Configuration Redesign and Prototype Flight Testing of an Unmanned Fixed-Wing eVTOL Aircraft with Under-Fuselage Hover Lift and Pusher Wingtip Propulsion System

Philipp Stahl
M.Sc.
Technical University of Munich
Garching/Munich, Germany

Christian Roessler
Dr.-Ing.
Technical University of Munich
Garching/Munich, Germany

Mirko Hornung
Prof. Dr.-Ing.
Technical University of Munich
Garching/Munich, Germany

ABSTRACT

The ‘Quad+Tilt’ fixed-wing eVTOL configuration is the combination of a quadrocopter in ‘+’ orientation and tiltable wings or wingtips. Its wingtips used for propulsion and control as well as the mounting of lift rotors on the fuselage are two major design features that are addressed in this paper. Inflight power consumption measurements on a small unmanned implementation of this configuration suggest a 4% reduction in cruise flight power consumption accredited to wingtip propulsion. Three alternative wingtip designs for a Quad+Tilt configuration with different control principles were proposed and flight tested. Two of them implement a pusher propeller configuration. Rotor thrust losses and fuselage cross section depict a sensible trade-off for the Quad+Tilt configuration. Taking helicopter tail rotors as an example, the mounting of a Quad+Tilt’s hover rotors below the fuselage is examined as a strategy to overcome this trade-off. Verifying measurements on the thrust loss caused by blocking objects in the in- and outflow of a rotor were performed and used for modelling. Crucial topics to realize the advantages of underbody rotor mounting like foreign object damage, rotor strike and noise emission are addressed and solutions proposed. Despite the required measures implemented, a gain of 3% in cruise endurance seems achievable for a 5 kg Quad+Tilt aircraft with lift rotors mounted to the fuselage bottom instead of the fuselage top.

INTRODUCTION

Fixed-wing eVTOL UAV are electrically driven, unmanned aerial vehicles capable of both hover and fast forward flight. Lift during take-off and landing is generated by rotors or ducted fans. After takeoff, they transition into forward flight mode in which a wing produces the lift. Many existing types of fixed-wing VTOL aircraft (see Ref 1, 2, 3) show the wide range of possibilities to combine vertical flight capabilities with efficient forward flight. The question arose which of these configurations is best suited for a certain mission. Using a dedicated conceptual design and mission simulation tool (see Ref 4), a benchmarking of typical fixed-wing eVTOL configurations was performed. A configuration that combines a quadrocoper in ‘+’ orientation with tiltable wings or wingtips, called ‘Quad+Tilt’ in this paper (see Figure 1 and Figure 2), showed significant performance benefits compared to its contenders.

Figure 1. Boeing’s ‘Phantom Swift’ as a Representative for a ‘Quad+Tilt’ Configuration ©Boeing

Figure 2. Autel Robotics’s ‘Dragonfish’ as a Representative for a ‘Quad+Tilt’ Configuration ©dronerush.com

To keep power consumption in hover low and, by that, enable increased battery energy density, the majority of lift thrust is efficiently generated by hover optimized, fuselage mounted fans or rotors. The small amount of thrust generated by the wingtip propulsion system is vectored to provide yaw control in hover, as well as forward thrust and roll control in cruise. Differential thrust on the wingtip powertrains is used to control roll in hover and yaw in cruise flight. Aircraft control

Presented at the Vertical Flight Society Autonomous VTOL Technical Meeting and Electric VTOL Symposium, Mesa, Arizona, UAS, Jan. 29-31, 2019.

is realized with a minimum number of effectors and thus minimal system mass. The optimization of the wingtip powertrain for the cruise condition, the beneficial interaction between propeller or fan swirl and wingtip vortex (see Ref 5, 6, 12) and a wing clean of nacelles enable efficient cruise flight.

As visible in Figure 1 and Figure 2, the integration of lift powertrains is challenging for Quad+Tilt configurations. Lift fans take valuable space inside the fuselage and have diameter limitations, while rotors mounted outside the fuselage suffer from thrust loss as their stream tube is blocked by the fuselage. Further, the tiltable wingtip carrying powertrains is a sophisticated aircraft system.

This paper first validates the performance benefits of wingtip mounted propulsion with inflight measurement data of a prototype aircraft. To implement a tilt-wingtip with integrated powertrain, three designs are proposed, evaluated and flight tested. The paper further experimentally examines and models the thrust loss of blocked rotors. Especially, an unconventional mounting of rotors under the fuselage is addressed.

The performed measurements and proposed designs primarily have unmanned, fully electric aircraft with take-off masses up to 25 kg in mind.

ASPECTS OF TILT-WINGTIP PROPULSION AND CONTROL

The positioning of cruise powertrains on tiltable wingtip sections combines the principle ideas of

- using the actuators and powertrains for aircraft control and propulsion in both hover and cruise flight to reduce system weight
- using the wing span lever arm to achieve
  - roll and yaw hover control moments with little thrust, respectively power, and thus enable a powertrain optimization for cruise
  - very high hover control moments using the full thrust capability of the wingtip powertrains if superior agility and gust handling is required
- keeping the wing clean of the drag, mass and manufacturing related penalties of nacelles or control surfaces
- using the beneficial interaction of propeller swirl and wingtip vortex

Opposed to that stand challenges like

- robust mechanical implementation of the tilt-wingtip
- power distribution to the remote wingtip location (cable mass, ohmic losses, risk of electro-magnetic compatibility issues)
- significant contribution to the aircraft’s roll and yaw inertia (aircraft dynamic behavior)
- handling of ‘one engine inoperative’ scenario
- trade-off between wing geometry parameters and pitch trim effort due to cruise thrust vector above/below center of gravity (CoG)

Wingtip Propulsion Benefits

While most above points are obvious and well describable in conceptual design tools (like used in Ref 4), the presence and extent of wingtip propulsion benefits was of special interest.

