CONTROL CONCEPT OF A TILTWING UAV DURING LOW SPEED MANOEUVRING

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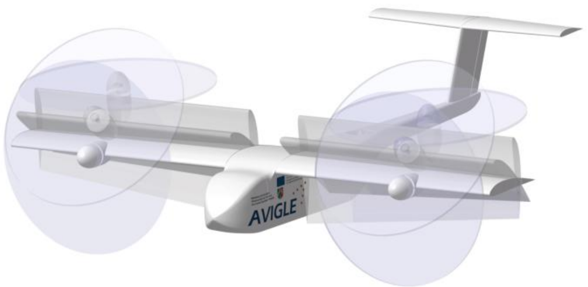

Fig. 1. Illustration of the AVIGLE Tiltwing

Abstract

The unmanned AVIGLE Tiltwing illustrated in Fig. 1 is intended to operate as a multi-role service platform in a wide velocity range between hovering and horizontal flight to serve different mission tasks. In this context the low speed operation, when the aircraft is not solely borne by aerodynamic lift forces, is of particular interest. According to the required operational speeds the UAV changes its aerodynamic configuration by tilting the wing to a certain position and simultaneously adapts the corresponding thrust and control forces to keep the altitude and to compensate resulting moments. The whole transformation process is managed by a control system, which stabilizes the vehicle in its different flight states. The modelling of the transition manoeuvrings as well as the development of the controllers was conducted in a six degrees of freedom simulation environment.

1 Introduction

In this contribution a transition control concept of a Tiltwing UAV is presented, which allows low speed operations beyond aerodynamic stall velocities.

Within the AVIGLE project an unmanned aerial vehicle is currently in development at the Institute of Flight System Dynamics at RWTH Aachen University. The autonomous multi-role aircraft is considered to be used as a flying service platform for various mission tasks with exchangeable payloads [1]. One fundamental design requirement is a particular flexibility regarding different operational flight velocities in combination with a good manoeuvrability within the entire required speed range of 0 to 40 m/s. In this context the operation with flight velocities below the aerodynamic stall speed, which is determined at 13 m/s for the AVIGLE aircraft, is of special interest to achieve defined mission tasks. For this reason a Tiltwing configuration was selected which is capable to transform its flight mechanical configuration and adapt to different flight states [2]. The conversion process as well as the flight operation is managed and controlled by a controller system which is designed with particular attention to the required low speed manoeuvring capabilities.

2 Tiltwing Aircraft

A Tiltwing is a convertible aircraft. The special design concept joins two completely different aircraft types. It combines the advantages of a common fixed-wing aircraft concerning flight performance and energy consumption with the vertical take-off and landing (VTOL) capabilities of a rotary-wing configuration. The transformation is achieved by tilting the wing about its lateral axis and thus changing the aerodynamic configuration as well as the orientation of the propulsion system. However, it has to be kept in mind that such an aircraft is a special configuration. The increased flexibility to operate in a great range of totally different flight states comes always at the expense of energy efficiency, system- and control complexity as well as increased mechanical stress.

2.2 Specification AVIGLE Tiltwing

According to the requirements for the different mission tasks the following specification for the AVIGLE Tiltwing was defined in [2] and [3] (see Table 1).

Configuration	VTOL (convertible)
MTOW	10 kg
Wing span	2 m
Propeller diameter	0.7 m
Minimum speed	0 m/s
Design speed (horiz.)	15 m/s
Maximum speed	40 m/s

Table 1. AVIGLE Specification

The air vehicle, as shown in Fig. 2 is completely built of CFRP. It is powered by two counter rotating brushless electric motors and an additional impeller in the aft. A 12.4 Ah battery ensures a flight endurance of approximately 60 minutes.

Fig. 2. AVIGLE Tiltwing

2.3 AVIGLE Flight Modes

The AVIGLE UAV is designed to operate in different flight modes serving its various mission tasks. The vertical flight mode is intended for VTOL, vertical climbing and descending as well as hovering. For repositioning manoeuvers in hovering flight longitudinal and lateral movements are feasible e.g. for aligning the vehicle after wind disturbances. Additionally the aircraft can yaw on the spot to adjust its orientation.

The transition mode ensures stationary operation with all airspeeds between hovering and aerodynamic stall speed in any defined mission altitude at a fixed pitch angle. Because in this case the aircraft is not solely borne by aerodynamic forces additional lift has to be generated by the propulsion system.

The horizontal flight mode is intended for energy efficient long term operations above the aerodynamic stall speed. To ensure smooth handovers the transition mode overlaps with vertical and horizontal flight mode, as shown in Table 2.

