CEAS Aeronaut J (2015) 6:17–30
DOI 10.1007/s13272-014-0126-z

ORIGINAL PAPER

Flight control law design criteria for the transition phase for a tiltwing aircraft using multi-objective parameter synthesis

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Received: 20 November 2013 / Revised: 18 July 2014 / Accepted: 18 July 2014 / Published online: 5 August 2014

Abstract Aircraft in tiltwing configuration combine the advantages of helicopters, such as hovering and vertical take-off and landing capabilities (VTOL), with the advantages of conventional fixed-wing aircraft, in particular long endurance and economic flight at higher velocities. During the transition phase between hovering and aerodynamic horizontal forward flight the aerodynamic forces and moments, the direct forces due to propulsion system and propulsion-induced aerodynamic forces and moments have to be properly balanced. Tilting the wing from vertical to horizontal position (and vice versa) poses a significant change in configuration. In combination with the given large velocity range this influences the control device efficiency significantly. At the same time, the tilting of the wing provides an additional control parameter. During flight control law design for an unmanned tiltwing aircraft with focus on the transition phase multi-objective parameter analysis and synthesis provides a powerful means to identify interdependencies and sensitivities. Key aspects of the longitudinal motion during the transition phase are investigated in this study using the multi-objective parameter synthesis tool MOPS, developed by the DLR Institute of System Dynamics and Control. Aim of this paper is to analyze quality criteria with respect to design and evaluation of control laws during transition phase. To achieve these parameters forward velocity and pitch attitude controller are optimized with respect to control and disturbance responses. At the same time the overall robustness against selected uncertain model parameters, such as actuator dynamics is considered explicitly. Different quality criteria characterizing these motions are developed and discussed in detail.

This paper is based on a presentation at the German Aerospace Congress, September 10–12, 2013, Stuttgart, German.

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Keywords Tiltwing · Flight control · MOPS · Parameter synthesis · Parameter optimization · Robust control · UAV

List of symbols

D	(N) Drag
H	(m) Height
K	Controller gains
L	(N) Lift
M	(Nm) Pitching moment
T	(N) Thrust
$T_{T\mathrm{aux}}$	(s) PT1 Time parameter
T_{t}	(s) Delay time
W	(N) Weight
X	(N) Force in x-direction
Z	(N) Force in z-direction
q	(rad/s) Pitch rate
r	(rad/s) Yaw rate
t	(s) Time
t_s	(s) Step size
u	(m/s) Horizontal forward velocity
v	(m/s) Horizontal lateral velocity
w	(m/s) Vertical forward velocity
x	X-axis along aircraft axis
y	Y-axis along aircraft axis
z	Z-axis along aircraft axis
α	(°) Angle of attack
Δ	Difference
ζ	(°) Rudder deflection
η	(°) Elevator deflection

ξ	(°) Aileron deflection
Φ	(°) Roll angle
θ	(°) Pitch angle
σ	(°) Tilt angle
$\Delta\sigma_{on}$	(°) σ backlash
ΔT_{lon}	Longitudinal thrust distribution
$_{main}$	Index main propulsion system
$_{aux}$	Index auxiliary propulsion system
$_0$	Index initial condition
$_a$	Index coordinate axis along free stream
$_c$	Index control
$_D$	Index derivative
$_g$	Index geodetic coordinate axis
$_I$	Index integral
$_P$	Index proportional
UAV	Unmanned aerial vehicle
VTOL	Vertical take-off and landing

1 Introduction

Within the AVIGLE project, funded by the European Union and the German federal state of North Rhine-Westphalia, the Institute of Flight System Dynamics at RWTH Aachen University develops an unmanned aerial vehicle (UAV) in tiltwing configuration. AVIGLE is a loose acronym consisting of the words avionic, agile, vehicle and flexible. The tiltwing UAV is designed to serve as an avionic digital service platform to support rescue forces in various tasks during catastrophic events. A tiltwing aircraft can rotate its wings including the propulsion system around the lateral aircraft axis, enabling it to take-off and land vertically as well as to fly aerodynamically like a conventional aircraft. Hence, it combines the advantages of helicopters, hovering and VTOL, with the advantages of conventional fixed-wing aircraft, in particular long endurance and economic flight at higher velocities.

The transition phase of a tiltwing includes all flight states between purely aerodynamic horizontal forward flight and hovering. Within the AVIGLE project one design goal of the tiltwing aircraft is to allow steady-trimmed flight over the entire range of velocity. In such a transition all occurring forces and moments have to be continually balanced. Tilting the wing represents a significant change in configuration. In combination with a large velocity range the control surface efficiencies are influenced. At the same time, tilting the wing is an additional control parameter. Furthermore, wing stall occurs at low velocities and high tilt angles leading to buffeting and vibrations [1]. All above poses a challenge for developing efficient flight control laws valid within the complete velocity range. Quality criteria are a suitable mean to evaluate a controller and are valuable during design. Applying multi-objective optimization requires well-formulated quality criteria.

Research concerning small scale tiltwing and tiltrotor configurations and their control strategies has been done. A controller is investigated by Dickeson et al. [2] for a 2 m span width tiltwing. The aircraft dynamics is linearized for different tilt angles and the longitudinal and lateral motion is analyzed to find suitable transition trajectories. For these trajectories a H_∞ transition controller is designed. In contrast to the multi-objective design approach of this contribution, Dickeson solely aims at a time optimal transition. Furthermore, within the controller design robustness against model uncertainties is not accounted for; the controller is only checked for robustness against transition duration. Dickeson evaluates his controller qualitatively but not with quantitative criteria. Oner et al. [3, 4] developed a quadrotor aerial vehicle with a tiltwing mechanism. Vertical control is achieved by a linear quadratic regulator and a sliding mode controller. Transition control is not yet presented and the influence of the propeller on the aerodynamic coefficients is neglected. Ta et al. [5] describe transition control for a tiltrotor using a cascaded PID structure in combination with a neural network. During transition no altitude control exists. Design and performance evaluation of flight control laws for a tiltwing in transition phase with the help of quality criteria has not been done yet.

Multi-objective optimization can be used as a parameter tuning technique in control law design. The software environment developed by the Institute of System Dynamics and Control from the Robotics and Mechatronics Center of the German Aerospace Centre (DLR) called MOPS (Multi-Objective Parameter Synthesis) [6] supports a straight forward definition of analysis and design tasks as a multi-objective optimization and has been successfully used for analyzing and optimizing flight control laws [7]. For the special application of tiltwing analysis and control design MOPS helps to identify interdependencies and sensitivities occurring within the transition phase. Well-formulated criteria are essential for flight control law design using MOPS.

Joos [6] describes quality function deployment and its use in multi-objective design assessment and flight control synthesis tuning. He lists several design requirements inducing possible quality criteria. For unmanned flight these include mission requirements, stability and robustness, safety, and control activity. The resulting criteria are differentiated in performance specifications, such as rise time, settling time, overshoot and cross coupling, disturbance attenuation and control requirements. Criteria derived from the requirements of the GARTEUR Robust

Flight Control Design Challenge [8, 9] for the longitudinal control law design are described. State variables in this case are airspeed and altitude and control variables such as throttle and tailplane deflection. For tiltwing aircrafts in transition phase a third control variable, the tilt angle, is added to the system, which provides an additional mean for controlling the pitch angle separately. Besides adding such tiltwing-specific criteria the large velocity range has to be considered. The method proposed in [6] is also used in [10] for the design of autoland controller functions. Different levels of the controller are included successively in the optimization. Criteria include the above mentioned performance criteria as well as criteria resulting from linear analysis. This concept can be adapted to the tiltwing analysis to successively analyze different forward velocities.