An inflight experimental attempt was made to evaluate the expected positive impact of wingtip vortex and propeller swirl interaction. As the positive effect is ascribed to the reduction of the wingtip vortex (a source of induced drag) by a counter-rotating propeller swirl, the approach is to compare the power consumption for the same aircraft, in similar flight conditions between flights with propellers rotating ‘inward blade up’ (counter-vortex) and flights with propellers rotating ‘inward blade down’ (vortex-wise). The ‘inward blade up’ should exhibit the lower power consumption of both. According to Ref 12, the overall efficiency of an aircraft with only the wingtip motor nacelle mounted (no forward thrust) is right in the middle of counter-vortex and vortex-wise wingtip propulsion. Subtracting the end plate effect of the wingtip motor nacelle yields the overall efficiency of an aircraft without any wingtip device. Measurability of the difference in power consumption is expected best for airspeeds close to stall speed. Here, the vortex and induced drag almost gains maximum intensity relative to other drag components. The recorded power consumption P and airspeed data v was averaged and translated with the aircraft’s total weight G into the overall efficiencies $\frac{L}{D}\eta$ by

$$\frac{L}{D}\,\eta = \frac{G\,v}{P}$$

Table 1. Test Flight Data on Wingtip Propulsion Benefit

Day-Flight		1-1	1-2	2-1	2-2
Prop Rotation w.r.t. Wingtip Vortex		counter	co	co	counter
Test Duration [min]		22.7	25.3	28.0	28.7
Airspeed [m/s]	av.	17	16.5	17.7	16.9
	dev.	0.4	0.4	0.4	0.7
Power [W]	av.	117.7	132.8	127.4	120.3
	dev.	14.9	23.1	12.2	22.6
$\frac{L}{D}\eta$ [-]	abs.	4.30	3.70	4.16	4.21
	rel.	1.162	1	1	1.011

Table 1 summarizes the flight test data and results. The aircraft depicted in Figure 3 (span 2.1 m, mass 3 kg, wing aspect ratio 14) was used to obtain the data. The propellers providing forward thrust are each mounted at the wingtips before the leading edge in a tractor configuration (see Figure 4). In total, four test flights were performed on two days, one after another with just a short break to change the propeller direction and the battery. Early-morning environmental conditions with minimal horizontal and vertical air movement

Figure 3. Aircraft to Evaluate Wingtip Propulsion Benefits and Wingtip Designs in Flight

were chosen. Airspace restrictions only allowed a trajectory of earth-fixed, 15° nominal bank angle circles. Throughout the trajectory, constant altitude and an airspeed of 17 m/s were controlled by an autopilot. These parameters result in a nominal lift coefficient of 0.58. The trajectory shape and a slight daytime dependent increase in wind speed seem to cause an increased deviation in power consumption for the later flight of each day. The higher variations in power consumption may impair the overall efficiency. Looking at the figure of relative $\frac{L}{D}\eta$, an increase of 16.2% and 1.1% (despite the higher variations in power consumption of the later flight) in overall efficiency for the aircraft with counter-vortex rotating propellers can be observed against the aircraft with propellers rotating in the direction of the wingtip vortex. If one conservatively (not subtracting the nacelle end plate effect) assumes the overall efficiency of an aircraft without wingtip propulsion right in-between the efficiencies of wingtip propulsion with different propeller directions, counter-vortex wingtip propulsion would achieve an increase in overall efficiency $\frac{L}{D}\eta$ in the order of 4% over an aircraft without wingtip propulsion. Due to the underlying assumptions, precision of data acquisition and deviations in the data records, the statements made have to be considered with care. They will differ further for different aircraft and flight conditions.

Wingtip Design for Quad+Tilt Configurations

The key enabler for a Quad+Tilt's propulsion and control concept is its wingtip. To understand the origin of the challenging wingtip design, a brief outline of the requirements for actuation, bearing and power supply is given:

- sufficient roll and yaw authority in hover and cruise flight (tilt angle range of typically >140°)
- dimensioned for the following load cases
  - engine thrust
  - oscillating propeller unbalance (fatigue!)
  - wingtip aerodynamic forces
  - movement related inertial and precession forces
  - operator handling
  - ground contact
- low aerodynamic drag
- stable against aero-elastic divergence or flutter
- integration within given aerodynamic surfaces
- good accessibility for integration, maintenance and repair

Three wingtip designs, namely 'tiltable tractor', 'tiltable pusher' and 'fixed pusher', are proposed.

'Tiltable Tractor' Wingtip The 'tiltable tractor' wingtip design (see Figure 4) combines the tilting of an outermost

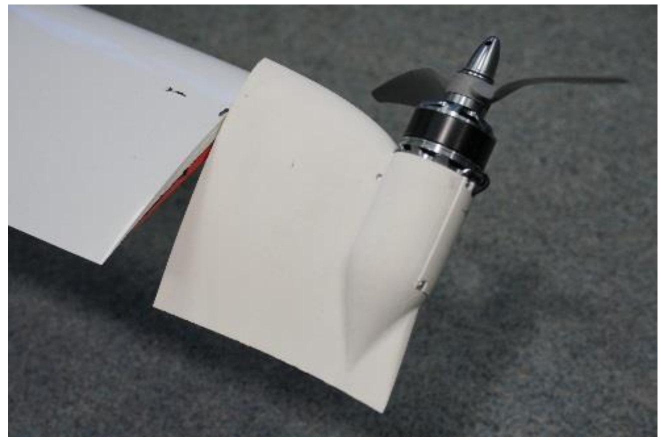

Figure 4. 'Tiltable Tractor' Wingtip

wing section with the vectoring of the propeller thrust. In hover, the downwash is only minimally blocked by the wingtip section. In a vertical position, the propeller cannot touch the ground during a turnover while the trailing edge is more robust against ground strike. In cruise, both the deflection of the wingtip surface as well as the thrust vectoring generate a roll moment. The propeller swirl is partly straightened by the wingtip surface, however can still interact positively with the lift-induced wingtip vortex (see chapter 'Wingtip Propulsion Benefits'). However especially for the deflected wingtip, major parts of the wing vortex already form at the gap between inner wing and wingtip. As a consequence, the intensity of the wingtip vortex positively interacting with the tractor propeller swirl is reduced, and so are the interaction benefits. As well, control effectiveness of the wingtip section is decreased. A gap sealing e.g. by an endplate is advised. The propeller's swirl increases the angle of attack on the wingtip section. Under certain flight conditions, this might lead to stall and its related drawbacks. The tilt axis at quarter chord is behind the wingtip CoG to avoid flutter issues. The oscillating loads coming from blade unbalance or transverse flow effects depict a potential source of fatigue fracture. Main weak point are often the actuator gears. To reduce the loads to a minimum the distance between propeller plane and tilt axis is minimized.