Flight Modes	Horizontal speeds
Vertical	0 – 1.5 m/s
Transition	0 m/s – 15 m/s
Horizontal	13 m/s – 40 m/s

Table 2. AVIGLE Flight Modes

3 Transition

The transition phase describes the changeover between vertical and horizontal flight states. Because of the occurring nonlinear effects and instabilities due to stall or vortex ring states in transition, the transformation feature is usually not applied for stationary flight manoeuvrings outside of the aerodynamic flight. Most convertible aircrafts like Tiltwing, Tiltrotor or Tailsitter only use their outstanding capabilities to perform vertical take-offs and landings as an enhancement of the flight envelope regarding flexible ground-to-air / air-to-ground-procedures. They are not intended for long term operations in transition. After reaching a defined altitude outside the ground effect the transition procedure is initiated and performed as one single continuous process from vertical to aerodynamic horizontal flight or contrariwise in order to save energy and to avoid critical flight states. In this case typically time optimized or energy optimized control concepts are used, as described in [4] and [5].

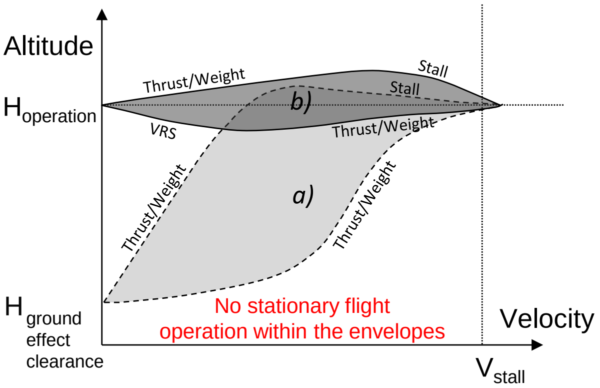

Fig. 3. Exemplary transition envelopes
a) from take off b) from operation height

Fig. 3 depicts two transition envelopes exemplarily. The possible trajectories are limited by the aircrafts flight performances as well as the above mentioned stall and vortex rings state effects. Usually the conversion is not performed at constant altitude. In order to stabilize occurring stall effects at the weak stages of transition, descent manoeuvres are conducted to accelerate the aircraft and to speed up the transition process.

In contrast to this the AVIGLE flight platform is designed to perform stationary operation at different requested speeds within the whole transition phase at constant altitude. Although this is less energy efficient than a solely aerodynamic borne flight, it gives an outstanding flexibility for various flight operations.

3.1 Control devices

Fig. 4 illustrates the control devices of the AVIGLE Tiltwing for horizontal and vertical flight. In horizontal flight the typical set of control surfaces, ailerons, elevators and the rudder, is used for steering and the main propulsion system for acceleration. In vertical flight the thrusts of the upright tilted propeller engines are used in connection with the slipstream flaps that can be deflected symmetrically and asymmetrically. Additionally an impeller is installed in the aft as an independent control device. Steering forces are generated by either coordinated differentiation of the thrust values or flap deflections. For quick responses the blade pitch angles of the propellers can be changed collectively. The rotary speed is adapted for better efficiency at long term trimmed states. Deflected ailerons cause a yawing moment, while a symmetric deflection of the flaps initiates a pitching moment. For the first development steps of the flight control system only the impeller will be utilized for pitch control. Tilting the wing influences the stability and the steering capabilities of the aircraft. This has to be considered for the flight control system to adapt the control commands according to the incidence angle of the wing.

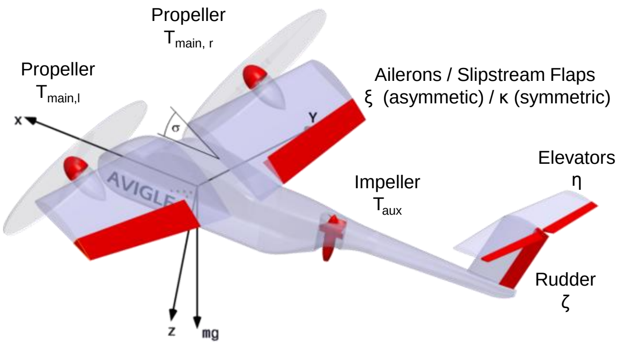

Fig. 4. AVIGLE control devices

3.2 Flight mechanics in transition

As the transition is a part of the longitudinal motion, the flight mechanics as depicted in Fig. 5 can be described in three degrees of freedom with equations (1) – (6). The aerodynamic forces D and L and the aerodynamic pitching moment M_{aero} consist of the freestream induced as well as of the slipstream induced effects. Thus they are dependent on the propeller thrust.