Similar quality criteria are also used by [11, 12] for lateral control system design. In [12, 13] stability criteria from linear analysis are included as well. Tabak [13] extends the control system design by analyzing Pareto-optimal (or noninferior) solutions providing a high flexibility for the designer since multiple design options to choose from exist. Pareto-optimal solutions are found by adjusting the demand values of conflicting criteria. This concept is used to analyze the optimization results and used criteria further.

In this contribution MOPS is applied to systematically develop a robust controller for the tiltwing aircraft. Quality criteria are used for the control law design with respect to uncertainties and differing flight states. A cascaded PID controller structure for the tiltwing analyzed was developed in previous research and used for this study. Focus is posed on the longitudinal motion and especially the controlling of horizontal and vertical velocities u and w and the pitch angle θ. Control and disturbance behavior is evaluated and different performance criteria are discussed. Aircraft parameters influencing the aircraft behavior during the transition phase are analyzed also regarding their effect on the specific criteria. The criteria are also analyzed with regard to interactions and scaling. In future studies well-formulated quality criteria for tiltwing aircraft can facilitate the flight control law design for tiltwing aircrafts in general. For the AVIGLE tiltwing sufficient information regarding its design, aerodynamic coefficients obtained through wind tunnel measurements and a basic controller within a 6° of freedom simulation exists [14, 15] and are used within this study.

In the following sections, first the flight mechanical and aerodynamical characteristics—different from conventional aircraft—are described together with the configuration and controller design of the example tiltwing. Then criteria describing the longitudinal motion in u, w and θ are formulated and scaled according to demand values at $u_0 = 4$ m/s. Based on these criteria a controller parameter synthesis using the multi-objective parameter synthesis tool MOPS [6] applying its Pattern Search algorithm is performed. Two different initial velocities, $u_0 = 4$ m/s and $u_0 = 8$ m/s are optimized while applying a disturbance and a control response scenario. Within the parameter synthesis the influence of the selected criteria is analyzed and discussed.

Table 1 Tiltwing specification

MTOW	10 kg
Wing span	2 m
Propeller diameter	0.7 m
Velocity range	0–40 m/s
Design speed (horiz.)	15 m/s
Max. thrust T_{main}	130 N
Max. auxiliary thrust T_{aux}	40 N

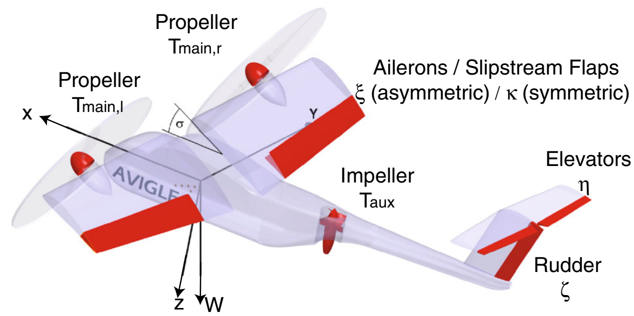

Fig. 1 Control devices of the AVIGLE tiltwing aircraft [15]

2 Tiltwing aircraft

The tiltwing aircraft configuration given in Table 1 was developed within the AVIGLE project. Design requirements were a high endurance, VTOL capability, stationary flight velocities from hovering to fast forward flight, modular payloads of up to 1.5 kg and compact outer dimensions. Further details on the design process and mission requirements can be found in [14, 16].

The AVIGLE tiltwing is designed with a static longitudinal stability margin of 5 % [14] in horizontal flight. In hovering (vertical) flight the tiltwing is basically unstable with respect to its longitudinal axes. During transition from vertical to horizontal configuration through tilting the wing the center of gravity is moved forward about 4 cm increasing longitudinal stability. Additionally, the tailplane only contributes to the longitudinal stability, if the airflow allows generation of significant aerodynamic forces which is only given at higher forward velocities.

Figure 1 illustrates the control devices of the AVIGLE tiltwing. In horizontal flight the control devices are those of a conventional aircraft: Ailerons are used for roll, elevators for pitch and the rudder for yaw control. Acceleration is achieved through modification of thrust by adjusting rotational speed and rotor pitch of the main propulsion system T_{main}.

In vertical flight the elevators and rudder remain ineffective due to very low forward velocity. Pitch control is given through an auxiliary impeller in the rear. The impeller provides thrust T_{aux} only in negative body-fixed z-direction. Control variable for the pitching moment is the longitudinal thrust distribution ΔT_{lon}. It describes the portion that the main propulsion system has on the overall thrust.

$$\Delta T_{\mathrm{lon}} = \frac{T_{\mathrm{main}}}{T},$$

with $T = T_{\mathrm{main}} + T_{\mathrm{aux}}$. The maximum value is 1 if the auxiliary thrust is 0 N.

Yaw control is achieved through asymmetric deflection of the slipstream flaps. For roll control the thrust distribution between the two propellers of the main propulsion system ΔT_{main} is adjusted.

During transition an adjustment between roll and yaw control, due to the change of the main efficiency of the ailerons and differential thrust has to be considered. For pitch control the elevator gains more influence with increasing forward velocity. Through σ , T_{main} and T_{aux} the forward and vertical velocity and pitch can be controlled individually.

2.1 Transition phase

The transition phase of a tiltwing is defined as the transfer from hover to aerodynamic horizontal forward flight and vice versa. This usually includes all flight states with forward velocities above zero and below purely aerodynamic flight. Within the transition the wing is rotated between horizontal and vertical position.

Different concepts for controlling the transition phase exist. One possibility is to consider the transition phase as a continuous process and to focus on controllability for one specific transition scheme through a pilot. Another concept is to optimize the transition phase regarding time or energy aspects. A third is to allow steady-trimmed flight over the complete velocity range. This allows very variable missions. Within the AVIGLE project this versatility was aimed for and the missions regarded require steady-trimmed flight at various velocities within the transition velocity range. The transition is controlled by tilting the wing and continuously adapting the thrust to maintain a given forward velocity and height.

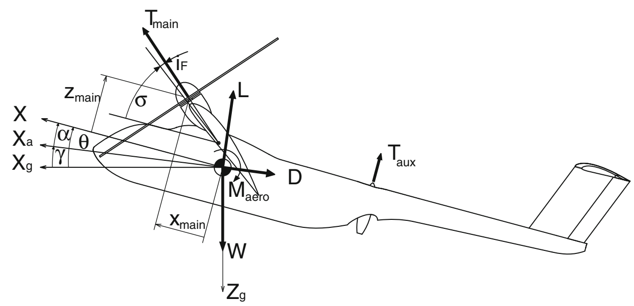

Fig. 2 Forces and moments in longitudinal motion [15]

During vertical flight or hovering the tiltwing aircraft behaves like a multi-rotor system, e.g. a quadrocopter. In the transition phase the characteristics of a conventional aircraft become more and more relevant. Still, within analysis, controller design, and optimization some of the typical assumptions made for conventional aircraft, e.g. small angles of attack and small wind speeds compared to flight velocities are not applicable. Additionally, while tilting the wing is used as a control device, it also significantly influences the aircraft configuration and thus the efficiency and impact of other control parameters. Therefore, a nonlinear model has to be used to cover the complete velocity range.

