DEVELOPMENT AND PERFORMANCE COMPARISON OF OPTIMIZED ELECTRIC FIXED-WING VTOL UAV CONFIGURATIONS

Philipp Stahl, Thomas Seren, Christian Rößler, Mirko Hornung
Institute of Aircraft Design, Technical University of Munich

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Abstract

Fixed-wing VTOL UAV are unmanned aerial vehicles capable of both hover and fast forward flight. Lift during take-off and landing is generated by rotors, ducted fans or jet engines. After takeoff, they transition into forward flight mode in which a wing produces the lift. The many existing types of VTOL aircraft show the wide range of possibilities to combine vertical flight capabilities with efficient forward flight. The question arises which of these configurations is best suited for a certain mission. As a starting point for this paper, two widely used electric fixed-wing VTOL configurations are analyzed for their key design features and their consequences. Based on these findings, a self-developed configuration is presented and the underlying design considerations are explained. To allow a quantitative comparison of aircraft properties and performance among the three aircraft configurations, a design and mission analysis tool was implemented. It calculates aerodynamic aircraft performance, selects off-the-shelf powertrain and system components, dimensions the aircraft structure and evaluates the mission performance within given aircraft requirements. For each investigated configuration, the design tool is adjusted for the characteristic features. For the comparison of the configurations, a test case for a fixed-wing VTOL UAV with 5 kg take-off weight, 0.9 kg payload and hover time of 60 s is chosen. Each configuration is optimized for that mission to ensure a fair comparison. Within the optimization, aircraft geometry and, consequently, the aircraft powertrains and subsystems are changed until each configuration's cruise endurance is maximized. For the exemplary mission, the wing-borne cruise endurance differs by up to 34% among the investigated configurations. The self-developed configuration thereby yields the best endurance.

1 Introduction

Both multirotor and fixed-wing UAV are already in use for tasks like aerial filming, surveillance, photogrammetric survey etc. Multirotor UAV offer the capability of take-off and landing in confined environments but cannot provide enough range and endurance for certain missions. Fixed-wing UAV offer the latter but require space and infrastructure for take-off and landing. Fixed-wing VTOL UAV try to close this gap. They can operate in a powered lift mode for vertical take-off and landing and in a wing-borne forward flight mode.

To add VTOL capabilities to a fixed-wing aircraft, a wide range of layouts is imaginable [1, 2, 3]. These configurations distinguish themselves in the type of the basic fixed-wing aircraft, amount, type and positioning of the hover propulsion system, grade of system share between the two flight modes, etc. Different configurations show different performance and suitability for certain flight missions, but also feature different impacts on safety, robustness and maintenance.

The presented research therefore analyses two common fixed-wing VTOL configurations for their mission performance and operational aspects. Based on this analysis, a new electric fixed-wing VTOL configuration is derived with the goal of improved performance and operability. The conceptual fixed-wing VTOL aircraft design tool, used for performance estimation and optimization of the three aircraft configurations, is introduced and its results are presented. The paper closes with a lessons learned during the realization of this aircraft.

2 Analysis of Representative Fixed-Wing VTOL UAV Configurations

To understand the strength and weaknesses of different fixed-wing VTOL aircraft but also the differences to conventional fixed-wing aircraft, the main design features of two representative and prevalent aircraft configurations were analyzed. From this analysis, requirements for a new improved fixed-wing VTOL configuration are derived at the same time. Tailsitter aircraft are hereby not considered. The fixed-wing VTOL aircraft depicted in Fig. 1 serves as an example for ‘tilt rotor’ configurations. Vertical hover lift and horizontal cruise thrust are generated by the same powertrains and therefore need to rotate their thrust vector during transition between hover and cruise flight modes. Aircraft control in hover is realized quadcopter-like by the thrust respectively rotational speed variation of the motors. This common electric VTOL design feature avoids complex and maintenance intense swashplates or variable pitch rotors. This however limits the rotor to a diameter which allows sufficient acceleration and deceleration of rotor RPM for control purpose. Some ‘tilt rotor’ configurations additionally apply a slight tilting of the thrust vectors to improve yaw authority. In forward flight, the thrust vectors are fixed in forward direction. The aircraft shown in Fig. 2 represents the group of ‘hover plus cruise’ configurations. Separate powertrains generate hover lift and cruise thrust. In hover, it operates like a traditional multicopter. In cruise, the control concept of both configurations is similar to a conventional fixed-wing aircraft with aerodynamic control surfaces.