'Tiltable Pusher' Wingtip The 'tiltable pusher' wingtip design (see Figure 5) implements thrust vector tilting for a pusher configuration. The motivation is that propeller efficiency benefits were obtained for propellers impinged with inflow swirl induced by a wingtip vortex (see Ref 6) and partly laminar flow over the wingtip surface reduces aerodynamic drag. However, simply moving the propeller aft of the trailing edge of the ‘tiltable tractor’ wingtip would result in several problems:

- The clearance between the ground and the propeller is reduced. A contact between a rotating propeller and the ground is significantly more critical than the trailing edge of the ‘tiltable tractor’ touching the ground.
- The increased distance between propeller plane and shaft axis promotes unbalance and static moment loads on the actuator.
- The aft CoG of the wingtip section promotes flutter.

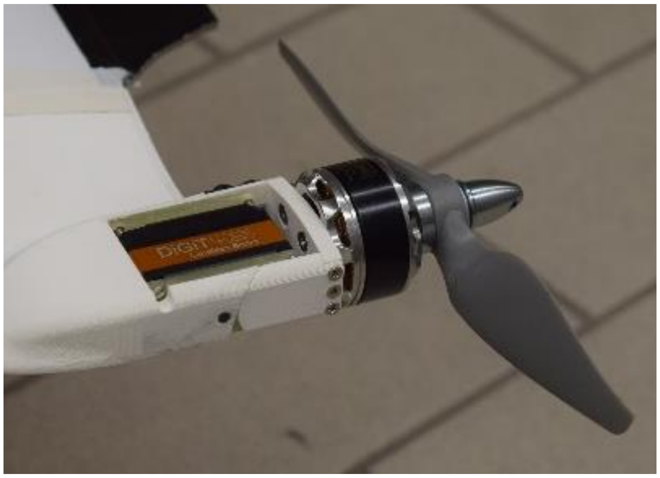

Figure 5. ‘Tiltable Pusher’ Wingtip

Furthermore, the gap between wingtip and inner wing and its related drawbacks remain. To solve or mitigate these issues, the motor is mounted on a shortest possible U-bracket that is directly driven and supported by the actuator. A tiltable aerodynamic surface, the related gap flow and flutter tendency is omitted. Thrust vectoring is solely used for direct roll moment generation in cruise. Thus, roll authority in cruise is dependent on the cruise thrust level and, thus, on the flight state. For the aircraft depicted in Figure 3, roll rates around 37°/s are calculated for horizontal cruise and asymmetric tilt angles of 45°/-20°. If roll control authority is insufficient, conventional ailerons may be added. In hover, the propeller operates in sufficient distance to the wingtip surface such that no noteworthy thrust blocking is expected. The omission of a tilt shaft and its bearing reduce wing structural mass and complexity.

‘Fixed Pusher’ Wingtip The idea behind the ‘fixed pusher’ (see Figure 6) wingtip is to build up the thrust vector by two separate powertrains instead of tilting a single one. The tilt actuator is replaced by a ‘roll thruster’ electric motor which represents a significant gain in system robustness. In hover, yaw is controlled by differential thrust of the horizontal cruise powertrains. For fast control response and to avoid frequent switching of the spin direction, a forward thrust offset has to be set. This must be compensated by a slight nose-up attitude of the aircraft. The implied force fighting means increased power consumption in hover. The roll thruster can principally be designed with small diameter as it just has to provide little roll control thrust. Their installation close to the wingtip surface makes them suffer of thrust blocking. In combination

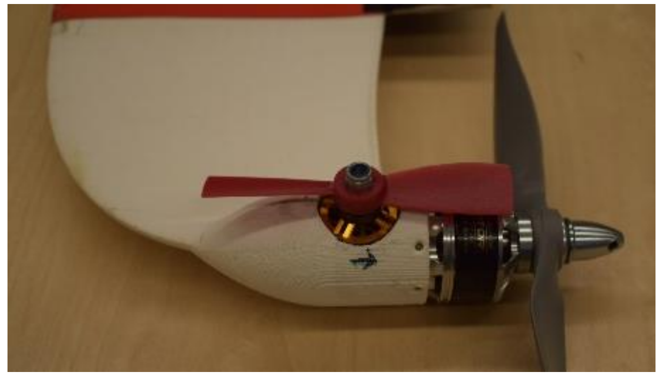

Figure 6. ‘Fixed Pusher’ Wingtip (bottom view)

with their small diameter, again, the ratio between thrust and power is unfavorable. The ground clearance of the horizontal thrust propeller is further reduced over the ‘tiltable pusher’ wingtip. As with the ‘tiltable pusher’, no aerodynamic control surface for roll control in cruise is available. The roll thrusters must be used for this purpose. As before, additional ailerons are imaginable to provide aerodynamic roll control in cruise. In forward flight, parasitic drag of both the spinning and stopped roll thruster rotors is present. The missing tilt shaft, bearing and a smaller extent of complex geometry reduce mass. The roll thruster powertrain as well is lighter than an actuator.

Table 2. Wingtip Mass Break Down

Wingtip Version	Tiltable Tractor	Tiltable Pusher	Fixed Pusher
Cruise Motor, Propeller, Adapter	100 g	100 g	100 g
Roll Thruster Rotor, Adapter, Motor, ECU	-	-	28 g
Actuator	46 g	46 g	-
Wingtip Structure	69 g	38 g	25 g
Tilt Shaft, Inner Wing Load Introduction	21 g	-	-
Inner Wing Extension	-	10 g	12 g
Wire Harness	58 g	58 g	58 g
Total (one wingtip)	294 g	252 g	223 g
Mass Saving w.r.t. ‘Tiltable Tractor’ in % of Aircraft Weight (two wingtips)	-	1.7	2.8

Table 2 breaks down the mass of the different wingtip versions as they were manufactured for flight testing on the aircraft depicted in Figure 3. The ‘fixed pusher’ is the lightest wingtip and saves 2.8% in aircraft overall mass compared to the ‘tiltable tractor’. The ‘tiltable pusher’ can still save 1.7% of the total aircraft mass.