2.2 Flight mechanics during transition phase

During a steady transition—even without considering disturbances—balancing the longitudinal forces and moments is a significant challenge. For all forward velocities within transition the resulting forces X and Z along the body-fixed x- and z-axis and the sum of the pitching moments M has to be zero.

Figure 2 gives an overview of the acting forces and relevant angles during transition. x_a and x_g represent the x-axis of the aerodynamic and geodetic coordinate system. The thrust of the propulsion system that is provided by the main propellers T_{main} and the auxiliary impeller T_{aux}, the aerodynamic forces lift L and drag D, and the weight W contribute to the sum of forces and to the pitching moment:

$$\sum X = T_{main} \cdot \cos(\sigma + i_F) + L \cdot \sin(\alpha) - D \cdot \cos(\alpha) - m \cdot g \cdot \sin(\theta), \tag{1}$$

$$\sum Z = -T_{\mathrm{main}} \cdot \sin(\sigma + i_F) - T_{\mathrm{aux}} - L \cdot \cos(\alpha) - D \cdot \sin(\alpha) + m \cdot g \cdot \cos(\theta), \tag{2}$$

$$\sum M = M_{\mathrm{aero}} - T_{\mathrm{aux}} \cdot x_{\mathrm{aux}} + T_{\mathrm{main}} \cdot (\sin(\sigma + i_F) \cdot x_{\mathrm{main}} - \cos(\sigma + i_F) \cdot z_{\mathrm{main}}). \tag{3}$$

Relevant angles are the angle of attack α, tilt angle σ, pitch angle θ, and the incidence angle of the propulsion system i_F. During steady transition from hovering to aerodynamic horizontal flight, with small changes in forward velocity, the thrust and tilt angle are continuously reduced, while the lift grows with increasing forward velocity. A change in σ rotates the thrust vector and directly influences the angle of attack at the wing and, therefore, the size and orientation of lift and drag of the wing and thus of the overall lift and drag. The aerodynamic forces at the wing and the thrust do not act in the center of gravity and thus result in additional pitching moments. The size of the pitching moments is also influenced by σ due to the changing of the effective lever arms.

2.3 Aerodynamics during transition phase

Due to the low forward velocities within the transition phase and the large overlap between propeller and wing the flow field around the wing is significantly influenced by the propeller slipstream. The propeller slipstream reduces the local angle of attack at the wing compared to the overall angle of attack of the aircraft. Additionally at low forward velocities the flow velocity and thus the dynamic pressure at the wing are increased by the propeller slipstream.

To describe the aerodynamic forces and moments dimensionless coefficients and derivatives are used. For conventional aircrafts these coefficients mainly depend on the angle of attack α, sideslip angle β, the aircraft design and the control device deflection δ. In case of the tiltwing the tilt angle σ is an additional parameter which significantly changes the aerodynamic coefficients. Furthermore, these coefficients also depend on the thrust. These dependencies are modeled by regarding aerodynamic coefficients C_{aero} and propeller induced coefficients C_i

$$C_{\text{aero}} = f(\alpha, \beta, \sigma, \delta), \tag{4}$$

$$C_i = f(\alpha, \beta, \sigma, \delta, T), \tag{5}$$

and hence considered explicitly in the applied simulation for analysis and control system design. The modeling and further details on the flight mechanical dependencies in particular during transition is further detailed in [17].

2.4 Controller structure of tiltwing aircraft

The basic control structure of the AVIGLE tiltwing system is given in more detail in [15]. An overview on the controller structure is given in Fig. 3. It consists of three parts: (1) the vertical flight controller for forward flight velocities $u < 2$ m/s, (2) the horizontal flight controller for $u > 15$ m/s, and (3) the transition controller for 2 m/s $< u >$ 15 m/s. The transition controller manages the tilting process and depending on commanded forward velocity and tilt angle different parts of the horizontal and vertical controller are activated. Both the horizontal and vertical controllers are cascaded controllers with mainly P, PI and PID sub-controllers.

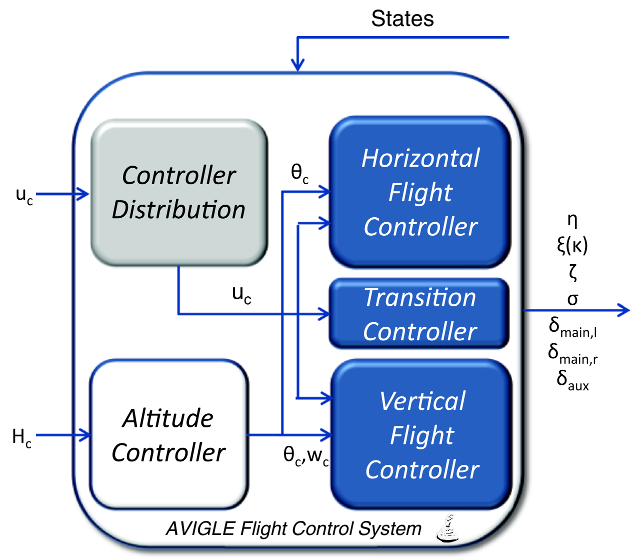

Fig. 3 Controller structure [15]

During vertical flight the aircraft's attitude and movement is controlled by adjusting thrust while considering the aerodynamic effects at the slipstream flaps. The three velocity components u, v, and w, and the yaw rate r are controlled. The vertical speed w is controlled by a collective throttle command T in body-fixed z-direction which is distributed between the main and auxiliary propulsion system. The horizontal velocities u and v are controlled via changes in roll and pitch angle, which in turn are controlled through thrust distribution between the two main propellers for roll control and between the main and auxiliary propulsion system ΔT_{lon} for pitch control. Out of these three control commands, collective throttle, lateral and longitudinal thrust distribution, the thrust settings for the two main propellers and the impeller are calculated. The yaw rate is controlled by the ailerons in the propeller slipstream.

In horizontal flight mainly the horizontal speed u, pitch angle θ and roll angle Φ are controlled. Height and azimuth are controlled via pitch or roll angle, respectively. Control devices used are collective thrust, elevator and ailerons. The elevators are also used for turn compensation. The rudder is used for yaw control and turn coordination.

During the transition phase the transition controller is activated and the horizontal speed is controlled by adjusting the tilt angle. This process is supported by the vertical controller which remains controlling altitude and pitch. The longitudinal part of the transition controller is shown in Fig. 4. Since u is controlled through σ and not θ, it is thus possible to independently command u, w and θ. In the

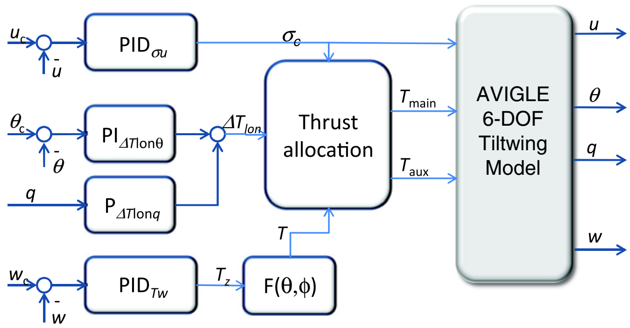

Fig. 4 Longitudinal part of transition controller

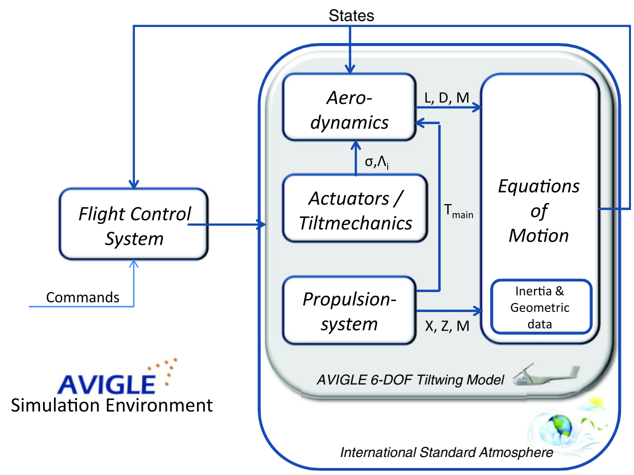

Fig. 5 Simulation environment [15]

lateral motion roll and yaw rate control are crossfaded depending on the tilt angle.