Fig. 1. ‘Tilt Rotor’ Configuration in Cruise ©Germandrones

Fig. 2. 'Hover Plus Cruise' Configuration ©Icarus Drone Services

VTOL aircraft in general need to provide hover thrust of more (typically by a factor of 1.1 to 1.5) than their take-off weight. By that, their thrust-to-weight-ratio is significantly higher compared to a conventional aircraft. The consideration of the electric power demand in hover, the powertrain mass, structural integration, cooling, power distribution and energy storage gains substantial importance in aircraft design. Compared to fixed-wing electric aircraft, the high power demand further impairs the contrary requirement of power and energy provision for the anyway low energy-dense batteries. This chain of consequences linked to the hover power demand is mainly influenced by aircraft mass. Mass sensitivity is drastically increased over electric fixed-wing aircraft. Hover power demand is however also driven by hover powertrain design and installation which is addressed in the chapters 2.1 and 4.4. Advantages for aircraft design arising from the VTOL capabilities can be yielded in the aerodynamic layout of the aircraft. The neglect of slow speed aerodynamic lift requirements and control authority shrink wing and tail plane size and mass. The typical trade-off between high lift phases and fast cruise performance is mitigated. Fixed-wing VTOL wings and airfoils can generally be designed for narrower ranges of lift coefficients and Reynolds numbers. High lift systems mostly become obsolete. Mass saving ambitions result in small sized, highly loaded wings operating in their upper regime of lift coefficients. A disadvantage from aerodynamic point of view is the parasitic and interference drag of nacelles. An obvious design advantage concerning the landing gear comes from the missing forward landing requirement.

2.1 Degree of Powertrain Share for Hover Lift and Cruise Thrust

A main difference between the two considered aircraft configurations can be expressed as the degree of the powertrain share for the hover lift and cruise thrust. 'Tilt rotor' powertrains are used for both tasks, while 'hover plus cruise' configurations have dedicated powertrains for each task.

In first place, a 'tilt rotor' powertrain appears as the lightest solution, as all installed powertrains contribute to the sizing requirement of hover lift. It however has to be designed for the two contrary operating points of hover and cruise. A hover lift force of more than the aircraft weight has to be provided at very low rotor inflow airspeeds. High diameter rotors with low pitch and low blade tip speed are able to provide hover lift thrust under low power consumption and noise emission. In cruise, the thrust force requirement is down to around one tenth, but at very high inflow airspeeds. Here, an efficient design requires high pitch blades with limited diameter to not approach the speed of sound at the tips. The separated hover lift and cruise thrust design approach allows to apply these ideal rotor layouts to the respective powertrain and achieve maximum powertrain efficiencies. A single powertrain operating at the two concurrent conditions of hover and cruise will need to tolerate efficiency losses. The consequence is a higher power demand in typically both hover and cruise flight. With the increased power demand in hover, engine size and mass increase. The significant reduction of required thrust between hover and cruise results in very low throttle settings during the cruise phase. This part throttle operation negatively affects electric motor and electronic speed controller (ESC) efficiencies. Battery mass and size rise due to the increased required energy content, but also due to a reduced energy density that comes with higher battery current drain. As well, lowered powertrain efficiency means an increased amount of waste heat and cooling effort.

The tilt mechanism and actuation has to be considered as a part of the 'tilt rotor' powertrain, as they represent a prerequisite for non-tailsitter aircraft to use the powertrain in both hover and cruise. Dimensioned to actuate the rotating and high-thrust load of a VTOL rotor, the tilt mechanisms adds considerable mass to the aircraft. Their inherent complexity and wear are main drivers for development and maintenance cost.

Performance-wise, the 'tilt rotor' design approach commends itself for missions with very short hover times. The advantage of the basically lighter powertrain is then not yet used up by the negative impact of the powertrain design tradeoff. A 'hover plus cruise' aircraft will be able to provide longer hover times.