All wingtips need to be tested in flight. Especially for the pusher versions, partly significant compromises have to be made in operability (reduced propeller clearance) and controllability (dismissal of aerodynamic roll control). These must proof to be feasible in first place and furthermore be justified by enhanced effectiveness of favorable wingtip propulsion interactions. The aircraft depicted in Figure 3 was fitted with fuselage mounted rotors to enable VTOL.

Wingtips in Hover Flight Test In hover, very good yaw authority is achieved with the 'tiltable tractor' wingtip. Position control can be achieved without changing the pitch attitude respectively wing's angle of attack, solely by rotating the wingtips over their range of 20° backwards and 120° forward from vertical position. Both provide the aircraft with good wind and gust handling capabilities in hover. The thrust share between wingtip propellers and fuselage rotors can be reduced down to 20% while still achieving sufficient controllability in hover. This contributes to a low absolute power consumption of the non-hover optimized wingtip propellers. The 'tiltable pusher' wingtips behaved likewise from controllability and power consumption point of view. The reduced propeller clearance resulted in occasional ground strikes. As expected, the roll thrusters on the 'fixed pusher' wingtip had to perform wide changes in RPM to stabilize the roll axis in hover. Due to the motor's high RPM, they were well audible out of the homogenous spectrum of the other powertrains. Despite very aggressive control gains and elevated idle RPM on the roll thrusters, it was not possible to realize a control behavior as tight as with the tiltable wingtips. Therefore, the roll thrusters likely lack in available thrust. Yaw control via differential thrust, in contrast, was surprisingly good in the general context of high yaw axis inertia of the aircraft. To avoid force fighting, it was tried to set the RPM of the horizontal motors to zero if no yaw control input is given. The increased response time due to the start-up time of the electric motors leads to unsatisfactory yaw control performance. The required force fighting for yaw control, the wide variation in thrust for roll control in combination with the inefficient thrust generation of the roll thrusters becomes apparent in the aircraft's average power consumption for static hover (see Table 3) as well as in the peak power consumption during hovering manoeuver flight. The average power loading during stationary hover flight is 26% higher for the Quad+Tilt test aircraft equipped with 'fixed pusher' wingtips instead of 'tiltable pusher' wingtips.

Table 3. Hover Efficiency for the Test Aircraft with Different Wingtip Designs

Wingtip Version	Tiltable Pusher	Fixed Pusher
Power Loading [W/N]	13.3	16.8

In high agility maneuver flight, the temperature of the roll thrusters approached the allowable limit. For practical use, the sluggish roll control in combination with the smallest propeller clearance lead to frequent cruise propeller ground strikes and damaged blades on the 'fixed pusher' wingtip. Here, the 'tiltable pusher' proved to be significantly less critical. The higher clearance and roll attitude controllability comparable with the 'tiltable tractor' wingtip helped to reduce the occurrence of propeller strikes. The more parallel attitude of the propeller plane with regard to the ground also reduces the extent of damage. A ground strike of the trailing edge on the 'tiltable tractor' showed to be uncritical.

Wingtips in Cruise Flight Test In cruise, roll control with the 'tiltable tractor' behaved as expected thrust dependent. Maximum feasible roll rates with cruise speed of 17 m/s and corresponding thrust setting ranged between 75 and 130°/s. But even at low speed, windmilling conditions (representing slight reverse thrust), no control reversal is present and sufficient roll rates of 25°/s can be achieved. Excellent yaw authority and damping is solely provided by differential thrust. In case of one engine inoperative and the other still in cruise thrust setting, the aircraft immediately introduces sustained stall spirals. With stopped propellers, controllability and directional stability is sufficient to e.g. perform an emergency landing. For the 'fixed pusher', it was not possible to achieve roll rates beyond 7°/s using full throttle on one of the roll thrusters. A likely reason is the roll thruster's rotor operating in stall conditions. At a tip speed of around 25 m/s and a cruise speed of 17 m/s, the retreating blade barely generates lift. The advancing blade faces an increased angle of attack due to the wingtip vortex and the horizontal inflow speed. Therefore, the occurrence of stall is likely. Hence, a limited directional control of the aircraft was solely possible via differential cruise thrust and yaw-roll coupling. With the 'tiltable pusher' wingtips mounted, sufficient roll rates in the order of 37 to 63°/s could be achieved in cruise flight with asymmetric deflections of –20° and +45°. As expected, the roll authority proved to be strongly thrust dependent. Roll rates of 22 to 28°/s could still be achieved during descent flight with repeated roll doublets and a glide angle of -14°. One must be aware of the increased drag of the performed flight maneuvers (adverse yaw and sideslip). At idle thrust, no roll control reversal occurred. Regarding the noise emission, no significant differences among the wingtip versions could be noticed by the flight test crew. As well, the emitted noise was rated as low enough for typical mission scenarios. Dedicated measurements on the pusher wingtips' power consumption in cruise could not yet be performed.

REDUCTION OF THRUST LOSS DUE TO ROTOR BLOCKING

Most fixed-wing VTOL aircraft have to accept thrust losses as their rotors' in- or outflow field is blocked by structure that

Figure 7. Representative of the Popular Fixed-Wing VTOL Configuration 'QuadXCruise' ©AltiUAS

holds the rotor and its engines. As the cross section of the blocking structure is typically small (see Figure 7), no relevant thrust blocking losses arise. Quad+Tilt configurations use their fuselage to hold its engine and rotor. While weight and drag of nacelles can be saved, thrust losses due to the larger blocking cross section of a fuselage are significantly increased. The consequence is a higher required gross thrust and hence increased power consumption. This, in turn, causes secondary effects like

- increased powertrain mass (rotor, motor, engine control unit, wire harness)
- mass, power consumption and aerodynamic drag of improved powertrain cooling
- reduced battery energy density due to higher required battery power capability

To reduce thrust losses at a given blocking cross section, the tail rotor of most helicopters is mounted in a pusher configuration to the tail fin (see Ref 9). This principle applied to the Quad+Tilt configuration leads to rotors mounted below the fuselage structure.