In the longitudinal motion of the transition, even though u, w and θ are controlled separately significant interactions exist since all three control variables influence the forces in x- and z-direction as well as the pitching moment. The magnitude of the influence depends on the flight state and σ. In lateral motion the interactions are even more obvious, since at tilted wing positions no control device solely to be used for yaw or roll control exists. Furthermore, a coupling between longitudinal and lateral motion exists. For example, an increase in collective thrust by the longitudinal controller changes the propeller slipstream and thus the efficiency of the slipstream flaps controlling the lateral motion.

The parameters synthesized in this contribution are the controller gains of the longitudinal part of the transition controller. u and w are controlled by σ and T through a PID controller, with the controller gains $K_{\mathrm{P},u}$, $K_{\mathrm{I},u}$ and $K_{\mathrm{D},u}$ and $K_{\mathrm{P},w}$, $K_{\mathrm{I},w}$ and $K_{\mathrm{D},w}$. θ is controlled by the thrust distribution between the main and auxiliary propulsion system, using a PI controller. The gains are $K_{\mathrm{P},\theta}$, and $K_{\mathrm{I},\theta}$, respectively. Additionally the pitch rate q is damped by $K_{\mathrm{P},q}$. The initial values of the controller parameters were calculated manually according to tuning rules by Ziegler and Nichols and adjusted slightly to the given configuration. The controller gains and their initial values are given in Table 4.

3 Analysis and synthesis setup

This study focusses on the design and analysis of key parts of the longitudinal flight controller during the transition phase of flight, requiring stable and constant pitch angle and low vertical speed at different forward velocities. To synthesize the corresponding controller gains different operating points within the transition, the control and disturbance behavior as well as robustness with respect to uncertain model parameters are analyzed. Furthermore suitable design criteria are formulated and interdependencies of the criteria within the transition are investigated. The state variables analyzed are u, w and θ within the controller structure as given in Fig. 4. In the following subsections the general approach, relevant controller gains (tuners), the investigated scenarios, uncertainties and the design criteria are described.

3.1 General approach

Although the presented approach is meant to be valid for any velocity during transition, in a first step only two velocities are analyzed in detail. From this analysis knowledge about the validity of criteria and sensitivity of uncertainties for the design of the controller gains can be gained. As forward velocities 4 and 8 m/s were selected, due to their equal spacing within the transition corridor. At these two velocities a parameter synthesis is performed taking into account the control response behavior, disturbance behavior as well as robustness by varying uncertain model parameters. During the parameter synthesis nonlinear simulations in the time domain are performed. Out of these simulations performance criteria are calculated. These criteria are evaluated by varying the parameters within the MOPS environment. Within the first investigations, a Pattern Search algorithm was selected as optimization method to tune the controller gains. In a second step the resulting controller gains are applied within the transitions airspeed envelope.

3.2 Investigated scenarios

For the simulations a nonlinear six degree of freedom simulation of the tiltwing is used. The simulation was developed in Matlab/Simulink and includes the flight dynamics, an atmosphere model and the flight control system [3]. The simulation environment is depicted in Fig. 5. Within the atmosphere model wind and gusts can be applied. Wind and gust parameters can be time-dependent or dependent on the current aircraft position.

Two different scenarios, one for the control response behavior and the other for the disturbance response of the system, are analyzed. For analysis of the control response a step command of $\Delta u_c = 1$ m/s is performed. Pitch angle θ and vertical velocity w are commanded to be kept constant. The time responses of u, θ and w are analyzed.

For the disturbance response a 1-cos gust in u-direction is simulated. The gust is effective over 3 s with a maximum amplitude of 2 m/s. u, w and θ are commanded constant during the gust. The magnitude of the 1-cos gust is kept constant for all forward velocities. This reflects the given mission scenarios where usually the atmospheric conditions do not vary with the flight state, but also implies that the relative influence of the gust amplitude of 2 m/s is higher at smaller forward velocities compared to larger forward velocities. In both scenarios the dynamic behavior settles within 20 s after the control command is given or the disturbance is applied.

3.3 Modeled uncertainties

For the robustness analysis uncertain model parameters are included in the simulation. Uncertainties in the aircraft simulation model result from uncertainties in the measured aerodynamic coefficients and other, such as mass, center of gravity location, correct modeling of the tilting process, and uncertainties in the modeled dynamics of the actuators and propulsion system. Since the aerodynamic effects were extensively measured and investigated in wind tunnel tests their uncertainties are small compared to the time dynamics of the propulsion system and the tilting mechanism. Therefore, in this study only these uncertainties are regarded. Specifically, the time delay and PT1 behavior of the dynamics of the auxiliary propulsion system and the response characteristics of the tilting mechanism are analyzed.

The dynamic behavior of the auxiliary propulsion system T_{aux} was identified and modeled as a first order system with additional time delay T_t with the following transfer function

$$G(s) = \frac{1}{1 + T_{Taux} s} \cdot e^{-sT_t} \qquad (6)$$

The time constant T_{Taux} and time delay T_t are varied according to their variance that was identified by wind tunnel measurements.

The dynamic behavior of the tilting mechanism is also modeled by a first order system with time delay and, additionally, the maximum rate of change of σ is limited. To model backlash in the tilting mechanism, a switch on $\Delta\sigma_{on}$ point for σ is included. $\Delta\sigma_{on}$ specifies the control deviation of σ necessary to activate the tilting mechanism. The backlash in σ is assumed to be smaller than 2°. The nominal values and range of the uncertain parameters investigated are summarized in Table 2.

Table 2 Uncertain model parameters

	Nominal	Minimum	Maximum
T_{Taux} (s)	0.0632	0	0.10
T_t (s)	0.0362	0	0.05
$\lvert\Delta\sigma_{on}\rvert$ (°)	0	0	2

3.4 Design criteria for transition phase

To analyze and optimize the flight control laws, design relevant criteria are formulated. These criteria are minimized by tuning the controller parameters using optimization. Using the above mentioned scenarios two nonlinear simulations are performed from which criteria, best characterizing the response behavior, are calculated. MOPS requires criteria to be scaled such, that a value <1 is satisfactory. To achieve this, all calculated criteria are divided by their demand value. Criteria are set to be minimized or are set as inequality constraints which means that any value below one is not further improving the constraint. All criteria considered relevant for the transition maneuvering, their computation, their demand value and criteria type are detailed in Table 3.