From a redundancy and safety perspective, a failure in the 'tilt rotor' powertrain affects both hover and cruise functionality. A 'hover plus cruise' vehicle is able to vertically land even in case of a cruise powertrain failure.

If designed for independent operation, the tilt mechanisms of a 'tilt rotor' configuration can support control authority in hover. A main benefit refers to the yaw authority which is often unsatisfying with traditional multicopter control approaches that the 'hover plus cruise' configurations use.

The transition from hover to cruise flight is typically more complex for 'tilt rotor' configurations. The increase of forward thrust is coupled to the loss in vertical lift thrust by the tilt angle. The loss in vertical lift must be compensated by the increase of aerodynamic lift by the wing, which requires the acceleration to sufficient airspeed. Due to the separated powertrains, forward thrust is mostly independent from hover lift for 'hover plus cruise' configurations. Due to the drag of the hover rotors' sideward inflow and counteraction of rotor pitch up moments, the forward thrust requirement is higher for 'lift plus cruise' configurations. Dependent on the overall aircraft design and mission, it might even exceed the cruise climb thrust requirement and represent a sensible limit for design stall airspeed.

A result of separated hover and cruise propulsion is that the vertical thrust rotors are inactive during wing-borne cruise flight and negatively affect the aerodynamic performance by their drag. In the context of the typically high design airspeed of fixed-wing VTOL aircraft and the need for low-power cruise to reach sufficient ranges with battery driven vehicles, the inactive rotor drag becomes a factor necessary to be explicitly addressed within fixed-wing VTOL aircraft design. A range of approaches – from simply accepting the drag of inactive rotors to dedicated systems to eliminate the drag completely – is imaginable [4].

2.2 Integration of the Hover Lift Powertrain

Due to the electric VTOL aircrafts' inherent use of distributed electric propulsion, multiple motors and rotors have to be attached to the airframe. Most of the powertrain arrangements involve nacelles on the wings or twin boom fuselage mounts. The convenient access to fuselage components, battery or the payload remains unaffected by that. Besides providing sufficient lever arms towards the aircraft center of gravity (CG), the downwash of the rotor shall be blocked as little as possible. A blocking reduces the net hover thrust and inversely increases the power demand in hover. Dependent on the shape of the blocking body, its distance to the rotor, the blocked rotor disk area and the downwash velocity of the rotor the penalty varies. Due to typically lower rotor disk loading and smaller blocked disk area fraction, 'hover plus cruise' configurations tend to show less blocking losses.

Nacelles add, besides their own parasitic drag, interference drag to the wing. They trigger wedges of turbulent flow on the elsewise laminar dominated UAV airfoils. A disruption of the lift distribution is as well present.

Structural mass of the nacelles but also the reinforcement of the inner wing structure add to the aircraft total mass. These elements must be dimensioned to provide load transmission within tolerable deformations and oscillation propagation.

To provide power to the rotor locations, cables with mass, ohmic losses and potential electromagnetic interference issues must be foreseen.

The nacelle design must satisfy the cooling requirements of the high power hover powertrain while still keeping aerodynamic drag in cruise at a minimum. Dependent on the number of powertrains, the cooling requirement of a single motor location can be influenced.

In case of 'tilt rotor' configurations like in Fig. 2, tilt mechanisms and their actuators are stored inside the nacelles. Often batteries are located in the nacelles as well.

3 Development of the '5TOL' Configuration

Based on the previous fixed-wing VTOL UAV analysis, design guidelines were established (denoted with number in brackets) to implement the general objectives of mass reduction (structure, actuation, powertrains), efficiency increase (powertrains, aerodynamics) and maximum energy installation (available mass for battery, high energy density). The result is the '5TOL', an unmanned fixed-wing VTOL aircraft with 5 kg take-off mass (see Fig. 3 and Fig. 4). The working principles and considerations behind this configuration are presented hereafter.