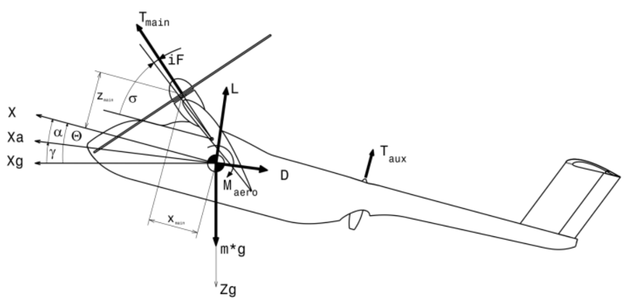

Fig. 5. Forces and moments in longitudinal motion

$$T_{main} = T_{main,l} + T_{main,r} \tag{1}$$

$$\sum X_f = T_{main} \cdot \cos(\sigma + iF) + L \cdot \sin(\alpha) - D \cdot \cos(\alpha) - m \cdot g \cdot \sin(\theta) \tag{2}$$

$$\sum Z_f = -T_{main} \cdot \sin(\sigma + iF) - T_{aux} \qquad (3)$$
$$-L \cdot \cos(\alpha) - D \cdot \sin(\alpha)$$
$$+m \cdot g \cdot \cos(\theta) \overset{!}{=} 0$$

$$\sum M_f = M_{aero} + T_{main} \cdot (\sin(\sigma + iF) \cdot x_{main} \qquad (4)$$
$$-\cos(\sigma + iF) \cdot z_{main})$$
$$-T_{aux} \cdot x_{aux} \overset{!}{=} 0$$

For the development of the transition controller equations (2) and (3) can be simplified for small α and θ as can be seen in (5) and (6).

$$\sum X_f = T_{main} \cdot \cos(\sigma + iF) - D \qquad (5)$$

$$\sum Z_f = -T_{main} \cdot \sin(\sigma + iF) - T_{aux} \qquad (6)$$
$$-L + m \cdot g \overset{!}{=} 0$$

In order to find stationary solutions for each requested horizontal speed during transition, the aircraft has to fulfil the equations shown above using its different steering controls.

3.3 Control Concept for transition and low speed operation

Hence the transition in context with AVIGLE is not an end-to-end process from stationary vertical to horizontal flight; it gets a different meaning for the control system. The controllers must not only be capable to manage a quick complete transition process, but also to find certain configurations for the aircraft to perform stationary operations at each demanded flight speed. This means that even non-stationary states have to be handled in a systematic way.

The basic principle is an adaption of the wing tilt angle combined with a simultaneous thrust adjustment corresponding to the requested velocity. Thus the primary steering parameter for transition is the demanded horizontal speed, which is predetermined by an operator or the flight management system. Based on this pre-set value the wing is assumed to change its tilt angle and respectively the orientation of the thrust vector. So basically this is a cruise control which is supported by coordinated thrust adjustments to maintain attitude and altitude. The horizontal thrust component which accelerates the aircraft depends on the tilt angle and the thrust value of the main propulsion system. The latter depends on the required vertical thrust component that is used to keep operation altitude as well as the moment equilibrium as a combined effort with the other control devices. While tilting the wing, a shifting of the centre of gravity occurs in particular due to the weight of the motors, which are installed near the leading edge. This has to be taken into account because it influences the pitching moment considerably and thus has to be equalised by the thrust distribution.

Due to rising aerodynamic effects with increasing speed, the vertical thrust component has to be adapted while the freestream induced pitching moment needs to be equalised with the steering components.

4 Simulation Environment

For the design and evaluation of the flight control system a simulation of the Tiltwing flight system dynamics as well as an atmosphere model were developed in Matlab/Simulink® The six degrees of freedom simulation model is outlined in Fig. 6 and described in the following subchapters.