The criteria used can be grouped into performance criteria, control criteria, coupling and mission criteria. To some extent criteria can belong to more than one group. Performance criteria such as rise time, overshoot and settling time are used for quantifying the control response [6, 10, 13]. Their demand values are derived experimentally from previous simulations combined with mission requirements. Additionally, the settling times of θ and w are included to characterize the coupling effects of a step command in u. For the disturbance scenario the settling times are included and, as a consequence, can also be considered as performance criteria.

Coupling and mission criteria maximum deviation from commanded flight states are included for all three state variables for the control and disturbance response. Similar formulations can be found in [6] for cross coupling. In [6] a scaling of the demand value by the size of the step command is done. In our case absolute values are used due to mission requirements within the AVIGLE project [18]. These missions include taking pictures for three-dimensional virtual modeling and spanning an ad-hoc mobile network. For both missions it is desirable to reduce the deviation from the commanded flight states given by $u_{c'}$, w_c and θ_c. Absolute values have the disadvantage, that the

Table 3 Design criteria and scaling for multi-objective optimization

Criterion (name)	Computation	Demand value	Type[a]
Scenario 1 control response, step in u			
Rise time* u (u_RT)	see Remarks	3.5 s	m
Overshoot u (u_OS)	$\max\{\frac{u(t)}{u_{\mathrm{end}}}\} - 1$	0.02	m
Settling time u (u_ST)	$\min\{t\}\,\lvert\forall\tau > t \wedge \lvert\frac{u(\tau)-u_{\mathrm{end}}}{u_{\mathrm{end}}}\rvert \leq 0.02$	5 s	m
σ control activity (σ_CA)	$\int \lvert\dot{\sigma}\rvert$ dt	6°	c
θ max. deviation (θ_MD)	$\max\{\lvert\theta\rvert\}$	0.2°	m
Settling time θ (θ_ST)	$\min\{t\}\,\lvert\forall\tau > t \wedge \lvert\theta(\tau)\rvert \leq 0.1^\circ$	5 s	m
ΔT_{lon} control activity (T_CA)	$\int \lvert \Delta\dot{T}_{\mathrm{lon}} \rvert$ dt	0.03	c
θ deviation (sumΔθ)	$\int \lvert\theta\rvert$ dt	0.8° s	m
u deviation (sumΔu)	$\int \lvert u - u_{\mathrm{end}}\rvert$ dt	10 m	m
w max. deviation (w_MD)	$\max\{\lvert w\rvert\}$	0.15 m/s	m
Settling time w (w_ST)	$\min\{t\}\,\lvert\forall\tau > t \wedge \lvert w(\tau)\rvert \leq 0.025$ m/s	5 s	m
w deviation (sumΔw)	$\int \lvert w\rvert$ dt	0.6 m	m
Scenario 2 disturbance response, 2 m/s gust			
u max. deviation (u_MD)	$\max\{\lvert u - u_0\rvert\}$	0.75 m/s	m
Settling time u (u_ST)	$\min\{t\}\,\lvert\forall\tau > t \wedge \lvert\frac{u(\tau)-u_0}{u_0}\rvert \leq 0.025$	5 s	m
σ control activity (σ_CA)	$\int \lvert\dot{\sigma}\rvert$ dt	10°	c
θ max. deviation (θ_MD)	$\max\{\lvert\theta\rvert\}$	1°	m
Settling time θ (θ_ST)	$\min\{t\}\,\lvert\forall\tau > t \wedge \lvert\theta(\tau)\rvert \leq 0.1^\circ$	5 s	m
ΔT_{lon} control activity (T_CA)	$\int \lvert \Delta\dot{T}_{\mathrm{lon}} \rvert$ dt	0.6	c
θ deviation (sumΔθ)	$\int \lvert\theta\rvert$ dt	2° s	m
u deviation (sumΔu)	$\int \lvert u - u_0\rvert$ dt	2 m	m
w max. deviation (w_MD)	$\max\{\lvert w\rvert\}$	0.2 m/s	m
Settling time w (w_ST)	$\min\{t\}\,\lvert\forall\tau > t \wedge \lvert w(\tau)\rvert \leq 0.025$ m/s	5 s	m
w deviation (sumΔw)	$\int \lvert w\rvert$ dt	0.6 m	m

Simulation step time $t_s = 0.01$ s

Rise time Δt between 10 and 90 % of command

c inequality constraint, m minimize

[a] Remarks

demand values have to be adapted to larger step commands or gusts with different amplitudes and durations. Furthermore, the results of the synthesis show that the forward velocity also influences the criteria values.

Other mission and coupling specific criteria included are the overall deviation of u, w and θ. For this the absolute values of the overall u, w and θ deviation are integrated over simulation time. In [10] a similar criterion using least squares is applied and scaled by the time over which was integrated. Scaling with respect to time is not included in the criteria used, since the simulation time is not changed. Demand values are set for the specific mission scenarios. When investigating different step sizes or disturbances the criteria values change significantly. This becomes obvious in the different demand values for step and disturbance response. Taking into account such scalings and influences from different mission velocities is planned for future studies.

For the control activity the gradients of tilt angle σ and longitudinal thrust distribution ΔT_{lon} are included as criteria. Beside noise and vibration aspects the control activity of the auxiliary propulsion system T_{aux}, characterized through ΔT_{lon} is of interest with respect to energy efficiency. The control activity of σ is desired to be smooth to minimize coupling effects since the influence of σ on the aerodynamic forces at the wing, the thrust interactions and control efficiency of the slipstream flaps and pitching moment is highly nonlinear. Different ways to account for control activity can be found [6, 10]. In these publications control activity is calculated as the integral over the squared control input, the integral over the squared derivate of the control input and the maximum derivate after a time $t > t_x$. In this contribution the absolute values of the gradients are included, which provides similar results as the square of the gradient. Analog to all other criteria the demand values are set for the specific scenarios analyzed.

With the described control and disturbance scenarios evaluation runs at $u_0 = 4$ m/s were performed to check the limits of the formulated criteria and to specify suitable demand values. Especially the control activities and θ and u deviations depend on the initial flight state.

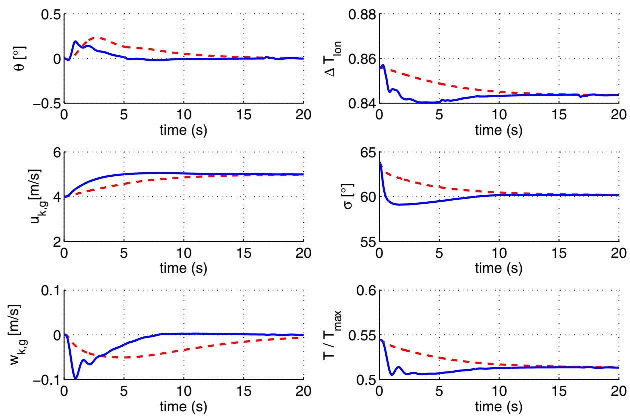

Fig. 6 Step response for initial (*red-dashed*) and first synthesis (*blue*) of tuning parameters

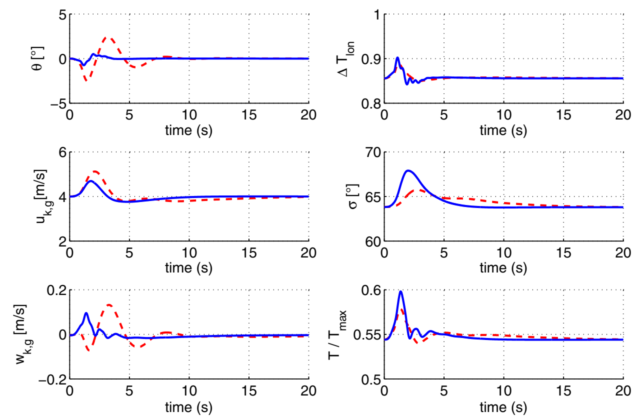

Fig. 7 Disturbance response for initial (*red-dashed*) and first synthesis (*blue*) of tuning parameters

4 Parameter synthesis

In this section the results of the parameter synthesis, dependencies between the criteria and parameter values and the robustness analysis are discussed in detail.