Fig. 3. '5TOL' Configuration in Hover Mode

Fig. 4. '5TOL' Configuration in Cruise Mode

To keep the powertrain mass low, (1) all powertrains, including cruise powertrains, shall be active and contribute to lift thrust in the maximum thrust flight phase of hover. To keep power consumption in hover low and, by that, enable high battery energy density, (2) the majority of lift thrust shall be efficiently generated by hover optimized rotors. The logical consequence is that just (3) the small amount of cruise thrust vector is tilted. That enables robust tilt mechanisms at reasonable mass. To further diminish their mass penalty, (4) tilt mechanisms and their actuation shall also be used for control purposes in hover and cruise. In cruise, they shall replace dedicated control surfaces and actuators. The dual use of the cruise powertrain in hover and cruise dictates a tilt axis parallel to the aircraft y-direction. To avoid pitch moment couplings, the tilt axis should settle close to the CG in regard to the aircraft z- and x-coordinate. The space of possible positions for the tiltable cruise thrust vector root is hence a slim cylinder with its axis parallel to the aircraft y-axis running through the aircraft's CG. The generation of control moments with small force variations (the majority of the anyway small cruise thrust vector shall still point upwards to support lift in hover) requires a large distance to the CG along the aircraft y-coordinate. To avoid the resulting high yaw moment in cruise mode, a second cruise powertrain must be mirrored at the aircraft x-z-plane. An aircraft with a tiltable split powertrain positioned like this is able to use thrust vectoring for yaw control in hover and roll control in cruise, and differential thrust for roll control in hover and yaw control in cruise. Traditional rudder and ailerons are omitted. The split of the cruise powertrain in two is well feasible with the scaling characteristics of an electric motor. This will nevertheless slightly reduce the propellers' cruise efficiency due to a smaller diameter compared to a larger, single propeller. The fact, that only the small amount of cruise thrust is tilted to contribute to hover lift, makes it possible to fully optimize the cruise powertrain to its cruise condition. Although this powertrain operates with bad efficiency during hover, due to its small thrust contribution, the absolute power penalty is acceptable.

A disadvantage of the split cruise powertrain is the case of 'one engine inoperative' (OEI). The consequent yaw moment in cruise typically represents a trade-off between the size of a compensating vertical tail plane and the reduction of OEI cruise thrust. In the case of VTOL aircraft, the hover flight mode can be used as an OEI fallback flight mode. In hover only one of the two tiltable cruise powertrains is required if the propeller is able to produce only a small amount of reverse thrust. Electric motors typically provide the ability of fast switching between forward and reverse rotation. A temporary forward flight OEI fallback mode is gliding flight if alternatingly wind milling and forward thrust of the residual powertrain is used to maintain yaw stability and control. To ensure roll control in this scenario, aerodynamic control surfaces have to be coupled to the tilt actuation as the small thrust magnitude, although vectored, cannot generate sufficient roll moments.

To (5) keep the wing clean of aerodynamic disturbances, the symmetric split powertrain is located at the wingtips. A tiltable outermost wing section carrying the cruise motor and propeller combines the tilting of the thrust vector and the deflection of an aerodynamic surface. Blocking of the prop flow is avoided at the same time. On the '5TOL', the propeller is mounted in front of the leading edge to guarantee ground clearance during hover takeoff and landing. Thereby, the CG of the wing section is forward of the tilt axis to avoid flutter problems. The distance of the cruise propeller plane to the tilt axis is critical as it amplifies the propeller's unbalance to an oscillating high-frequency moment load on the tilt actuator. A hollow tilt shaft and its bearing use the space at the thickest chordwise position of the airfoil. A robust actuator finds room in the engine nacelle behind the electric motor. Cables are routed through the hollow shaft. To reduce lift losses, the gap between tiltable and inner wing section is sealed. The inner wing structure does not feature any control surfaces which promotes extended laminar flow and easy manufacturing. The cruise propellers spin in opposite direction to the wingtip vortex. Numerous investigations show that induced drag can be reduced with this measure [5, 6]. In the context of operation at high lift coefficients, the positive effects of wingtip propulsion are pronounced.