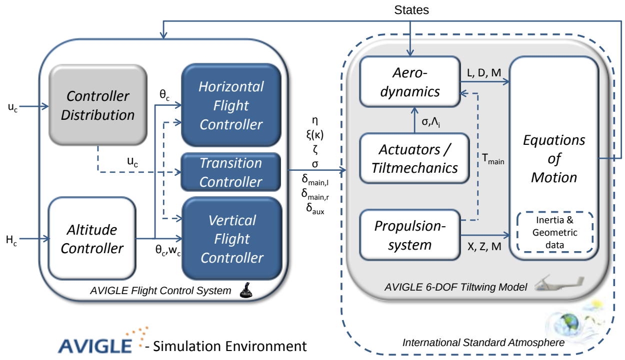

Fig. 6. Simulation Environment

4.1 Aircraft Simulation

The aircraft simulation consists of a propulsion system model and a model of the aerodynamics. Since the evaluation of the real propulsion system has not been completed successfully it is represented by simplified motor models using estimated response times. The aerodynamics model in contrast is based on data which was collected during extensive wind tunnel tests with a scaled Tiltwing-model and additional numerical calculations for dynamic states. As the slipstreams of the propellers affect almost 2/3 of the wing area and thus influence the aerodynamics considerably, the occurring effects are divided in freestream induced and propeller slipstream induced aerodynamic effects, which have been derived from the measured data in a complex post process. The resulting forces and moments were calculated to coefficients and arranged in several grids that contain the dependencies of the aerodynamic angles α and β, the wing tilt angle σ, the control surfaces deflections η, ξ (κ), ζ and also the thrust value T_main.

In order to model the partial independence of the aerodynamic effects at the wings from the flight velocity, a calculation of the occurring dynamic pressure in the slipstream which is dependent on the propeller thrust was implemented. The aircraft model also contains the complete geometric data set as well as the inertia data of the Tiltwing. Thus the shifting of the centre of gravity depending on the tilt angle of the wing is implemented and taken into account for the calculations of the resulting moments. In addition to this all actuators are modelled as well as the tilt mechanics according to their identified dynamics.

The resulting forces and moments of the propulsion system and the aerodynamics are summed up and lead to new states which are calculated in the equations of motion model.

4.2 Atmosphere Model

The aircraft simulation is embedded in an environment model of the international standard atmosphere (ISA) which influences the current states according to the aircrafts position. For evaluation purposes different wind and gust parameters can be defined.

4.3 Flight Control System

The flight control system consists of two basic flight controllers for vertical (VC) and horizontal (HC) flight in addition to a third controller for the transition phase (TC), which manages the tilting process in combination with certain functions of the VC and the HC. The VC is intended to be used for the VTOL procedures, vertical climb and descend, hovering as well as for very low speed manoeuvres in hovering flight like longitudinal and lateral slipping or yawing for alignment of the body-fixed payload.

Due to the fact that no dynamic pressure is available at the tail in hovering flight the aircraft's attitude and movement has to be completely controlled by thrust forces in consideration of the slipstream induced aerodynamic effects.

The VC generally consists of P, PI or PID sub-controllers to manage vertical speed w, horizontal speed components u and v as well as the yaw-rate r. The vertical speed is controlled by a collective throttle command to the two propeller engines and the impeller. The subdivision of the collective throttle value for each motor to keep a balanced attitude is part of the horizontal speed sub-controllers, which control pitch and bank angles.

Due to the upright position of the wing in vertical flight, the horizontal speeds for longitudinal and lateral motion cannot be generated directly applying thrust. Instead the speed is controlled by changing the attitude of the aircraft and thus bending the thrust vector. For this reason the collective throttle command is subdivided between the main propulsion system and the impeller for longitudinal as well as between the main engines for lateral motion. To keep the mission altitude during this manoeuvre the collective thrust is adaptively adjusted by the vertical speed controller. The yawing procedure is initiated by deflecting the ailerons in the slipstream.

The HC consists of P and PI structure controllers to manage horizontal speed u, pitch angle θ and bank angle φ. The horizontal speed is controlled via a collective throttle command for the propeller engines only. Attitude control is provided by coordinated deflections of the elevators for pitching and curve compensation, ailerons for rolling and the rudder for yawing and curve coordination. The attitude controllers of the VC and the HC are additionally equipped with dampers that use the rates of roll, pitch and yaw to avoid oscillations. As initial conditions the controllers are provided with pre-set trim values for various flight states.

In addition to HC and VC the TC is used when operational speeds between hovering and aerodynamic horizontal flight are demanded. For the transition phase the horizontal speed controllers of VC and HC are deactivated and cruise control is assigned to the TC. The TC initiates a change of the wing tilt angle supported by the thrust controllers of the VC, which manage the vertical thrust as well as the thrust distribution to keep the attitude and altitude until a new stationary operation point with balanced forces and moments at the demanded speed up to 15 m/s is found. The most challenging stages in transition are the states when aerodynamics becomes effective while accelerating and more important when aerodynamic stall occurs while tilting the wing upright and decelerating. Although the stall characteristics are smoother due to the continuous dynamic pressure caused by the propeller slipstreams, it also appears with a sudden loss of lift and steering effectiveness at the aerodynamic parts, which are not affected by the propellers.