4.1 Synthesis considering one forward velocity

For the initial velocities of $u_0 = 4$ m/s and $u_0 = 8$ m/s a parameter synthesis regarding the nominal values of the uncertain parameters using a pattern search is performed. In Figs. 6 and 7 the control and disturbance response of θ, u, w and the control progress of ΔT_{lon}, σ and T is depicted for the initial values and the result of the first tuning synthesis for $u_0 = 4$ m/s. The respective tuning parameters are given in Table 4. As can be seen from the time responses the initial controller parameters ensure stable behavior at this flight velocity. In the control response nominal case a θ-deviation smaller than 0.2° can be achieved whereas the θ-deviation for the gust after optimization is below 1°. This is also reflected in the differences in the demand values of the criteria of the two scenarios (compare Table 3).

The first parameter synthesis improved the response behavior regarding the specified criteria. The effect of the two sets of tuning parameters can be compared in Fig. 8 using so-called parallel co-ordinates [7]. In this visualization all scaled criterion values are plotted on an individual axis and connected through a line. Different colored lines represent different sets of tuning parameters. All scenarios and cases are depicted individually. The first tuning was able to push all scaled criteria except the settling time of u in the disturbance response below the value of one. Looking at the time responses the maximum deviation of u and θ, overshoot of θ and rise time of u and θ were reduced significantly. This went to the cost of the control activities and maximum deviation of w as can be seen in Figs. 6 and 7.

All these effects could also be seen for $u_0 = 8$ m/s. The corresponding step and disturbance responses are not

Table 4 Tuning parameters for the parameter synthesis at $u_0 = 4$ m/s and $u_0 = 8$ m/s

Tuning parameter	Initial value	$u_0 = 4$ m/s	$u_0 = 8$ m/s
$K_{P,\theta}$	0.3	2.593	3.226
$K_{I,\theta}$	0.5	2.136	4.075
$K_{P,q}$	−0.25	−0.317	−0.487
$K_{P,u}$	−1.08	−4.610	−4.700
$K_{I,u}$	−0.671	−2.503	−2.666
$K_{D,u}$	0	−1.109	−3.284
$K_{P,w}$	−0.2	−0.341	−0.645
$K_{I,w}$	−0.05	−0.123	−0.023
$K_{D,w}$	−0.025	0.014	−0.080

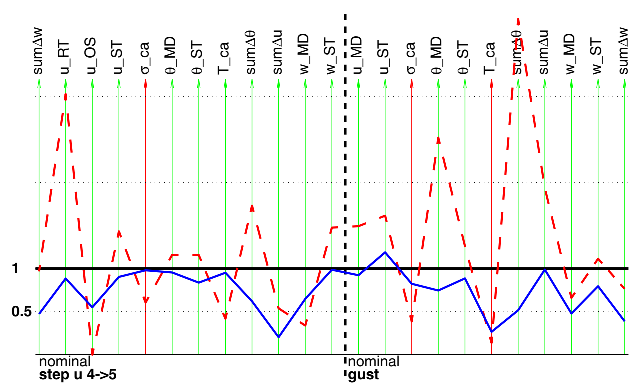

Fig. 8 Normalized criteria for initial (*red-dashed*) and first synthesis (*blue*) of tuning parameters for $u_0 = 4$ m/s

Table 5 Criteria values at $u_0 = 4$ m/s and $u_0 = 8$ m/s

	$u_0 = 4$ m/s	$u_0 = 8$ m/s
Rise time u (u_RT)		
Initial	3.0	3.5
Synthesized	0.9	1.5
θ deviation (sum$\Delta\theta$)		
Initial	3.8	4.8
Synthesized	0.5	0.8

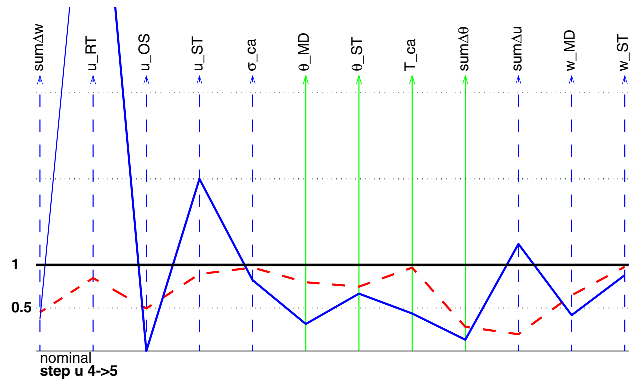

Fig. 9 Synthesis using only θ criteria of θ controller gains (*red-dashed*) and all controller gains (*blue*)

depicted here since they are very similar to the ones at $u_0 = 4$ m/s, compare Figs. 6, 7, 8. At $u_0 = 8$ m/s the simulations resulted in higher criteria values for the initial controller gains as well as for the synthesized gains. This is detailed further in the following section. The synthesized controller gains are also given in Table 4.

4.2 Criteria analysis

The design criteria demand values given in Table 3 were defined based on simulations with the initial controller gains at $u_0 = 4$ m/s. The first synthesis at $u_0 = 8$ m/s showed that the calculated criteria values were significantly higher than at $u_0 = 4$ m/s. As example the rise time u criterion and the θ deviation of the disturbance response are given in Table 5 that were computed in simulations with initial and synthesized controller parameters for both velocities.

Since the same demand values for the criteria at $u_0 = 4$ m/s and $u_0 = 8$ m/s are used, this leads to higher scaled criteria values (>1) at $u_0 = 8$ m/s. The step and disturbance response in the time domain still are acceptable, though. In future evaluations, the demand values of the criteria should be adapted to the flight velocity. This can be achieved through using relative, flight velocity dependent values.

To analyze the influence of the chosen criteria on the optimization results parameter syntheses at $u_0 = 4$ m/s were carried out activating different sets of criteria and tuner. The criteria were grouped according to the three state variables u, w and θ. Two optimization runs with each of these three sets activated, one with only the corresponding controller gains set as variable parameters and the other with all controller gains were carried out. Activating only the corresponding criteria and controller gains of one state variable led to slightly worse results than the previously described synthesis using all criteria and controller gains. Still the results were good enough to consider an individual analysis of the three sub-controllers (u, w and θ) in future analyses. controller gains ($K_{PID,\theta}$, $K_{PID,u}$, $K_{PID,w}$) within the optimization but only activating one set of criteria (e.g. u criteria) improved the specific criteria compared to the previous synthesis, but led to significant degradation in other criteria. Especially θ and w can be improved by tuning the controller gains $K_{P,u}$, $K_{I,u}$ and $K_{D,u}$. In both cases this led to a degradation of the u criteria. This effect can be seen in Fig. 9 which shows the optimization results for the two θ analyses, where the vertical solid (green) lines are the activated θ criteria and the vertical dashed (blue) lines are the other criteria.