The dedicated hover powertrain correspondingly moves to the fuselage. Two rotors are located before and after the wing, symmetric to the CG. (6) They are rigidly mounted to the fuselage structure to limit the tilting of the rotor plane due to flapping. The desired disk loading can be achieved by two rotors by just a 41% increase in diameter compared to a four rotor hover powertrain. Hover efficiency benefits from the larger rotor blades which still show sufficiently short spool up time for tight aircraft control. A downwash blocking by the wing is avoided. For the same areal blocking factor, the higher rotor diameter allows wider fuselages. Due to the airfoil-like shape of the fuselage cross section, blocking losses are further reduced by a favorable drag coefficient and a straightening of the rotor swirl. The rotors are installed on the fuselage upper side in tractor configuration. This limits noise emission and provides clearance to the ground. In cruise, the two-blade rotors are aligned with the fuselage axis to save drag. Access to the fuselage from the top is prohibited by the rotors and the objective of a closed fuselage structure. Therefore, battery exchange happens from the rear of the aircraft.

The vertical tail plane is integrated into the fuselage and serves as rear landing gear. It is small in size due to differential wingtip thrust yaw stabilization and control. The elevator is designed all-moving to support pitch authority during transition.

4 Modelling and Performance Comparison of Optimized Fixed-Wing VTOL Configurations

To compare the three different configurations, an automated design and mission simulation tool has been developed. With this tool, the configurations can also be optimized for a certain mission. This is done by the variation of parameters like cruise speed, aspect ratio, tailplane surface ratio, airfoil camber and thickness, etc.

The optimization target is the maximization of cruise endurance.

The design tool generates, besides optimum aircraft parameters sets, also parameter sensitivity charts.

4.1 Simulated Mission

The simulated mission is split in two different flight phases: the hover phase and the cruise phase. The forward and backward transition phases have not been taken into account.

The simulated mission has a hover time of 1 min which is split into a fraction with the thrust equal to the aircraft weight and a fraction with the thrust increased by a maneuver factor of 1.4. The cruise phase is separated into three different flight conditions, which are steady horizontal flight, climb and turn at a constant bank angle.

The take-off weight is set to 5 kg. A fixed payload with a mass of 885 g and dimensions of 210x100x100 mm is installed in the CG. Additional fixed masses consist of a rescue parachute of 315 g and the flight control computer of 113 g.

The cruise altitude is set to 1500 mMSL.

4.2 Simulated Configurations

In comparison to the above discussed configurations, there are slight changes regarding the modelling in the design tool:

The ‘tilt rotor’ configuration (see Fig. 5) only uses the forward facing motors to provide thrust during the cruise phase. The backward facing motors are stopped, tilted and the propellers folded to the back.

The ‘hover plus cruise’ configuration (see Fig. 6) is simulated with a double T-tail instead of an inverted V-tail.

The simulated ‘5TOL’ configuration (see Fig. 7) features a non-inverted vertical tailplane.

