [18], a quad rotor consists of two pairs of counter rotating propellers. Each shaft will be driven by it's own motor and unlike the flaps in a coaxial system, every motor in a quadcopter attributes to the lift vector. Having the freedom to control each blade independently gives the pilot advanced manoeuvrability, with minimal mechanical complexities. This also reduces the complexity of the control algorithms as six degrees of freedom can be obtained by simply adjusting the speed of the motors, the multirotor can even rotate on the spot without any change in altitude [18]. Besides the poor hover efficiency, the biggest downside of the multirotor designs is their size and weight. Each blade requires a drive system and space to rotate without interference.

E. Tilt Rotors

A tilt rotor is a very sophisticated system that attempts to harness the benefits of both the fixed and rotor wing aircrafts. With the addition of a pivoting axis for each blade the craft has the forward flying speeds of a fixed wing craft while still being able to take off an land vertically like a rotorcraft. The tilt rotor's major downfall is related to the required highly complex and intricate mechanical design [5].

VTOL applications require a larger blade to decrease the disk loading ratio, while in forward flight a smaller diameter blade is desired to increase the efficiency of propulsion. Hager [11] developed a telescopic system that transforms the blades to get the optimal benefits out of each configuration. These and other improvements have established the tilt rotor as a competitive design in the field of aeronautic transportation [5]. The main advantage of the VTOL system compared to other rotorcraft is the flight efficiency in longer flights.

Table 2 below is an example of a weighting matrix that tries to summarise the points discussed above, the example is for a drone used for aerial photography. The weighting values will be different for each application.

V. CONCLUSION

From the above discussion it can be seen that there is not a single configuration that is best suited for all applications. Instead each set up has it's own pros and cons which can

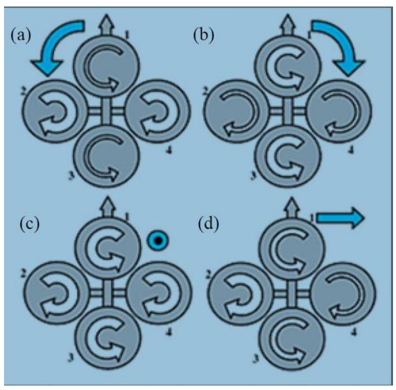

Fig. 6. Quadrotor configuration (Taken from [18])

Factor	Weight	Heli	Co	Dual	Multi	Tilt
Hover Efficiency	2	8	8	6	3	2
Payload Capabilities	4	5	4	7	9	2
Physical Size	1	5	9	5	3	5
Manoeuvrability	3	5	4	6	9	2
Control Algorithms	3	4	4	6	8	4
System Simplicity	3	3	5	7	6	2
Flight Distance	3	6	4	5	4	10
Disturbance Rejection	5	4	3	5	7	4
Stability	5	5	5	6	8	5
Top Lateral Speed	1	5	3	6	7	10
Total Score	300	145	135	178	208	126

TABLE II

ROTOR CONFIGURATION SCORING MATRIX FOR AN AERIAL PHOTOGRAPHY PLATFORM

be utilised in different situations. To conclude this review, each standard configuration will be discussed in it's ideal situation.

Starting with the most application specific, the tilt rotor will only be the most advantageous in a situation that requires flight duration over long distances. With the added need of VTOL, the tilt rotor will trump the conventional fixed wing design. As expected the tilt rotor is also the best choice when it comes to top lateral speed.

The traditional helicopter and the coaxial fulfil a very similar role. They can be sensitive to disturbances and can't handle the payload their multi rotor relatives can. However Their hover efficiency is very high which gives them a significant flight time and that's where the traditional set up earns it's place. When an application's main criteria is that it needs to have an extended flight time, these should definitely be considered. The choice between coaxial and traditional comes mainly down to size and flight speed. The coaxial will be able to fit in more refined spaced without the additional tail boom assembly, while the traditional will be able to reach higher speeds and fly laterally more efficiently.

The multirotor is the easiest use, can take the biggest payload and is the most stable, but it will have a shorter flight duration as it is a power hungry system. For the case of the aerial photography it's no surprise that the multirotor was chosen as the best choice as flight duration is not as important to a photographer as stability would be. The multirotor is also the easiest to control which makes it the ideal hobbyist platform as no extensive control laws need to be applied.