An additional altitude controller (AC) in PI structure provides the VC with command values for the vertical speed and the HC with command values for the pitch angle to keep the required height.

The whole flight control system is supervised by the controller distribution (CD) that decides which controllers or controller parts are active and manages the complex handover between the controllers while changing between different flight phases. The decisions are based on the commanded horizontal speeds in combination with the current flight conditions.

5 Test & Validation

Applying the simulation environment different hover and transition manoeuvres of the AVIGLE Tiltwing have been evaluated. The results for three distinct test cases are presented in the following subsections.

5.1 Case 1: Manoeuvring in hover

In this test case the Tiltwing performs a manoeuvre in vertical mode using only the VC distributed by the CD. After hovering for 5 seconds the UAV gets a speed command of 1.3 m/s forward flight. After 50 seconds the command is reduced to 0.65 m/s and after 100 seconds the aircraft is requested to hover. In Fig. 7 the red dotted line shows the commanded speeds and the blue solid line the actual simulated speed. The results show quick responses and a high accuracy for manoeuvring.

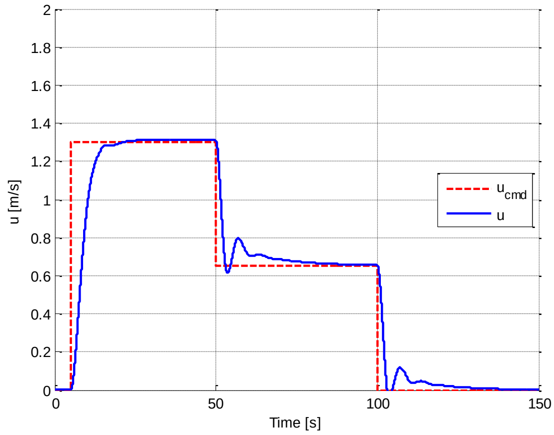

Fig. 7. Horizontal Speed

The blue line shows some oscillation effects during deceleration. This is caused by the thrust control which is adjusted for high agility as can be seen in Fig. 8. The peaks show rapid thrust commands at the decision points which immediately initiate the desired changes of the pitch angle to bend the thrust vector according to Fig. 9.

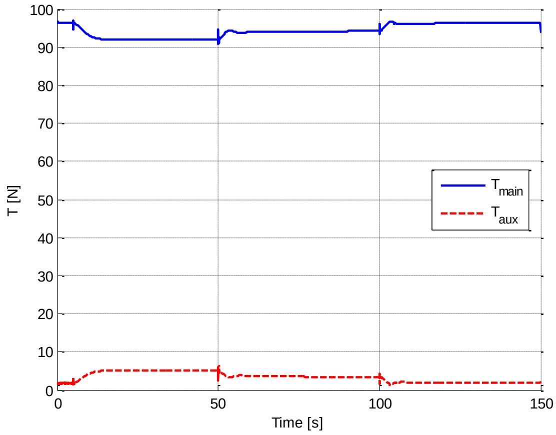

Fig. 8. Thrust distribution

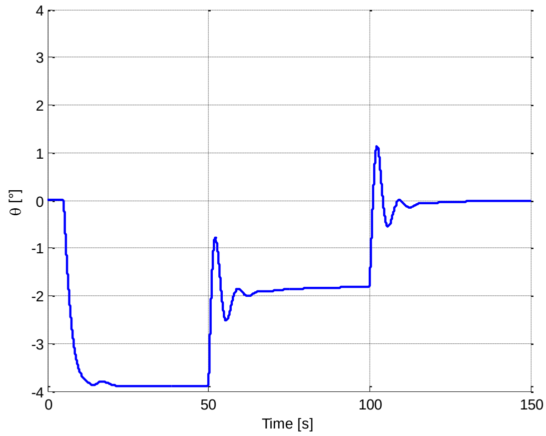

Fig. 9. Pitch angle

The simulation runs show that the vertical speed as well as the resulting deviation of the height during manoeuvring is negligible as depicted in Fig. 10.