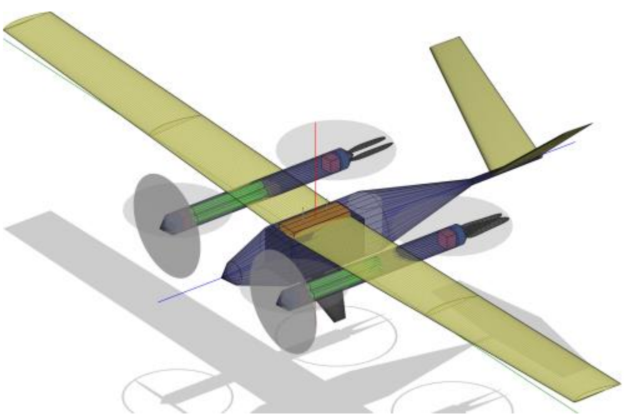

Fig. 5. Simulated 'Tilt Rotor' Configuration

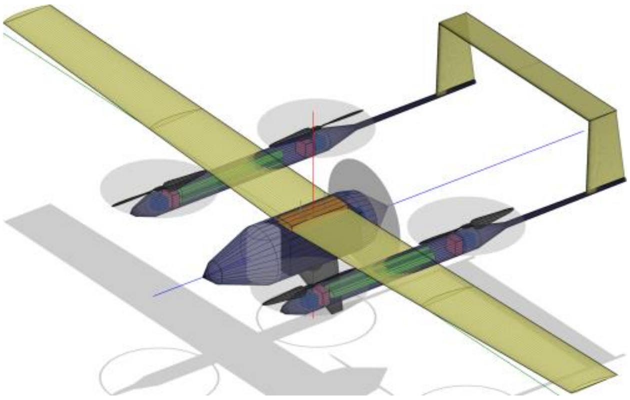

Fig. 6. Simulated 'Hover Plus Cruise' Configuration

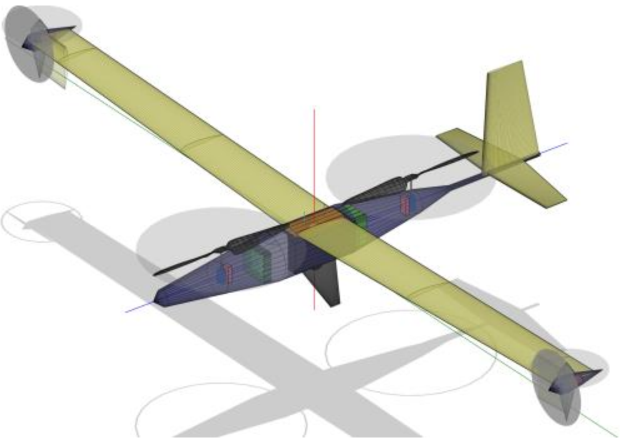

Fig. 7. Simulated '5TOL' Configuration

4.3 Simulation Model

The different disciplines within aircraft design are modelled using the approaches presented in the following sections.

4.3.1 Propulsion System

The propulsion systems are purely electric and consist of a single battery, the cables, the ESC, the motor, an optional gearbox and the rotors respectively propellers.

The battery is modeled as a constant voltage source with an inner resistance, depending on the battery's connection. The effective capacity C_{eff} is calculated with a method based on Peukert's Law [7] using the timespan t, a current I is drained from the battery.

$$C_{eff} = I^{pk} \cdot t$$

The cables are modeled as ohmic resistances. Their length depends on the position of the motors and the size of the aircraft. Their cross-section is chosen based on their maximum current requirement.

The ESC is modeled as an ohmic resistance for the full throttle calculation. For part throttle calculations, an overall model for ESC and motor is used. It calculates the part throttle efficiency η_{PT} based on the full throttle efficiency η_{FT}, input voltage U, an empiric part throttle factor PTF and the throttle setting θ. This model is based on the method by Rößler [8].

$$\eta_{PT} = \eta_{FT} - \frac{PTF}{\mathrm{U}} \cdot (1 - \theta)$$

The electric motors, respectively their angular velocity ω and torque Q, are modeled based on three coefficients and their derivatives. These coefficients are the inner resistance R_i, the rotational speed constant K_V and the idling current I_0. This approach is based on the method by Lundström et al. [11].

$$\omega = (U - I \cdot R_i) \cdot K_v$$
$$Q = \frac{I - I_0}{K_v}$$

These constants origin from the motors' technical data sheets and are stored in a data base which the design tool accesses.

For the propeller database, the measurements performed by the University of Illinois are used [12, 13].

The propulsion systems are calculated in two steps. First, full throttle performance is calculated, then part throttle performance.

4.3.2 Aerodynamic Model

The calculation of the airfoil lift coefficient c_l is based on airfoil polar data calculated with XFOIL. For the finite wing, the lift coefficient c_L is calculated with an approach based on the method by Polhamus for unswept wings with an aspect ratio Λ at Ma=0:

$$C_L = \frac{C_l \cdot \Lambda}{2 + \sqrt{\Lambda^2 + 4}}$$

The drag components taken into account are:

- airfoil drag
- induced drag
- fuselage and nacelle drag
- propeller drag
- landing gear drag
- external components drag
- interference drag

The airfoil drag is taken from the polar data calculated with XFOIL.

The induced drag C_{Di} is calculated based on the lift coefficient, wing aspect ratio and Oswald factor e.

$$C_{Di} = \frac{C_L^2}{\pi \cdot \Lambda \cdot e}$$

The fuselage and nacelle drag is based on the surface friction method by Raymer [9].

