Mission Control Concept for Parcel Delivery Operations Based on a Tiltwing Aircraft System

M. Schütt, P. Hartmann, J. Holsten and D. Moormann

1 Introduction

The tiltwing aircraft configuration is a combination of two different concepts of aircraft that allows stationary flight in a wide range of velocities from hover to fast forward flight. Within a tiltwing configuration the advantages of rotary-wing and fixed-wing configurations are combined to perform energy efficient high speed flight and vertical take-off and landing (VTOL). For a research project, an aircraft in tiltwing configuration (displayed in Fig. 1) was used within a parcel delivery application [6]. During operation, a remote location in a mountainous area had to be supplied with time-sensitive goods in a frequent and fully automated way. This included all different control levels during flight beyond the line of sight and interaction of the aircraft and ground facilities.

In literature some solutions for different aspects of tiltwing control are available, two approaches can be found in [9, 11]. Both show control concepts that subdivide the flight envelope in discrete points and present manual flight only. Indoor transition methods for a quad rotor-biplane without considering disturbances are described in [7]. Piloted approach maneuvers requiring a runway were analyzed in [2]. In [10] the L1 adaptive control architecture for the manually piloted NASA tiltwing GL-10 is presented. In previous articles the authors have developed a velocity controller [3, 12] to mask the complex flight mechanics and variations of the tiltwing configuration. Higher level control to perform a transition from hover to cruise flight in form of a straight lined maneuver is presented in [4]. For fully automated operations, e.g. in severe weather conditions, several additional issues have to be solved. A higher level mission control system is necessary to allocate tasks to different sub-controllers during all flight phases.

M. Schütt (✉) · P. Hartmann · J. Holsten · D. Moormann
Institute of Flight System Dynamics, RWTH Aachen University, Aachen, Germany
e-mail: schuett@fsd.rwth-aachen.de

B. Dołęga et al. (eds.), *Advances in Aerospace Guidance, Navigation and Control*, https://doi.org/10.1007/978-3-319-65283-2_26

Fig. 1 Tiltwing aircraft during transition from Hover to Cruise flight

Within this paper a control concept for the entire mission operation, based on an existing maneuver control concept [3, 4], is proposed. The control system for flight guidance includes precision take-off and landing, hover as well as cruise flight. The conversion between hover and cruise requires special attention to allow stationary flight and avoid discontinuities. The design of the waypoint pattern and the integration of different landing spots is discussed with regard to regulations and environmental constraints. The fully automated flight is observed and commanded by an operator in charge of safety procedures. Assessment of the entire design and the tiltwing's characteristics was performed by simulation and flight tests. The performance of the mission control system has been proven during a 3-month trial operation in civil airspace.

This paper is structured as follows: Sect. 2 presents the specific features of the mission scenario and the aircraft system, including ground facilities. In Sect. 4 the control system associated with the mission controller is described. The mission control system itself is presented in Sect. 4.3, before presenting the operator interaction to control safe operation. In Sect. 5 the assessment and operation results are discussed. At last, Sect. 6 gives concluding remarks.

2 Mission Scenario: Parcel Delivery Operation

The tiltwing aircraft is used within a parcel delivery scenario, where a remote location in the Bavarian Alps had to be supplied with parcels on a regular basis. The trial operation was conducted by 'RWTH Aachen University' and 'DHL Parcel'. Time-sensitive goods had to be transported from 'Reit in Winkl' to the 'Winklmoosalm'. Two parcel handling stations, called skyports, were used as landing spots. In the following the characteristics of the mission and specific challenges in terms of regulations are presented.