In the history of rotorcraft aviation, the approach to mount rotors to the bottom of a fuselage is unused. The concerns are obvious:

- close ground operation with the risk of foreign object damage (FOD) and restrictions for the blade movement and the aircraft's attitude
- limitations for operation with spinning rotor and insufficient passenger/operator safety
- typically increased noise emission of rotors with disturbed inflow
- complicated landing gear design

In the context of unmanned electric fixed-wing VTOL aircraft, these issues either vanish or can be solved by reasonable design compromises.

Avoidance of Rotor Strikes Issues arising from close ground operation of the rotors relate to the impact of the rotor blade with the ground or objects that were blown up by the rotor downwash. Due to the multirotor control principle and high stiffness of the hingeless blades with comparatively small diameter, the rotor's coning, tilting and flapping movement is marginal. The required clearance between rotor and fuselage to allow for the vertical amplitudes of the blade tips are well arrangeable in aircraft design. Ref 11 finds that the clearance between rotor and fuselage only plays a minor role for the aerodynamic drag of the stopped rotors in cruise flight. Furthermore, certain pitch and roll angles must be possible for the aircraft on the ground without a rotor ground strike. Besides an unobstructed payload field of view and the limitation of rotor tip vortex-landing gear noise interaction, the provision of this freedom of movement is the main driver for landing gear height and position. Here, the flatness of the VTOL pad (e.g. high grass) is as well relevant. Fortunately, the mass for a VTOL landing gear is reduced compared to conventional take-off and landing. It however must be pointed out that for an underbody rotor vehicle, a failure of the landing gear means a rotor ground strike. The mass and drag penalty of a higher and more robust VTOL landing gear will however be still moderate. Most transition VTOL aircraft's ability to control their position to a certain degree independent from pitch angle can help to reduce ground clearance required for VTOL in wind or from sloped surfaces. The consequences of dust whirl-up are mitigated by the nature of unmanned electric vehicles. An electric engine does not need to ingest the contaminated air for operation, hence can be enclosed easier. Furthermore, brown-out is irrelevant for autopiloted vehicles. In case of a harmful object uptake into the rotor or a rotor ground strike, an electric multicopter's rotor system is highly robust and damage-tolerant. For most missions however, a favorable VTOL site can be found or prepared with no effort.

Pusher Rotor Noise Mitigation Propellers and rotors in pusher configuration are known for their increased noise emission. In hover flight, the induced velocity of the rotor produces vertical flow around the fuselage cross section. The aft flow field that enters the rotor contains uneven velocity distributions out of potential flow, boundary layer or separation effects. This disturbed inflow produces pressure fluctuations on the rotor blades which are a source of pusher noise. The hover optimized rotors of the Quad+Tilt configuration work with low disk loading and therefore induce low vertical flow velocity. This helps to limit the unevenness of the inflow. A further source of pusher noise is the interaction of the rotor blades' pressure distribution with the fuselage geometry. For both mentioned pusher noise sources, the distance of the rotor plane to the object that blocks the inflow is crucial. In terms of the shape of noise propagation, reflections on the fuselage bottom may yield noise maxima in a wedge below the fuselage. Combined with the general in plane noise maxima of a rotor, this unfortunately corresponds with the position of operators and spectators. Human noise perception highly depends on the frequency of the noise (see Ref 8). Below 1 kHz, the perceived loudness for the same sound pressure level progressively decreases with frequency. The relevant frequency derives from the frequency the blade passes the blocking object. The low rotational speed of Quad+Tilt's hover optimized rotors are favorable also in this regard. Not having performed more in-depth noise modelling, these simple considerations and easily tuneable parameters to further reduce the pusher noise component (distance fuselage-rotor plane, rotational speed of rotors) raise hopes that noise might not evolve as a show stopper. Finally however, it must be evaluated during flight testing if a satisfactory noise level can be achieved.

Rotor Thrust Blocking of the Fuselage Rotor thrust blocking is a driver towards narrow and streamlined cross sections of Quad+Tilt fuselages (see Figure 2). A rectangular or elliptical fuselage shape however better matches the components' geometry and thereby reduces unusable space inside the fuselage. Besides a reduced volume and a better volume-to-surface ratio, fuselage drag benefits from rounded cross sections which are less prone to flow separations under sideslip. Also, more freedom can be given to the designer to create an appealing look of the fuselage. One obvious and easy to model source of thrust loss is an object's aerodynamic drag in the rotor induced flow field. Other reasons are the interaction of pressure distributions of rotor and object or the disturbance of a uniform rotor inflow velocity distribution. Using simple actuator disk theory, thrust loss due to parasitic drag on a rotor in hover can be expressed by

$$D = \frac{\varrho}{2}\, v(z)^2\, c_D\, S(z) \qquad \text{eq. I}$$

$$v(z) = k_v(z)\, v_{disk} \qquad \text{eq. II}$$

$$S(z) = 2\, r(z)\, b \qquad \text{eq. III}$$

$$\varrho\, r(z)^2\, \pi\, v(z) = \varrho\, R^2\, \pi\, v_{disk} \qquad \text{eq. IV}$$

$$v_{disk}{}^2 = \frac{T}{2\, \varrho\, R^2\, \pi} \qquad \text{eq. V}$$

$$\frac{D}{T} = \frac{1}{4}\, c_D\, \frac{S_{disk}}{A_{disk}}\, k_v(z)^{\frac{3}{2}} \qquad \text{eq. VI}$$