The hover rotors which are in the free airstream during the cruise phase add parasitic drag. This drag consists of pressure drag, friction drag, rotor shaft drag and interference drag.

Pressure and friction drag are calculated by the method by Hoerner [10], with the rotor blades modelled as ellipsoids. The shaft is modelled as a cylinder which is perpendicular to the stream. To take into account the interference drag, the complete drag is increased by 50%.

The landing gear is modelled as small wings with drag force only.

The external components consist of cylindrical antennas and radomes, representing a gimbal camera. Their drag is based on the method by Hoerner [10].

The interference drag is calculated between wing and fuselage, wing and nacelles, empennage and fuselage, two empennage parts and between landing gear and fuselage. The calculation method for these interferences is also based on the method by Hoerner [10].

4.3.3 Geometry Calculation

Since no horizontal take-off and landing is needed, the wing is sized based on the stall speed at a bank angle of 45°. There is a requirement that the stall speed at this bank angle is 3 m/s lower than the cruise speed.

The fuselage and nacelles are sized such that their volume and surface is at a minimum around the required components.

The powertrain positions are based on a minimum lateral propeller clearance and a proper force and moment equilibrium during the hover phase.

4.3.4 Flight Mechanics

The longitudinal stability is based on the moment equilibrium around the CG x_{CG}, the lift slopes $L_{\alpha,i}$ and neutral points $x_{NP,i}$ of wing and tailplane at a stability margin of $\sigma_l = 15\%$:

$$\sum M_{CG} = 0$$

$$x_{NP} = \frac{x_{NP,w} \cdot L_{\alpha,w} + x_{NP,t} \cdot L_{\alpha,t}}{L_{\alpha,w} + L_{\alpha,t}}$$

$$\sigma_l = \frac{x_{CG} - x_{NP}}{l_\mu}$$

The directional stability is calculated with the relative tailplane volume.

$$c_{VTP} = \frac{S_{VTP} \cdot \Delta x_{NP,T}}{b \cdot S_{ref}}$$

4.3.5 Structure

The fuselage and nacelle parts are assumed to have a constant thickness of monolithic CFRP. For the wing and the tailplane parts, the structure is calculated more precisely. It is a sandwich shell construction. The components are sized according to a maximum allowable wing twist for torsion and a maximum load factor for bending.

4.3.6 Unimplemented Features

Some features which would be necessary to completely represent the real aircraft are not implemented yet. These include the transition phases and the descend phases. As well, the benefit of wingtip propulsion is not modelled. Checks on rotor dynamics to ensure hover controllability are not conducted.

4.4 Design Tool Results

The result of the design tool is, that the ‘5TOL’ configuration leads to the highest endurance. The second best configuration is ‘hover plus cruise’ with 91 % of the ‘5TOL’ endurance. The ‘tilt rotor’ configuration reaches only 66% of the ‘5TOL’ endurance.

This result is mainly driven by the efficiency of the propulsion systems and the available mass for the energy storage.

The ‘tilt rotor’ configuration has a significantly higher fixed component mass (see Fig. 8), as it needs more components for the tilt capability of the propulsion systems. This leads to a lower available weight for the battery. Additionally, the motors have to work in two very different conditions. This leads to higher power requirements (see Fig. 9), which, in combination with the smaller battery, yields a