2.1 Mission Overview

The route of the mission, connecting 'Reit in Winkl' and 'Winklmoosalm', is eight kilometers long and has an altitude difference of 460 m. As the scenario is located in a mountainous area (compare Fig. 2), the optimal route in terms of energy consumption

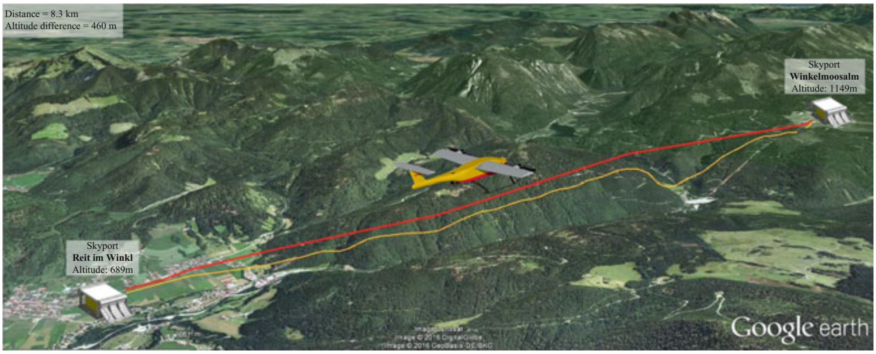

Fig. 2 Overview of the Route from Reit im Winkl to Winklmoosalm

is generated as a combination of shortest distance and lowest altitude difference. The route follows a mountainside and a highway, requiring special attention during design of cruise flight control in terms of track error tolerance.

To accomplish the mission, the aircraft had to fly beyond line of sight of the operator, which leads to special restrictions, as described in the following section. Flight beyond line of sight also requires high level of automation, to ensure safe operation. This includes flight control but also the entire turnaround process, which is handled completely automated by a manipulator inside the skyport. Most of the procedures are predefined and do not need confirmation from the operator. Essential and safety-relevant procedures, like time of take-off, are commanded manually supported by the system. The interactions of operator and automated safety procedures are explained in detail in Sect. 4.3.3.

The weather conditions in a mountainous area cause unknown wind conditions at altitude even if the wind is known at ground level, requiring robust flight control. Additionally there is a risk of icing, because of temperatures below zero degrees at altitude. For good performance at start, precision landing and approach maneuvers, the wind at the two skyports is measured in speed and direction.

As one of the skyports is located in an urban environment, buildings and streets are in close distance. Take-off and landing are performed on a small platform mounted on the skyport. For safety reasons, a certain area around the skyport was fenced off. The ground track of the aircraft has to be controlled precisely during maneuver, therefore track errors and overshoot had to be minimized.

2.2 *Regulations*

The design and testing of the controller had to consider the legal situation in Germany. Unmanned flight beyond line of sight is generally not allowed. For this research project an permission was granted, based on an airspace restriction. Therefore the project had to undergo a safety review in cooperation with authorities and partners involved. Different safety and environmental protection requirements were considered for designing the route.

The route was designed to keep the road intersections at a minimum and cross roads perpendicularly. The flight level between departure and approach was set to a minimum of 80 m above ground level for environmental protection reasons, the maximum altitude above ground was reached during a valley transit at 420 m. The flight path had to be predictable during the entire route, which influenced the design of the waypoint pattern, presented in Sect. 4.3.1. The limits for maximum accepted track deviation were set to 10 m. Thanks to the airspace restriction mainly interactions with emergency service helicopters had to be dealt with, as these were expected to cross the airspace frequently in the skiing-region. Therefore an ADS-B transponder broadcasted the UAVs position during all flights. A detailed analysis of the permission process and different regulations can be found in [6].

2.3 Skyport

The skyport acts as the landing spot and completes the turnaround process of the aircraft, as shown in Fig. 3. On top of the skyport a platform of 3 $\times$ 3 m is installed for take-off and landing of the tiltwing aircraft. While on the platform, the aircraft can be protected from snow, ice and vandalism under a dome.

Each skyport is equipped with an manipulator to interact with the aircraft. The manipulator is able to fasten the aircraft after touchdown and center it on top of the skyport for unloading. The container, including the battery and payload, are dismounted by the manipulator and stored inside the skyport. Inside the skyport

Fig. 3 Skyport and Tiltwing Aircraft during operation [8]

multiple slots store, charge and heat the batteries of different containers. Before take-off the manipulator turns the aircraft to head into the wind for take-off.