A sensitivity analysis between the controller gains and criteria also showed that the θ criteria are mainly influenced by the respective θ controller gains but also by $K_{P,u}$, $K_{I,u}$ and $K_{D,u}$. This correlates with the theoretic assumptions about the tiltwing aircraft that a change in σ influences all state variables in the transition phase.

Additionally a pareto analysis investigating the correlation between u, w and θ criteria for the control response behavior was performed keeping the control activities as constraints. The results show a correlation between the criteria of one state variable and conflicting behavior between u criteria and the other criteria. Exemplarily the interdependency between deviation of u (sumΔu), deviation of θ (sumΔθ), and maximum deviation of w (w_MD) is given in Fig. 10.

Multiple optimizations varying the criteria demands were performed to find the points on the displayed pareto-front. The stars displayed in the same shade represent identical control parameters. A set of parameters which is pareto-optimal for two criteria (e.g. sumΔu and w_MD), may not lie on the pareto-front of other two criteria (sumΔu and sumΔθ). The result of the 4 m/s synthesis is displayed as black diamond, in Fig. 10. It lies on the pareto-front of both cases.

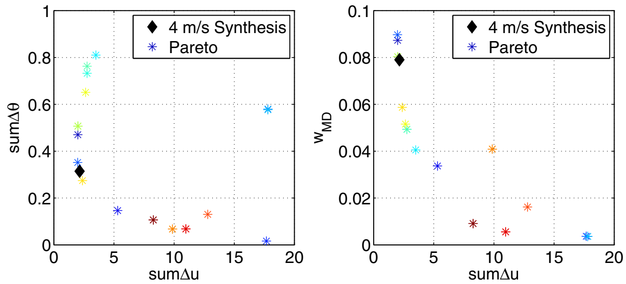

Fig. 10 Possible optimization results for different criteria demands

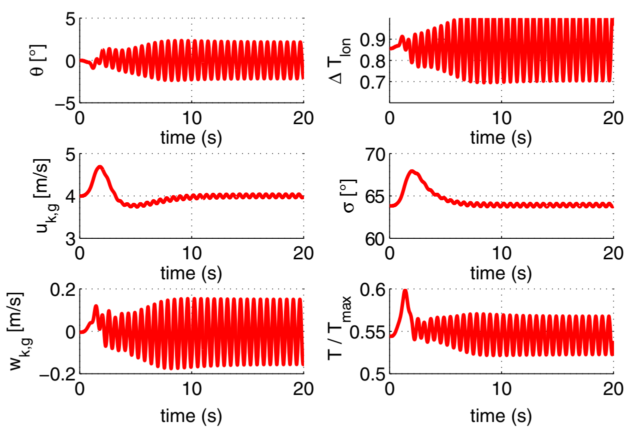

Fig. 11 Disturbance response with slow impeller dynamic and first set of tuning parameters

4.3 Robustness analysis

The influence of the dynamic of the propulsion system and tilt mechanic backlash was analyzed in parameter studies. The degradation of the dynamics of the auxiliary power system towards slower behavior and larger delay times led to an expected destabilizing of the system. The disturbance response for the worst-case dynamic of the auxiliary power system with the set of synthesized controller parameters is shown in Fig. 11. It can be seen that this set of parameters is at limit cycle with a frequency about 1.7 Hz.

Variation of the backlash in σ by including $\Delta\sigma_{on}$ was not as critical but slightly increased the criteria values. In a sensitivity analysis specified parameters, here $\Delta\sigma_{on}$, T_{aux} and T_t are varied within predefined grid points and the criteria are calculated for each case. For the σ backlash as well as the time dynamics the worst cases resulted from the uncertainty parameters being at the limit of the uncertainty range. New cases with these worst-case parameters were added to the parameter synthesis for the control response and disturbance response. The used parameter values are summarized in Table 6.

Table 6 Model parameters for the nominal and worst case

	Nominal	Worst case
T_{Taux} [s]	0.0632	0.1
T_t [s]	0.0362	0.05
$\Delta\sigma_{on}$ [°]	0	2

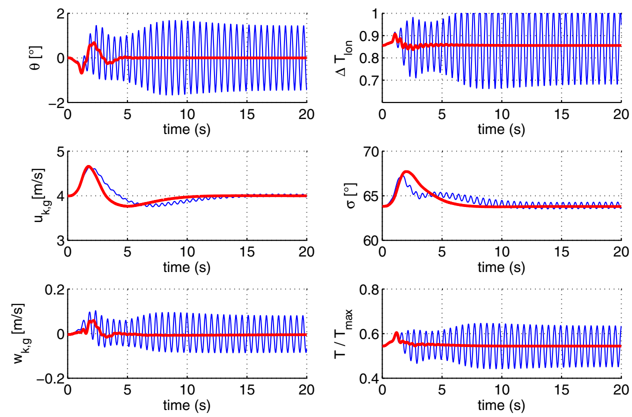

Fig. 12 Disturbance reaction at $u_0 = 4$ m/s for tuning parameters synthesized at $u_0 = 4$ m/s (*red*) and $u_0 = 8$ m/s (*blue*) considering worst-case parameters

A further parameter synthesis regarding the two scenarios and nominal and worst-case parameter settings was performed for $u_0 = 4$ m/s and $u_0 = 8$ m/s. For the control response all criteria could be satisfied. For the disturbance response especially with the worst-case parameters some scaled criteria exceed 1. All criteria for the disturbance response can be seen in Fig. 13. Especially, the settling time and deviation of u and only at $u_0 = 8$ m/s settling time in w exceed their demand values. For future analyses an adaption of the demand values seems to be reasonable.

4.4 Velocity analysis

To analyze the effect of differences in the forward velocities the synthesized controller gains for $u_0 = 4$ m/s and $u_0 = 8$ m/s are evaluated at the other velocity for the nominal uncertain parameters and worst-case parameters for the disturbance and control scenario.

Using the at $u_0 = 8$ m/s synthesized parameters at $u_0 = 4$ m/s showed a destabilizing effect in the disturbance reaction for the worst-case uncertainty parameters, due to the increased $K_{P,\theta}$ and $K_{P,q}$. The corresponding time response is depicted in Fig. 12 through the blue curve. The worst-case uncertainty parameters were considered in the synthesis at $u_0 = 8$ m/s.