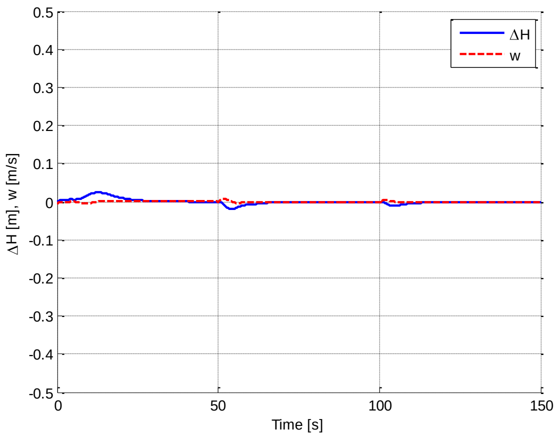

Fig. 10. Height deviation and vertical speed

5.2 Case 2: Low speed manoeuvring

Case 2 shows the manoeuvring in transition mode. The Tiltwing is controlled by the transition controller for cruise control in conjunction with the vertical flight controller for pitch and thrust control. Fig. 11 shows the commanded speed pattern and the resulting horizontal velocities. After 5 seconds in hover flight the aircraft is commanded to accelerate to 5 m/s horizontal speed and 35 seconds later to increase speed to 10 m/s. Another 35 seconds later the Tiltwing gets the command to decelerate to 7.5 m/s before it is finally initiated to accelerate to 15 m/s after 110 seconds.

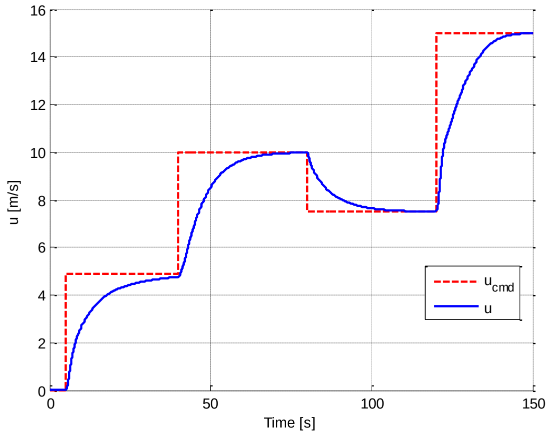

Fig. 11. Horizontal speed

The results show good performance and a reliable accuracy with only little deviations. Due to the transition controller commands in conjunction with adjusted controller parameters of the vertical flight controller for transition the accelerations are less aggressive than in vertical flight mode. This is intended to ensure smooth manoeuvres even in unstable flight conditions and can be seen in Fig. 12, which illustrates the tilt angle movement for different velocity commands.

Due to the propeller engine installation angle of 4° the tilt angle in hover flight is 86° in order to generate solely a vertical thrust component. The tilt mechanism initially starts the conversion process with full turning rate but quickly slows down in order to prevent rough manoeuvres as well as tilting too far. At 15 m/s the wing has still an incidence angle of about 11.6°. This corresponds to the pitch angle in horizontal flight at 15 m/s without tilted wings.

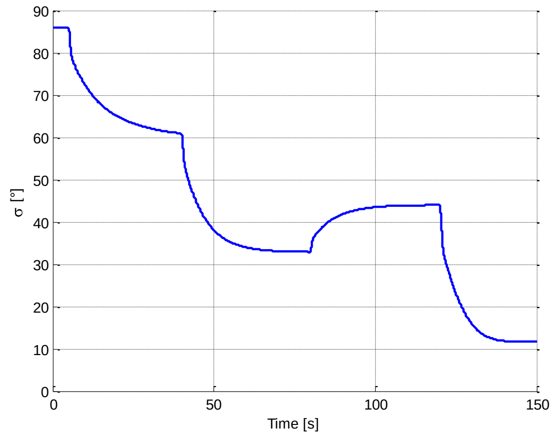

Fig. 12. Tilt angle

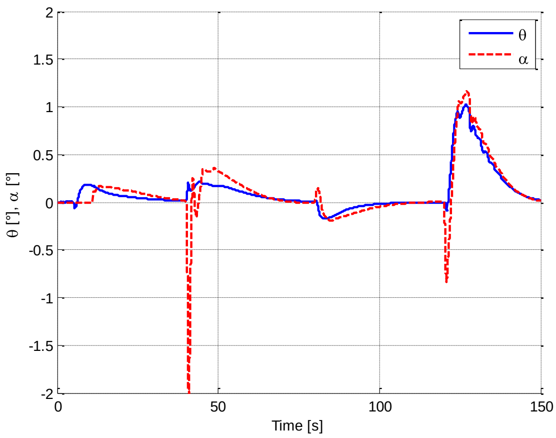

Fig. 13. Pitch angle and angle of attack

The pitch angle as well as the angle of attack is temporary affected by the initiated tilt process (see Fig. 13) but immediately equalized by the thrust which is illustrated in Fig. 14. The controller shows good performance. Despite small pitch angle overshoots with a maximum of 1° it ensures a stable transition procedure. At the maximum transition speed of 15 m/s the impeller has a high thrust value of about 14 N to keep attitude, which can be reduced using the elevators, which are already effective at this speed.