The transition maneuver from cruise to hover and precision landing on the platform require detailed information on the wind condition at the landing spot, as stated in Sect. 4. Therefore a anemometer is installed on each skyport. Additionally one of the skyports is equipped with a real-time-kinematic reference station, broadcasting satellite navigation correction data to the aircraft.

3 Parcelcopter: Tiltwing Aircraft System

In the following the flight mechanics and systems of the tiltwing aircraft configuration are presented. The aircraft system, consisting of the demonstrator aircraft, datalink and ground control station, is designed to allow for long range flight beyond the line of sight.

3.1 Flight Mechanics

The tiltwing configuration combines advantages of rotary-wing and fixed-wing configurations. During cruise the wing is rotated to a fixed wing configuration producing sufficient lift for level flight. In this configuration the thrust of the main propulsion system is used to overcome the drag of the aircraft. The tiltwing configuration includes all control surfaces typical to an airplane. For hovering and VTOL the tiltwing aircraft is able to rotate its wing around the lateral axis. As the main propulsion system is installed on the wing, the thrust is used to compensate the weight of the aircraft. The ailerons are located in the slipstream of the propellers to gain yaw control in hover. The elevator loses its effect without incident flow, which is why an auxiliary device (e.g. a ducted fan) to control pitching moment for hover is needed.

During the transition from hover to cruise flight and vice versa a distinct assignment of control surface effects and aircraft's rotational axis is not possible. Because of the changing aerodynamics at different flight states the actuators' effectiveness varies in direction and magnitude. Nevertheless the tiltwing aircraft can perform stationary flight in the entire flight envelope from hover to cruise. By adjusting the tilt angle and thrust to the current wind speed, precise vertical starting and landing is possible even at high wind speeds with low pitch angles. Avoiding lateral wind components, which would cause constant roll angles, a tiltwing heads into the wind while hovering and during VTOL. A tiltwing aircraft features efficient and fast cruise flight capabilities in contrast to multirotor systems. Therefore large cruise ranges are achievable also at headwind conditions.

3.2 Aircraft

The DHL-Parcelcopter is a tiltwing configuration with a wingspan of 2 m. The electric main propulsion system, including two counter rotating propellers with a diameter of 0.7 m, is installed in the wing. The aircraft can be seen hovering above the skyport in Fig. 3 and during flight in Fig. 1. The entire aircraft structure is of composite, leading to a MTOM of 14 kg, including a payload of 2 kg. The powertrain is designed to be weatherproof and with a focus on low noise emissions, as well as efficiency. The conversion by tilting the wing is performed by a spindle drive with limited actuator dynamic. The elevator is located in a T-tail configuration to reduce wing downwash influences. The ducted fan is included into the fuselage to reduce the drag during cruise flight.

To interface with the skyport's landing platform the aircraft is equipped with a landing skid. Furthermore the lower mid part of the of the fuselage is detachable and contains the batteries and the payload compartment. This fuselage part is called container and is exchanged for every flight. It can be automatically detached and recharged by the manipulator inside the skyport. The batteries have been optimized for this mission in terms of range and maximum payload. In total the hover time is kept as short as possible, due to an increase of power consumption in hover of approximately two-thirds compared to cruise flight.

The aircraft's flight control hardware is based on *ARM Cortex-M4* microcontrollers. The control algorithm is designed in *MATLAB/Simulink* and automatically translated to C-code. The navigation system consists of a MEMS-based IMU, a heated pitot-static-system, a barometer, a magnetometer and precision real-time-kinematic satellite navigation receiver. The aircraft's heading can be estimated precisely thanks to the dual-antenna operation of a *Novatel OEM-617D-GNNS-receiver*. The navigation solution's precision (relative to the reference station) is up to 1 cm in the horizontal plane and 2 cm in the vertical axis.