Air density ϱ is assumed constant, as actuator disk assumes an incompressible fluid. Drag depends on the encountered flow velocity $v(z)$ and the effective cross section $S(z)$ inside the rotor flow field (eq. I, refer to Figure 8). Both are dependent on the separation z to the rotor disk which is normalized by the rotor radius R and is positive for positions aft of the rotor disk. $k_v(z)$ describes the flow velocities with respect to the induced velocity v_{disk} (eq. II). Airflow $v(z)$ is generally accelerated along the z-coordinate. An object extending infinitely across the rotor disk is assumed (eq. III). Using conservation of mass (eq. IV) and momentum theory's the induced velocity for a hovering rotor (eq.V), thrust loss relative to the unblocked thrust is dependent on the drag coefficient, the blocking ratio S/A and the velocity distribution. As this is just a simple representation of one thrust loss component, measurements are used to validate, update and calibrate the model. Therefore, data from helicopter tail rotors (see Ref 9) and own measurements on a 17 inch two blade multicopter UAV rotor (see Ref 10) are used. Measurements on the UAV rotor were taken with objects placed both in the in- and outflow. To represent possible fuselage

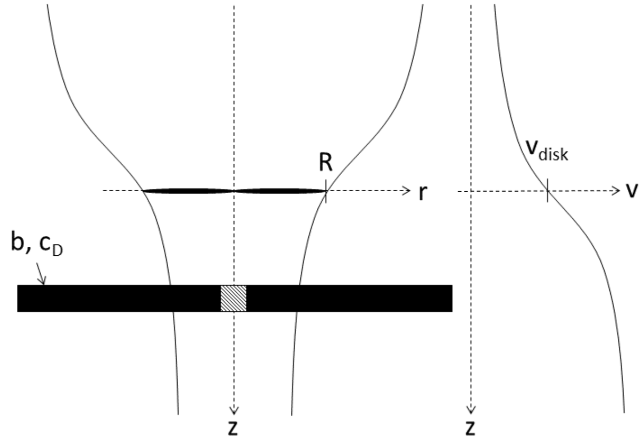

Figure 8. Schematic of Rotor Flow Field

shapes, a thick wing section with symmetrical airfoil and a flat plate were each placed with different distances in front and aft of the rotor. The objects were rotor-centered and extended far beyond the rotor diameter. Blocking ratio and disk loading of the rotor were kept constant. Figure 9 depicts the blocking ratio-normalized relative thrust loss $\frac{T_{loss}}{T}\frac{A_{disk}}{S_{disk}}$ for all measurements. As indicated by eq. VI, the different drag coefficients of airfoil and flat plate lead to a difference in thrust loss. Neither the absolute values nor the ratio of the thrust loss between flat plate and airfoil fits the measurements when using eq. VI with typical drag coefficients (known e.g. from Ref 13) and $k_v(0) = 1$. Besides the mentioned other effects, one must consider that objects like airfoils generate additional induced drag as the swirl of especially the aft rotor flow causes an angle of attack to the object. The tail rotor was blocked by a fin of identical cross section, but different

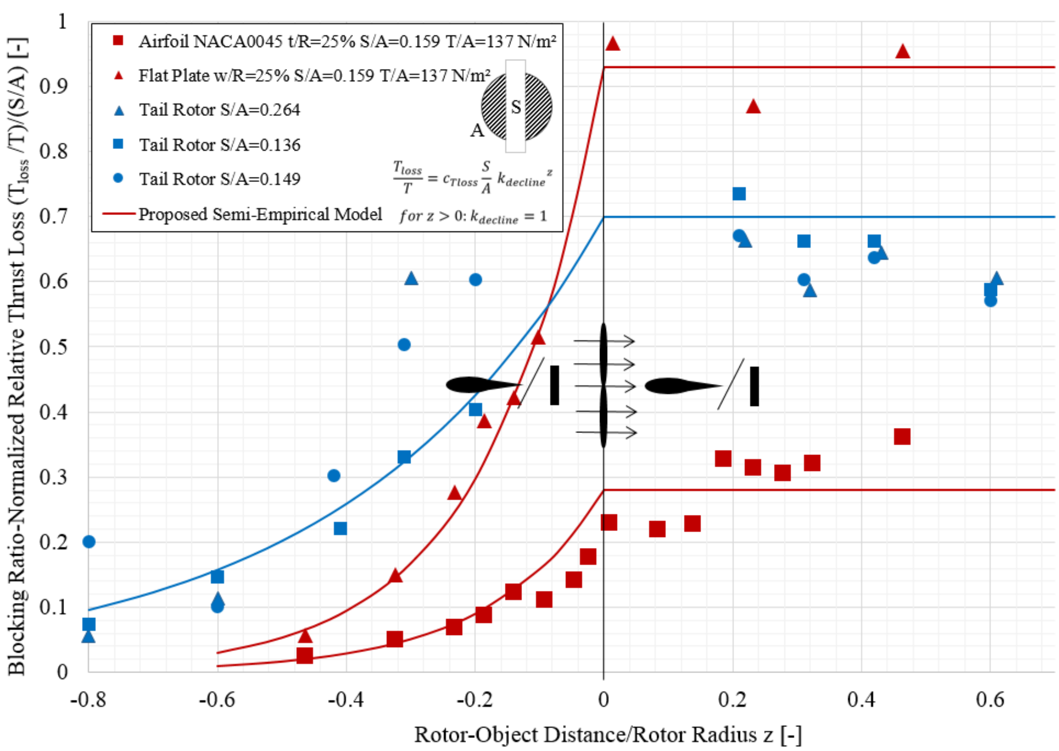

Figure 9. Measurements on In- and Outflow Blocking of a Rotor

blocking ratios. The good alignment of these measurements, at least for the aft rotor side, confirm eq. VI's linear dependency on blocking ratio. One would expect better alignment of flat plate with tail rotor measurements as their blocking objects have comparable cross sections. The placement of the blocking object with respect to the rotor disk is however not comparable. The velocity distribution within the disk of a z-coordinate is not uniform. Especially for aft rotor flow, the velocities have maxima at outer radius positions. Blocking of rotor disk regions with above-average velocities (as the flat plate does compared to the tail rotor fin) shows increased thrust loss. The flow velocity increase $k_v(z > 0)$ after the rotor would indicate an increase in drag. Looking at all aft rotor measurements, no such trend is visible. For simplicity, one can assume a constant drag, or better, thrust loss coefficient c_{Tloss}. This aligns with the approach of Ref 9. Based on given data, thrust loss due to blocking on the inflow side is always smaller than due to outflow blocking. Thrust loss decreases differently fast for tail rotor and UAV rotor measurements. It is likely affected by the present thrust loading. Taking tail rotor and UAV rotor data separately, the measurements show good consistency as identical thrust loadings and velocity trends exist. Eq. VII proposes a simple semi-empirical model for thrust blocking losses which combines information from eq. VI and Figure 9.