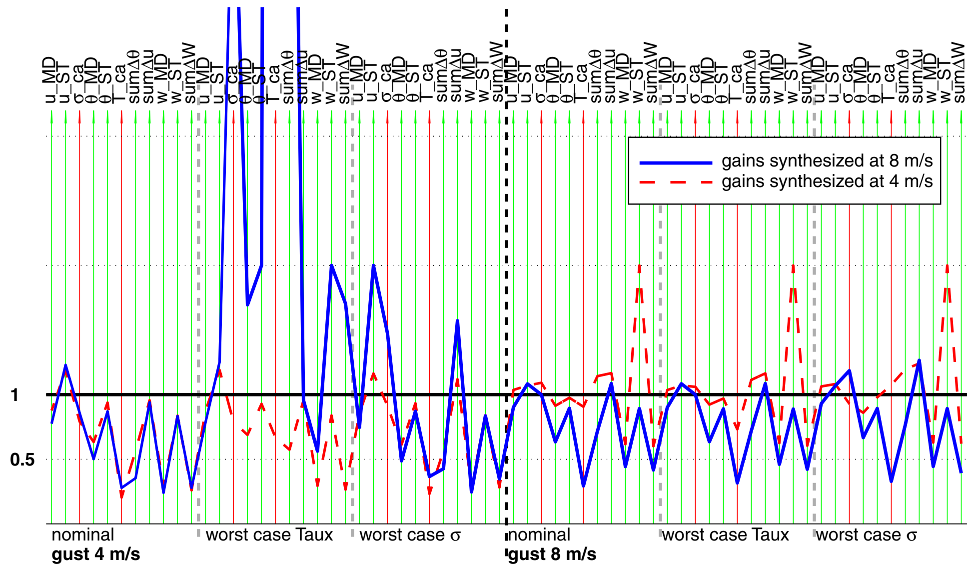

Fig. 13 Criteria for different velocities

Using the parameters synthesized at $u_0 = 4$ m/s for the $u_0 = 8$ m/s simulations showed no destabilizing effect. As mentioned in the previous sections the criteria increase at $u_0 = 8$ m/s, while the time curves are still acceptable. The two cross evaluations are shown in Fig. 13 for the disturbance response in parallel co-ordinates. The two different velocities are separated through the black dashed line. The different cases with different uncertainty parameters are separated through grey dashed lines. The small effect of the worst-case parameters at $u_0 = 8$ m/s can be seen in the almost identical values of the criteria in the nominal and worst case results in Fig. 13.

From the two analyzed velocities $u_0 = 4$ m/s proved to be harder to control and more susceptible to changing controller and model parameters. Hence, synthesized controller gains of $u_0 = 4$ m/s were assessed within different operating points in the transition velocity range.

Figures 14 and 15 show the assessment over different velocities for the disturbance response between the two operating points analyzed. Only velocities larger than $u_0 = 4$ m/s were regarded since the lateral motion at smaller velocities is not stable yet and couples into the longitudinal motion distorting the results. At velocities higher than $u_0 = 8$ m/s the controller gains synthesized lead to unstable behavior in w. The beginning of this can be seen in the higher values of the criteria for $u_0 = 8$ m/s in Fig. 15 and the light oscillation in w in Fig. 14. The vertical velocity w becomes harder to control with the given controller structure in Fig. 4 for increasing velocities and decreasing σ since the direction of the main propulsion system tilts forward and the controlling becomes more indirect. At this point a fading between the horizontal and transition controller, at least for w seems reasonable. Additionally, as the given controller gains were

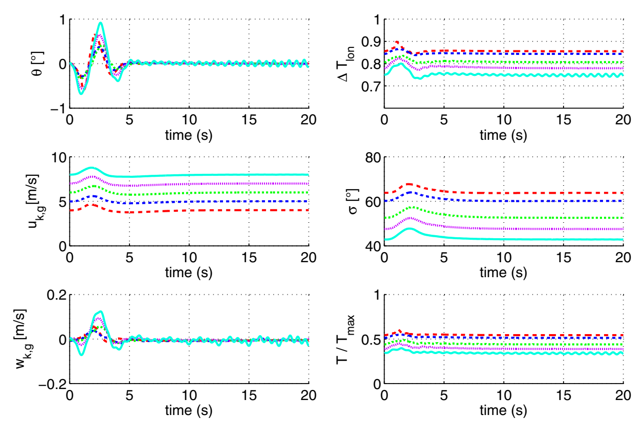

Fig. 14 Time response for different operating points

synthesized at $u_0 = 4$ m/s they are best suited for this velocity. A gain scheduling to adapt the controller gains to the different operating points would improve the performance at these points and might prevent the instabilities at higher velocities. This one set of controller gains works for all forward velocities between $u_0 = 4$ m/s and $u_0 = 8$ m/s and for large configuration changes with tilt angles ranging from 40 to 65°. For a controller design and parameter synthesis for the complete transition corridor more than two operating points have to be considered.

5 Conclusion

In this study the key challenges of control parameter design and design criteria of the longitudinal motion of a tiltwing UAV in transition are analyzed. Performance, coupling, mission and control related criteria were included in the

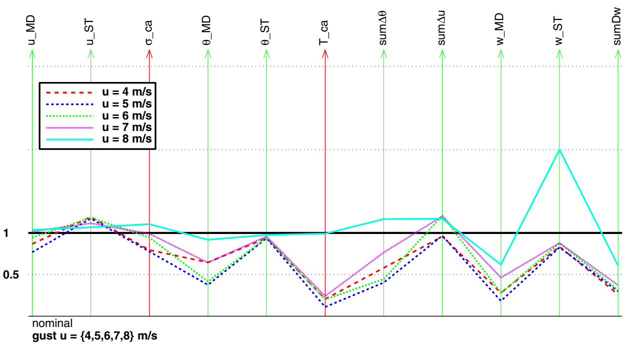

Fig. 15 Parallel co-ordinates for different operating points

control law design for the three longitudinal state variables u, w, and θ. Overall, the analysis showed that during transition the tiltwing is more prone to instabilities and more influenced by uncertain time dynamic parameters at smaller forward velocities. This is due to the lower longitudinal stability mentioned in Sect 2 and the comparatively larger influence of the gust at lower forward velocities.

Another observation is that a change in controller parameters has a larger influence at lower forward velocities. The criteria analyzed in this contribution are optimal for $u_0 = 4$ m/s. For further analysis the scaling of these criteria should be adapted to the flight state and to the scenarios (step size, magnitude and duration of gust). Additionally, alternative criteria formulations should be worked out to better map the desired behavior, e.g. reducing oscillation in the controls.

The analysis showed that a parameter synthesis for each state variable separately leads to only slightly worse results. In case of non-convergence due to too many criteria, this could be considered as an alternative. Synthesizing controller parameters for all three state variables simultaneously the u criteria are in conflict with w-, and θ-criteria leading to a pareto-front of optimal design possibilities.

Two uncertain model parameters, the dynamics of the auxiliary power system and tilt angle σ initial response characteristics, were investigated. The results show that these parameters significantly influence the stability at a given set of controller parameters and that this influence also depends on the given flight state. To find a suitable set of controller parameters for the complete transition range a larger number of flight states have to be analyzed. A linearization at selected flight states and analysis of stability criteria in the frequency domain is likely to provide further insight into these interdependencies.

In this contribution the forward velocity within the transition was solely controlled by the tilt angle. Within the analyzed scenarios this worked well. Still this concept has to be critically investigated with respect to all simplifications made. Additionally to the longitudinal motion the controlling of the lateral motion during transition contains interesting aspects due to fading of control efficiencies in roll and yaw axis. This effect should be investigated in further studies.

Acknowledgments Our work has been conducted within the AVIGLE project (Avionic Digital Service Platform) which is part of the High-tech.NRW research program funded by the German ministry of Innovation, Science and Research of North Rhine-Westfalia and the European Union. We thank all participants for their work and contributions to the AVIGLE project. Furthermore the Authors want to thank H.-D. Joos and J. Bals from the Institute of System Dynamics and Control from the DLR Robotics and Mechatronics Center for their support and the provision of the multi-objective parameter synthesis (MOPS) environment.

EUROPEAN UNION
European Fonds
for Regional Development

Ministry of Innovation
Science and Research
of North-Rhine-Westfalia

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