3.3 Ground Control Station and Datalink

The datalink to the ground control station is established via both skyports and has a redundant design. Based on two different data modems the system is able to ensure the required high range in the mountainous area. The data modems are *IMST LoRa* using 868 MHz and a *Sierra Wireless* mobile communication transceiver.

All telemetry and command data are processed by the Ground Control Station (GCS). One of the skyports is directly connected to the GCS. Both skyports are connected to each other and act as datalink repeater. Additionally a datalink repeater is located half way between both skyports. This maintains a steady datalink to the aircraft during the entire flight. Detailed explanation and analysis of the communication structure is given in [13].

The wind data and navigation correction data are transferred to the aircraft via datalink. The operator, located in the GCS, receives all flight data to observe the flight. The GCS needs a constant connection to the aircraft, so the operator is always able to intervene. During flight the operator could send different commands triggering safety procedures or change the route of the aircraft. The operator is also able to command the manipulators of the skyports after touchdown.

4 Mission Control System

The mission control system is designed to control the tiltwing during the entire mission. Figure 4 illustrates the flight mission elements in a conceptual way.

The typical flight starts with a vertical take-off from a skyport. After take-off the position controller holds the aircraft at the starting waypoint until the departure maneuver is initiated. The waypoint controller guides the aircraft during cruise flight until the approach maneuver is started. After reaching the target in hover state, the vertical descend and landing procedure is performed. Different alternative landing spots (ALS) are located along the route. Next to each skyport an ALS can be reached in hover flight.

An overview of the control system is shown in Fig. 5, illustrating the cascaded controller design approach: The innermost loop is the velocity controller, including attitude control. The flight path control loop is designed for different flight states: For take-off, landing and hover a position controller is controlling the aircraft's flight path. During cruise flight the flight path of the aircraft is controlled by a waypoint controller. To accomplish fully automated flight, the controllers have to interact and control authority has to be allocated by a mission control system, described in Sect. 4.3.

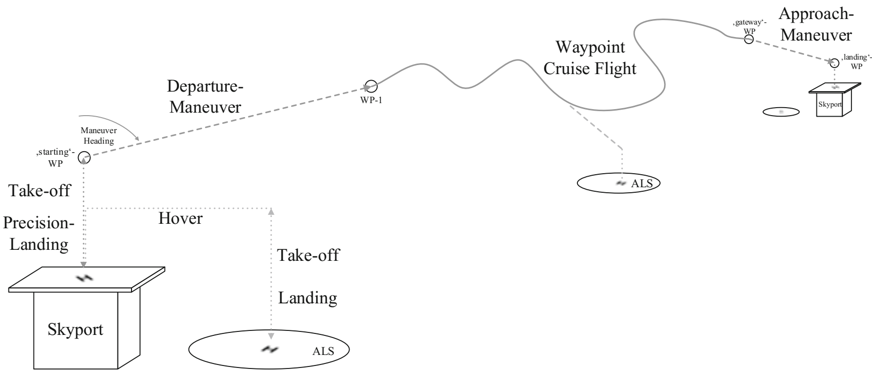

Fig. 4 Overview different flight mission elements

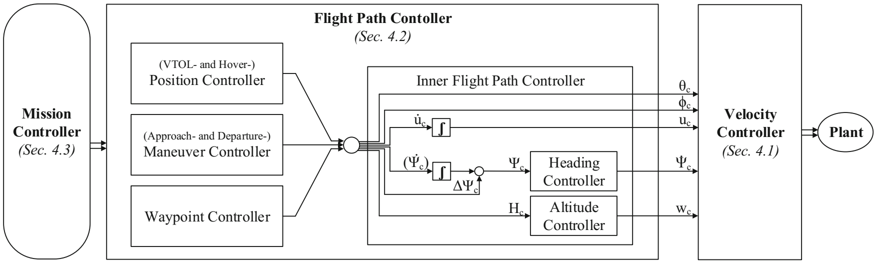

Fig. 5 Overview of the control system (adapted from [4])