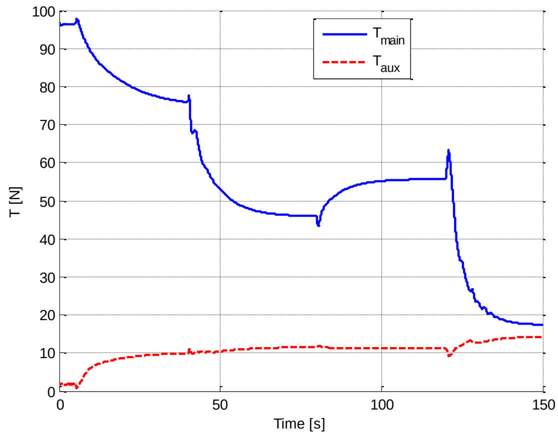

Fig. 14. Thrust distribution

Due to the quick response of the propulsion system with respect to vertical thrust as well as to the equalized attitude the height deviation is less than 0.25 m (see Fig. 15).

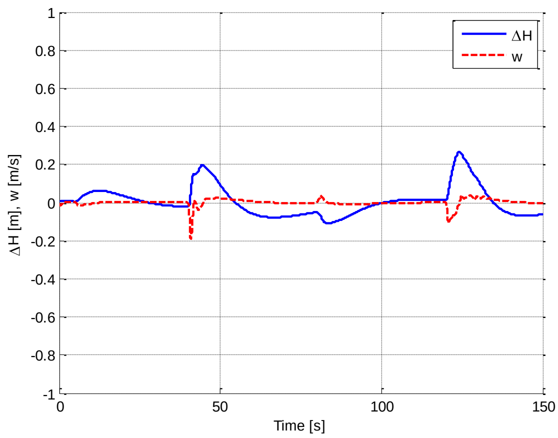

Fig. 15. Height deviation and vertical speed

5.3 Case 3: Complete Transition

The third test case shows a complete transition process including the handover from the vertical to the horizontal flight controller. Although the controllers are not yet completely optimized for this procedure at the current development stage the handover depicted in Fig. 16 proves already now the feasibility of the developed control approach. The acceleration to the maximum transition speed of 15 m/s is performed quickly by the transition controller and the vertical flight controller. After 75 seconds the handover is initiated and the horizontal flight controller takes over cruise control. There is no significant change in horizontal speed determinable. Fig. 17 shows the progress of tilting the wing. Due to the high velocity command the wing incidence angle is changed with maximum rate of 15 °/s in the first seconds. After 75 seconds the aircraft has a tilt angle of 11.6° and a pitch angle of 0°. In order to ensure a smooth handover to horizontal flight the tilt angle is decreased with a constant value.

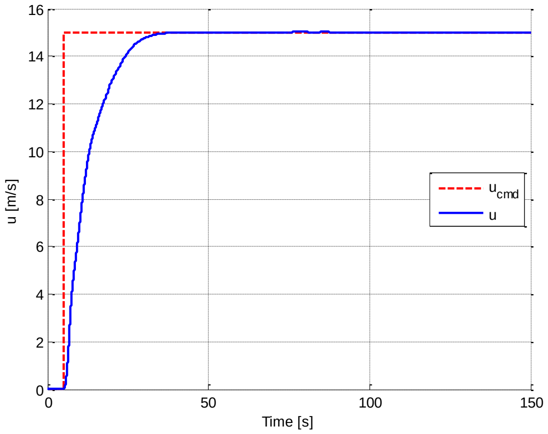

Fig. 16. Horizontal speed

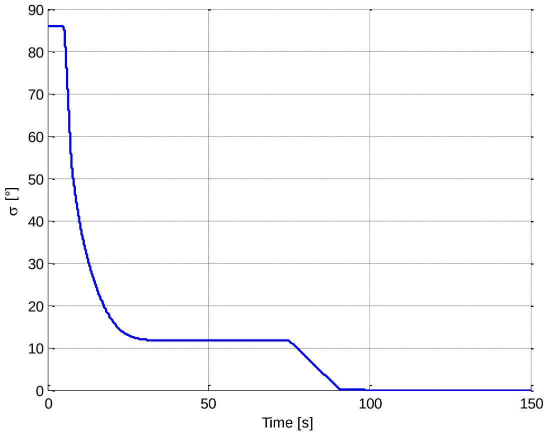

Fig. 17. Tilt angle

With initialization of the handover process the attitude controller of the vertical flight controller is deactivated and pitch control is assigned to the horizontal flight controller which uses the elevators. Due to the constantly decreasing tilt angle the pitch angle as shown in Fig. 18 rises from 0° to about 11° with a little overshoot at the end of the tilt process to equalize the height deviation. The angle of attack is aligned correspondingly. The impeller thrust is also decreased in accordance with the tilt process as can be seen in Fig. 19. During handover the main propulsion system shows some oscillation reaction but still a stable behaviour. It will be optimized within the ongoing design process.