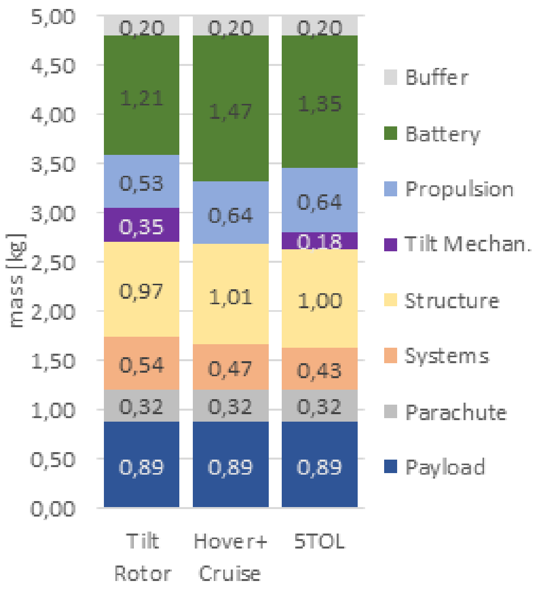

Fig. 8. Mass Breakdowns of the Investigated Configurations

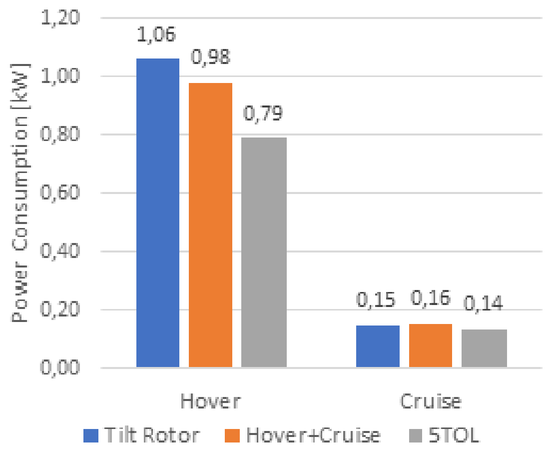

Fig. 9. Flight Phase Power Consumption of the Investigated Configurations

significantly shorter endurance in comparison to the other configurations.

Due to the four hover rotors, which are in the free airstream during cruise, the 'hover plus cruise' configuration owns the lowest aerodynamic efficiency. This cannot be compensated by the higher efficiency of the single cruise propulsion system (see Fig. 9, cruise power consumption). But due to the lowest fixed component mass of all configurations, the available mass for energy storage is maximal. This, in combination, leads to a reasonable endurance.

The '5TOL' configuration leads to the highest efficiency of the hover propulsion systems, as the main load is carried by only two motors with very big rotors. The wingtip propulsion systems can be optimized for the cruise phase, as they are not very loaded during the hover phase. The '5TOL' also shows the fewest components of all configurations and thus a relatively low fixed component mass. This combination of the highest efficiency of the propulsion systems and a big battery leads to the longest endurance.

5 Critical Review and Outlook

A qualitative analysis of two representative unmanned electric fixed-wing VTOL configurations for their main determining design features was conducted. The findings were used to state design guidelines for the development of fixed-wing VTOL configuration. The resulting '5TOL' configuration was presented. For the purpose of quantitative and fair comparison, the aircraft configurations were modelled and optimized for the same mission. The results confirm the initially anticipated consequences of the three different design approaches.

The ground and flight testing of the '5TOL' revealed the following points as more critical than estimated:

- Thermal management of the hover powertrain: A modification of the internal layout and the motor bulkheads was required to improve cooling air guidance through the electric motor.
- Electromagnetic interference on long power cable architectures: An initial attempt to store the ESC in the wingtip gondola was not successful. They now rest inside the fuselage and 3-phase motor cables are routed through the wing instead of a direct current power bus.
- Battery exchange: An initial but omitted design to exchange the battery through an opening in the fuselage back required a splitting of the battery and significantly reduced the fuselage torsional stiffness. The battery loading from the back solves these issues.
- Robustness of the tilt mechanism: Some design iterations were needed to establish

the presented wingtip tilt mechanism. Main challenges were the lack of space to integrate sufficiently dimensioned actuators and to identify the critical load case for the actuator (oscillating unbalance moments).

- Landing gear design: The width of the landing gear initially did not provide enough roll stability on the ground.
- Pitch up moment during transition: The pitch up moments and flapping of sideward blown rotors, even of rigid rotors, almost demand full pitch authority forces from the hover powertrains. It is recommended to quantitatively consider the transition flight phase in the aircraft conceptual design phase, also for 'hover plus cruise' configurations.

'5TOL' could approve its control concept and the superior hover performance in flight. Forward flight performance testing is currently starting. For the design of a successor, fixed-wing VTOL specific investigation findings are added to the design tool. As well, improvements to the '5TOL' configuration addressing the above issues are planned.

Acknowledgements

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Author Contact

Philipp Stahl
Institute of Aircraft Design, TU Munich
Boltzmannstraße 15
85748 Garching, Germany
mailto: philipp.stahl@tum.de

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