4.1 Velocity Controller

A convertible aircraft has to perform flight state transitions to make use of its entire flight envelope regarding forward speed. The complex flight mechanics and variations in the different flight states pose a challenging problem in terms of analysis and control. The performance of the velocity control concept, presented in [3], was demonstrated, using different tiltwing aircraft and performing trimmed flight at any airspeed within the flight envelope. The velocity controller allows for flight over the whole flight envelope and unifies the significant variations of flight mechanical characteristics. Thanks to this, the velocity controller is a well chosen inner control loop with a homogeneous set of command variables in all flight states.

The velocity controller uses a horizontal, body-fixed coordinate system, controlling airspeeds in longitudinal u_c and vertical direction w_c, with the longitudinal motion mostly controlled by tilt angle variations. The aircraft's heading rate $\dot{\Psi}_c$ is controlled, because the absolute heading is irrelevant for the velocity controller, and a turn coordinator controls a corresponding bank angle depending on the airspeed. The attitude angles θ_c and ϕ_c complete the set of command variables.

4.2 Flight Path Controller

The flight path controller consists of two different parts: Sub-controllers, that are activated by a mission controller, and a inner flight path controller, that is permanently active. In the following the inner flight path controller is described first, including the generation of the command variables heading and airspeed. Subsequently the three sub-controllers are presented.

The heading controller computes the velocity controller's command variable heading rate $\dot{\Psi}_c$. The controller employs a PD feedback. The proportional and derivative gains are gain-scheduled from hover to cruise, depending on airspeed. The heading's rate of change $(\dot{\Psi}_c)$, commanded by the three sub-controllers, is integrated, to prevent discontinuities.

The altitude controller generates the command variable vertical speed w_c for the velocity controller. The altitude controller feedbacks the altitude deviation proportionally and feedforwards the slope of the flightpath. Due to the aircraft's flight envelope, the vertical speed is limited depending on the forward airspeed. Most of the missions' altitude difference is climbed during waypoint flight, as vertical ascend and descend is kept short for energy consumption reasons. The altitude controller can be switched off for constant vertical speeds w_c during start and landing.

The commanded airspeed u_c is the most significant value for the velocity controller, as it has major influence on flight mechanical variation. To initialize the different sub-controller without discontinuities, an integrator is in charge to generate a continues airspeed command value u_c.

Position Controller The position controller is designed for hover of the tiltwing aircraft. Following a classical approach, the controller is divided in a longitudinal and a lateral part. Therefore the error in position and velocity between the aircraft and the designated position is transformed from the earth fixed to the body fixed coordinate system, see Fig. 6.

Both controller parts share the same structure and consist of a proportional/ derivative PD-part and an integral I-part, the control law is displayed in Fig. 6. Each PD-part feedbacks the position and velocity error to the corresponding attitude angle, showing fast response characteristics. While the PD-part features fast response for small position deviations or wind gusts, the I-part is used to compensate the effect of constant wind. As a consequence the aircraft ends up in a position presented in gray, heading into the wind at an adapted airspeed. The I-parts are used to change the inputs of the previously explained integrators for airspeed and heading.

Maneuver Controller The maneuver controller has to guide the aircraft's transition from hover to cruise flight and vice versa. Generally tiltwing aircrafts try to avoid sideslip angles especially during transition for a symmetric incident flow at this phase of significantly varying aerodynamics and flight mechanics. A classical approach