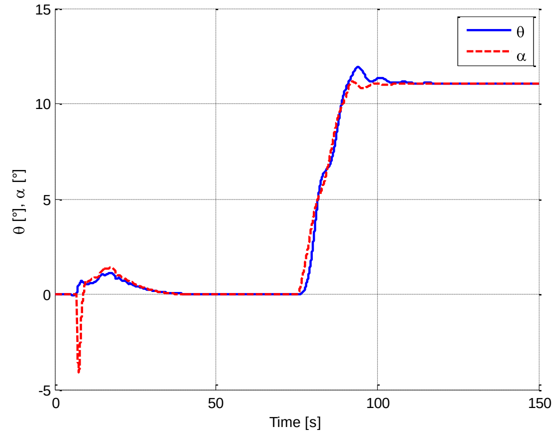

Fig. 18. Pitch angle and angle of attack

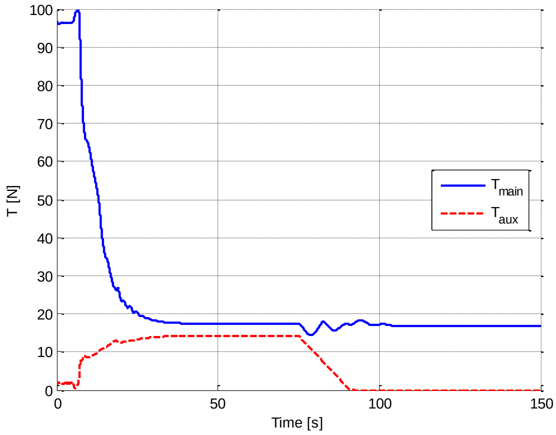

Fig. 19. Thrust distribution

Due to the reduced impeller thrust the lift forces decrease which results in a temporary height deviation of about 1.8 m as depicted in Fig. 20 until the lift is re-established by the height controller and a corresponding pitch command.

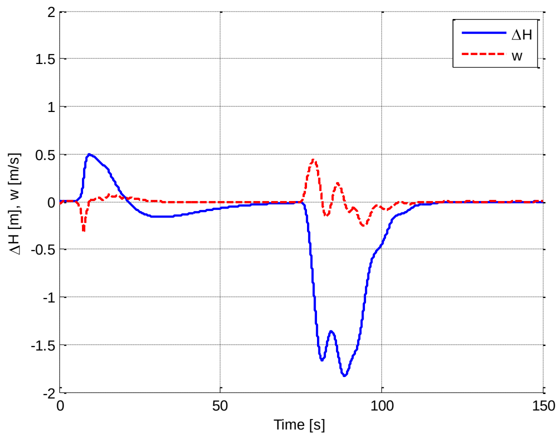

Fig. 20. Height deviation and vertical speed

6 Conclusion and Future Work

In this contribution the flight control system for the operation of the unmanned AVIGLE Tilt-wing with particular attention to low speed manoeuvring capabilities was introduced. Within the validation process several tests have been performed to demonstrate the applicability of the control concept for various speed commands as well as for complete transition manoeuvres from vertical to horizontal flight. The validation revealed good results and proved that the presented flight control system is basically capable to handle the different flight states as well as the handover between the corresponding controllers. The next development steps will be the implementation of enhanced motor models with measured response times as well as the integration of the slipstream flaps for pitching moment control. Later the controller parameters will be optimized and tested in a hardware-in-the loop test bed followed by flight test

Acknowledgment

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Nomenclature and Abbreviations

D	[N]	Drag
L	[N]	Lift
H	[m]	Altitude
M	[N]	Pitching Moment
T	[N]	Thrust
X	[N]	Forces x-direction
Z	[N]	Forces z-direction
iF	[°]	Installation angle motors
Λ_i	[°]	Control surface deflections
α	[°]	Angle of attack
β	[°]	Angle of sideslip
δ	[-]	Throttle command
ζ	[°]	Rudder deflection
η	[°]	Elevator deflection
θ	[°]	Pitch angle
κ	[°]	Slipstream flap deflection
ξ	[°]	Ailerons deflection
σ	[°]	Tilt angle

UAV	Unmanned Aerial Vehicle
c	Index command
f	Index body-fixed
main	Index main propulsion system
aux	Index impeller

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