The tandem has often been cast aside as a suitable configuration [6]. Mainly because it sits between the traditional and the multi-rotor on effectively every parameter. So generally one or the other is chosen and the dual rotor set up is neglected. The tandem is suitable for an application that needs a jack of all trades solution. It's a slightly simpler system and will provide a larger payload than the traditional helicopter. While it still has better hover efficiency and overall size compared to the multi-rotor.

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REFERENCES

[1] F.A. Association. *Rotorcraft Flying Handbook*. FAA Handbooks Series. Aviation Supplies & Academics, Incorporated, 2001.

[2] Felipe Bohorquez, Paul Samuel, Jayant Sirohi, Darryll Pines, Lael Rudd, and Ron Perel. Design, Analysis and Hover Performance of a Rotary Wing Micro Air Vehicle. *Journal of the American Helicopter Society*, 48(2):80, 2003.

[3] Adrien Briod, Dario Floreano, Przemyslaw Kornatowski, and Jean-Chirstophe Zuffery. A Collision-resilient Flying Robot. *Journal of Field Robotics*, 31(4):496–509, 2014.

[4] Adrien Briod, Adam Klaptocz, Jean-christophe Zufferey, and Dario Floreano. The AirBurr : A Flying Robot That Can Exploit Collisions. pages 569–574, 2012.

[5] Yihua Cao, Dong Li, Qiang Zhang, and Hang Bian. Recent Development of Rotorcraft Configuration. *Recent Patents on Engineering*, 1(1):49–70, 2007.

[6] Lozano R Dzul AE Castillo, P. *Modelling and control of mini-flying machines*.

[7] Pedro Castillo, Alejandro Dzul, and Rogelio Lozano. Real-time stabilization and tracking of a four-rotor mini rotorcraft. *IEEE Transactions on Control Systems Technology*, 12(4):510–516, 2004.

[8] Colin P. Coleman. A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research - NASA Technical Paper 3675. Technical report, NASA, 1997.

[9] Federal Aviation Administration. Helicopter Components , Sections , and Systems. In *Helicopter Instructor's Handbook*, chapter Chapter 5, page 183. US Department of Transportation, Oklahoma, 2012.

[10] Kenneth Warren Flanigan. Gas Powered Tip-Jet-Driven Tilt-Rotor Compound VTOL Aircraft, 2006.

[11] Lee N Hager. Drive System for a Variable Diameter Tilt Rotor, 2000.

[12] W. Johnson. Camrad - a Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics. Technical report, NASA, California, 1980.

[13] Adam Klaptocz, Adrien Briod, Jean-christophe Zufferey, and Dario Floreano. An Indoor Flying Platform with Collision Robustness and Self-Recovery. pages 3349–3354, 2010.

[14] J. Gordon Leishman. *Principles of Helicopter Aerodynamics*. Cambridge Aerospace Series. Cambridge University Press, 2nd edition edition, 2006.

[15] Andrew H Logan and Richard E Moore. Helicopter Antitorque System Using Circulation Control, 1980.

[16] Teppo Luukkonen. Modelling and Control of Quadcopter. *Journal of the American Society for Mass Spectrometry*, 22(7):1134–45, 2011.

[17] M.W. Mueller and R. D'Andrea. Stability and control of a quadrocopter despite the complete loss of one, two, or three propellers. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, pages 45–52, May 2014.

[18] Yogianandh Naidoo, R Stopforth, and Glen Bright. Rotor Aerodynamic Analysis of a Quadrotor for Thrust Critical Applications. Technical Report November, University of KwaZulu Natal, Durban, 2011.

[19] Paul Y Oh, Michael Joyce, and Justin Gallagher. Designing an Aerial Robot for Hover-and-Stare Surveillance. *IEEE Advanced Robotics*, (12):303–308, 2005.

[20] Kevin Sablan. Theory of flight.

[21] La Young, Ew Aiken, Jl Johnson, J Andrews, J Klem, and R Demblewski. New concepts and perspectives on micro-rotorcraft and small autonomous rotary-wing vehicles. Technical report, US Army Aviation, 2002.