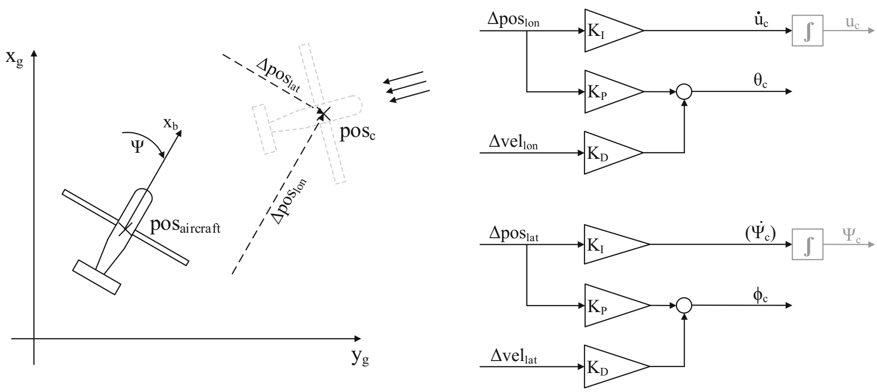

Fig. 6 The coordinate system and control law of the position controller (adapted from [4])

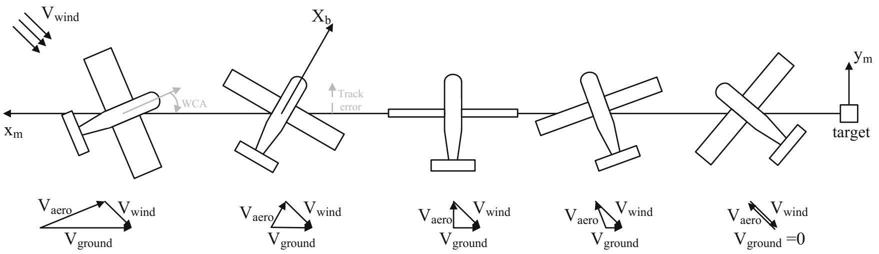

Fig. 7 The coordinate system and progress of the maneuver (adapted from [4])

including a turn flight to start decelerating while heading into the wind would end in a hover state without any sideslip angles. The covered ground track due to the turn is changing, depending on different wind conditions. The total area overflown for turn flight approach is not suitable for the given scenario in an urban environment. Instead, a straight lined maneuver was developed, which is described briefly in the following. For more details of the design of the maneuver controller see [4].

This control approach is taking advantage of the tiltwing to adapt the wing angle and works identically for all different wind conditions. The maneuver's principle of function is almost identical for departure and approach. Hence, only the approach is described here. The controller uses a coordinate system that has its origin located at the target and the x-axis pointing in direction of the departure track (compare Fig. 7). Due to the limited fenced off area all deviations from track and overshoot at the landing position should be kept at a minimum.

The process is displayed in Fig. 7 for a tail wind situation. The aircraft approaches from left to right, flying on a linear track. It decelerates and turns the heading into the wind in a coordinated way. When decelerating, the aircraft has to adapt the wind correction angle to compensate the lateral wind component. As soon as the wind correction angle reaches 90°, the aircraft has to start accelerating until reaching a hover state with airspeed opposing the wind speed. The maneuver works in a similar way for any other wind condition, which mainly determines the final hover state, while the process of turning and accelerating stays the same. The maneuver controller's task can be divided into three parts. The first task is to decelerate the aircraft as fast as possible, as Hover should be limited due to energy consumption reasons. Therefore the heading's rate of change ($\dot{\Psi}_c$) and airspeeds rate of change $\dot{u}_c$ should be as large as possible, but always coordinated to stay on track. The second part is to keep the aircraft on the straight lined track and to minimize the track error. The control law is working in the same way as the position controller. The third part is to reach hover at the designated position. Therefore, the current wind condition has to be known and the length of the maneuver at any given wind condition has to be pre-calculated. This allows starting the maneuver at just the right distance before the target to reach hover at target.

The departure maneuver doesn't need feedback, it is open loop and finished when reaching the cruise airspeed.