$$\frac{T_{loss}}{T} = c_{Tloss} \frac{S_{disk}}{A_{disk}} \, {k_{decline}}^{z} \qquad \text{eq. VII}$$

while $k_{decline} = 1$ for $z > 0$. $k_{decline}$ and c_{Tloss} must be calibrated from measurements. Further data is required to model the likely dependency between $k_{decline}$ and thrust loading. As a conclusion, the mounting of hover rotors in a pusher configuration leads to a significant reduction in blocking thrust losses for a rectangular fuselage cross section. 68% of the tractor configuration's thrust loss can be saved. The required rotor-fuselage separation of 0.2 R is small enough to be implementable in aircraft design. A further increase of rotor-fuselage separation depicts an effective means to e.g. allow for wider fuselages without additional rotor thrust loss.

Adding to the aspects of rotor tip movement and pusher noise generation, the study on thrust blocking again underlines the importance of rotor-fuselage separation for an underbody mounted rotor and the possibility to implement it with low penalties.

Overall Performance of the Under-Fuselage Pusher Rotor Configuration The modifications required to implement an under-fuselage pusher rotor configuration (like elevated landing gear and longer rotor shafts) entail mass and drag increase that face the benefits like reduced hover power consumption and reduced hover powertrain mass. To see the performance impact of these changes, simple estimation models were used to compare the cruise endurance of the under-fuselage pusher rotor configuration against its tractor rotor pendant. The VTOL version of the test aircraft depicted in Figure 3 equipped with a fuselage with rectangular cross sections serves as geometry baseline. Except for the rotor placement, the landing gear geometry and the rotor shaft lengths, the geometry of the compared aircraft versions is identical. The mass of the compared aircraft is each 5 kg. Non-powertrain components' mass and structural masses as well as cruise powertrain efficiency are identical between the aircraft. Linear, power-dependent powertrain sizing is used and calibrated with the test aircraft data. As well, the test aircraft's aerodynamic performance is used as baseline. Battery energy density is considered independent of power consumption. The thrust loss model is derived from measurements in Figure 9 ($c_{Tloss} = 0.93$, $k_{decline} = 300$). The airfoil shaped landing gear struts are elevated by the maximum height for the fuselage on the underbody pusher rotor aircraft. The rotor shafts are elongated to a separation of 0.2 R and housed with low drag fairings. The additional mass and drag of both modifications is modelled with the respective material densities and shape-dependent drag coefficient found in Ref 13. The modelling of the modifications can be considered conservative. The mission consists of a 2 min hover phase and a horizontal cruise phase with identical airspeed for which the residual energy of the battery is used.

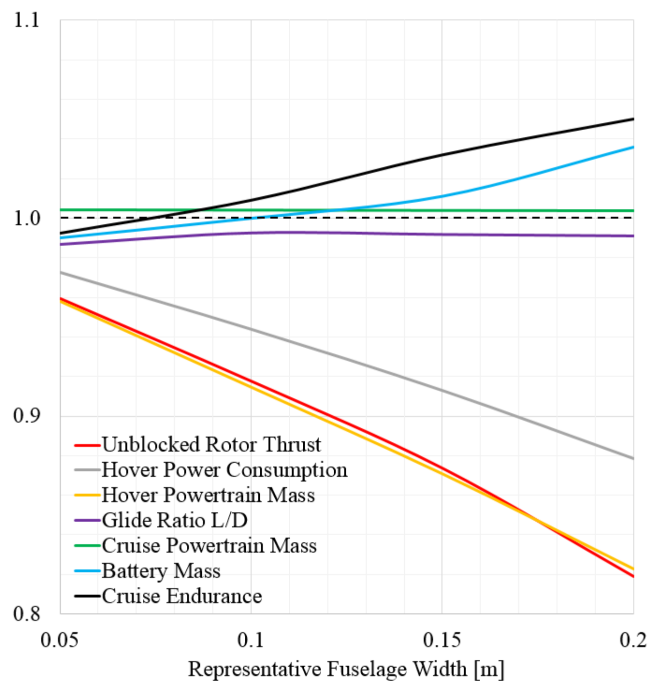

Figure 10. Relative Comparison of Under-Fuselage Hover Rotor Aircraft Over Its Tractor Pendant

Figure 10 depicts the change of selected performance relevant properties for different fuselage widths. The properties of the under-fuselage pusher rotor aircraft are normalized by the properties of the tractor rotor aircraft. Increasing fuselage width leads to increased occurrence of thrust blocking. Hence, lower gross thrust levels are required for the pusher rotor. Hover powertrain mass and hover power consumption decrease. As can be seen on the mass available for battery, additional landing gear and rotor shaft weight are just compensated by reduced hover powertrain mass for fuselage widths beyond 0.1 m. Already at this fuselage width, the small penalty in glide ratio and hence cruise power consumption is overcompensated by a higher energy available for cruise, as less energy is spent during the hover phase. As a result, the under-fuselage hover pusher aircraft achieves, with the exception of fuselage widths below 0.075 m, better cruise endurances. For a fuselage width of 0.15 m, as it is required to fit a typical payload of the examined aircraft, the improvement is around 3%. Conclusively, the trade of elongated landing gear and rotor shaft mass and drag against lower thrust blocking is beneficial for typically required fuselage widths. The trade-off gets increasingly beneficial for wider fuselages, especially if the low hover power consumption can still maintain the usage of high energy density batteries.

CONCLUSIONS

Motivated by a performance comparison of various unmanned fixed-wing eVTOL configurations, major effects and challenges of the superior Quad+Tilt configuration were addressed. Firstly, the benefits and implementation of wingtip propulsion providing roll and yaw control in both hover flight were approached. Secondly, the integration of Quad+Tilt's fuselage mounted lift rotors was investigated as a sensitive design trade-off is present here. The cross section of the fuselage causes a considerable amount of rotor thrust loss which triggers further performance compromising effects.