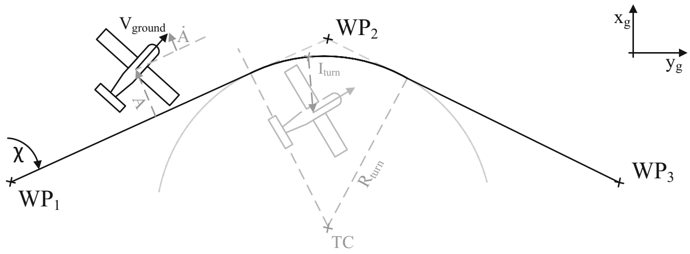

Fig. 8 Coordinate system of the paypoint controller and turn geometry

Waypoint Controller The waypoint controller uses a classic position line approach to follow a designated path. A preceding filter calculates the course χ, current lateral track error A and its derivative $\dot{A}$. A turn geometry is calculated, dependent on maximum roll angle and cruise airspeed, see Fig. 8. The combination of three waypoints (last, current and upcoming) defines the turn center TC and the starting and end points of the turn.

During straight flight and turn flight the three corresponding values (χ, A and $\dot{A}$) are transferred to the controller. The controller manipulates the heading command based on a PI-algorithm combined with a damping part. The control gains are higher than usual for cruise flight. The controller causes strong responses on track errors, which is driven by the terrain and surrounding infrastructure of the mission. The track follows a mountainside next to a highway, to which the aircraft has to stay in a sufficient distance. Therefore track errors and overshoot during turns are highly undesired.

Each waypoint has several attributes and most of them are employed by the mission controller, described in Sect. 4.3.1. Two of the attributes 'altitude' and 'airspeed' of each waypoint are interpreted by the waypoint controller. The altitude is interpolated linearly between last and upcoming waypoint by the waypoint controller to generate a current altitude command. The airspeed attribute of the upcoming waypoint defines the commanded airspeed by manipulating the integrator input of the inner flight path controller. The waypoint controller is only allowed to change the airspeed in a small range of cruise speeds.

4.3 *Mission Controller*

The mission controller is designed as a state machine, as shown in Fig. 9. The mission controller is directing the entire flight and allocating the control authority.

The definition of the route in terms of waypoints and nodes is depicted first. An overview on the standard procedures of an operational flight is presented and additional safety features are described subsequently.

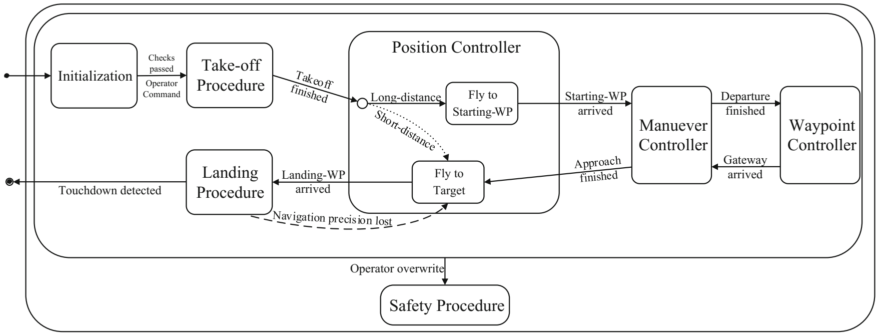

Fig. 9 State diagram of the mission controller

4.3.1 Mission Definition Data

Different information for waypoints, legs and departure or target nodes are stored in attributes. These attributes are interpreted by the mission controller, generating the route.

Waypoint Pattern Each waypoint is defined by an individual tag and position coordinates, displayed in Table 1. Additional attributes are 'airspeed' and 'altitude' (above mean sea level). Every node represents a possible take-off and landing spot. The current route is thereby defined by selecting a departure-node and target-node. A set of possible follow up waypoints are assigned to every waypoint. Depending on the selected target-node, the waypoints are pointing to a follower. The target-node can be changed during flight, causing a change of the following order of waypoints.