One aspect, which is difficult to model with wingtip propulsion, is the beneficial interaction between wingtip vortex and the counter-rotating swirl of the wingtip mounted propeller. Therefore, an inflight analysis using different spin directions of the wingtip propellers was attempted. It yielded A 4% reduction in cruise flight power consumption compared to an aircraft without wingtip propulsion was found. Three alternative designs were proposed to implement the control and propulsion tasks of a Quad+Tilt wingtip. The 'tiltable tractor' wingtip tilts an outermost wing section that carries the powertrain. It provides yaw and roll moments by a combination of thrust vectoring and the deflection of aerodynamic surfaces. The 'tiltable pusher' and 'fixed pusher' wingtips try to implement a pusher configuration as further wingtip propulsion benefits seem feasible. The 'tiltable pusher' omits the aerodynamic control component and solely relies on thrust vectoring. The 'fixed pusher' uses a second, perpendicular powertrain to substitute a tilt mechanism. This wingtip as well has no possibility of aerodynamic control moments. Flight testing of the wingtips shows that, despite its lowest mass, the 'fixed pusher' wingtip can overall not be recommended as it lacks control authority, requires the highest power in hover flight and is prone to damages due to propeller strikes. The 'tiltable pusher' wingtip seems to provide sufficient propeller clearance and can be compared to the 'tiltable tractor' in terms of hover controllability. As it lacks aerodynamic control surfaces, its roll authority is dependent on the thrust level. The 'tiltable tractor wingtip' provides good control authority, also in critical flight conditions. It is currently recommended over the other two wingtip versions. Further evaluation of pusher wingtip propulsion benefits may eventually justify the usage of the 'tiltable pusher' wingtip.

Taking helicopter tail rotors as an example, a mounting of Quad+Tilt's hover rotors below the fuselage is examined as a strategy to overcome the sensitive thrust blocking trade-off. Verifying measurements on the thrust loss caused by blocking objects in the in- and outflow of a rotor were performed. They revealed the distance of rotor to fuselage as critical to achieve low thrust blocking on a pusher configuration. The crucial topics to realize the advantages of underbody rotor mounting are foreign object damage, rotor strike and noise emission. Elevating the landing gear is, besides the inherent advantages of using sealed electric motors, fully automated flight control and small diameter, rigid rotor hinging, a measure that solves foreign object damage and rotor strike issues. The risk of unacceptable loudness is as well mitigated with sufficient rotor-fuselage clearance and a low blade pass frequency which is perceived as agreeable for the human ear. To quantify the overall aircraft performance, an aircraft with the under-fuselage mounted pusher rotor and the therefore required changes was compared to an otherwise identical aircraft with rotor mounted on top of the fuselage in a tractor configuration. The trade of higher landing gear and higher rotor-fuselage clearance for reduced thrust blocking results in a 3% gain in cruise endurance for the examined 5 kg pusher rotor aircraft. Up to now, the considerations on mounting rotors below the fuselage of a Quad+Tilt configuration yield no show-stopper. As a next step, such an aircraft must demonstrate in real-life operation if its rotor mounting still proves to be sensible.

Author contact:

Philipp Stahl philipp.stahl@tum.de

Christian Roessler christian.roessler@tum.de,

Mirko Hornung mirko.hornung@tum.de

ACKNOWLEDGMENTS

The author wants to thank the project team members Sebastian Oberschwendtner, Thomas Seren and Moritz Thiele for their support, as well as all students that contributed to fixed-wing VTOL aircraft development at Institute for Aircraft Design/Technical University of Munich.

REFERENCES

[1]Poisson-Quinton, P., "Introduction to V/STOL Aircraft Concepts and Categories", AGARDograph 126, 1968

[2]Hirschberg, M. J., "V/STOL: The First Half-Century", *Vertiflite*, March/April 1997.

[3]Anderson, S., "Historical Overview of V/STOL Aircraft Technology", NASA Ames Research Center: NASA Technical Memorandum 81280, 1981.

[4]Stahl, P., Seren, T., Rößler C., and Hornung, M., "Development and Performance Comparison of Optimized Electric Fixed-Wing VTOL UAV", ICAS 2018 Proceedings, Belo Horizonte, September 2018.

[5]Miranda, R. L., "Aerodynamic Effects of Wingtip-Mounted Propellers and Turbines", A86-31826, AIAA, 1986.

[6]Patterson, J. C., and Bartlett, G. R., "Evaluation of Installed Performance of a Wing-Tip-Mounted Pusher Turboprop on a Semispan Wing", NASA Technical Paper 2739, 1987.

[7]Prouty, R.W., *Helicopter Aerodynamics*, Vol. 1, Eagle Eye Solutions, Lebanon, 2009, pp. 147-150.

[8]Müller, G., Möser, M., *Taschenbuch der Technischen Akustik*, Springer Verlag , Berlin Heidelberg, 2004, pp. 104, 585-638.

[9]Johnson, W., *Rotorcraft Aeromechanics*, Cambridge University Press, Cambridge, 2013, pp. 149-150.

[10]Rieger, C., "Experimentelle Untersuchung der Auswirkungen von Objekten im Zu- und Abstrom von Propellern für Multirotor UAV", Institute of Aircraft Design, Technical University of Munich, Munich, 2017.

[11]Stahl, P., Roessler, C., Hornung, M., "Benefit Analysis and System Design Considerations for Drag Reduction of Inactive Hover Rotors on Electric Fixed-Wing VTOL Vehicles", Paper AIAA-2018-4150, AIAA Aviation and Aeronautics Forum Proceedings, Atlanta, GA, June 25-29, 2018.

[12]Dimchev, M., "Experimental and numerical study on wingtip mounted propellers for low aspect ratio UAV design", Faculty of Aerospace Engineering, Delft University of Technology, Delft, 2012.

[13]Hoerner, S. F., "*Fluid-Dynamic Drag*", Hoerner Fluid Dynamics, Bakersfield, CA, 1965.