In Fig. 10 a one-way route is illustrated. Node A is selected for departure and Node B as target, creating a route as each waypoint is pointing to another in ascending order from WP 0 to WP 6. A target change to Node C affects WP 3, pointing at WP 7 instead of WP 4. This makes WP 3 a 'decision'-waypoint, changing its following WP as a result of target change. The waypoint controller calculates a turn starting ahead of the waypoint, dependent on the maximum bank angle as shown in Fig. 8. A change of target right before reaching WP 3 would cause large track deviations, as the turn is initiated too late. Therefore every decision-waypoint is protected from target change by another waypoint located in a short distance ahead. This waypoint includes the attribute target 'locked', causing a change of target being not accepted by the mission controller on the following leg. The distance of the this leg between 'protection'- and 'decision'-waypoint is dependent on the maximum bank angle, ensuring a turn flight to any follower of the 'decision'-waypoint. While flying the leg from WP 2 to WP 3 a change of target from B to C doesn't affect the route, as the target is 'locked'. After passing WP 3 all following waypoints keep the order independent of the target, for both targets the follower of WP 4 is WP 5 for example. A waypoint pointing at a landing waypoint is tagged as a 'gateway'. Only on the leg from gateway- to landing-WP (from WP 5 to WP 6), the maneuver can be started

Table 1 Attributes of waypoints

ID	pos	'Airspeed'	'Altitude'	'Gateway'	'Locked'	'Default'	Target 'B'	Target 'C'
WP 1	x,y	16	115	no	no	WP 2	WP 2	WP 2
WP 2	x,y	19	250	no	yes	WP 3	WP 3	WP 3
WP 3	x,y	19	250	no	no	WP 4	WP 4	WP 7
...								
WP 5	x,y	16	180	yes	yes	WP 6	WP 6	WP 6

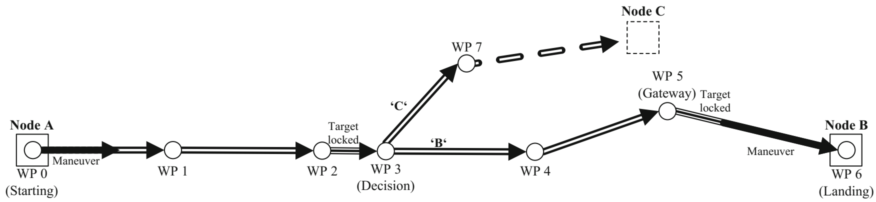

Fig. 10 Schematic overview of the waypoint pattern and the attributes of a waypoint

by the mission controller. After passing the gateway a change of target is no longer possible.

For safety procedures (described in Sect. 4.3.3) each waypoint has additional attributes like 'default' target. The properties of the waypoint pattern make every possible route predefined and predictable. Even a change of target, turn around or activation of safety procedure ends in a well-defined route. This way it is possible to simulate all flight paths in advance. For regulatory reasons and due to close distance to the mountainside this is a helpful feature of the waypoint pattern.

Node Definition Each node is working as a take-off and landing spot, therefore its position coordinates and altitude are attributes. Skyports as well as ALS are defined as nodes, the attributes can be found in Table 2. The approach and departure from and to a node are performed via maneuvers. The attribute 'maneuver heading' of each node is pointing in the direction of the following leg (see Fig. 4). Each node has an associated 'starting'-waypoint in a certain altitude above ground. After vertical take-off the departure maneuver is initiated from this 'starting'-waypoint. The departure maneuver is finished when reaching cruise flight on the first leg in direction of the 'maneuver heading'. At the target node, the deceleration maneuver is initiated while flying onto the gateway leg. Dependent on the current wind condition the mission controller activates the maneuver controller, to reach hover state at the corresponding 'starting'-waypoint above the target-node. The minimum gateway leg length is defined by the maximum maneuver length.

Landing onto a skyport requires a high precision navigation solution, due to the small landing platform. As the ALS are larger, no high-precision navigation solution is necessary to land on it. Besides the maneuver definitions, a node is also character-

Table 2 Attributes of nodes

ID	Pos	'Altitude'	'Maneuver heading'	'Starting'-WP
Node A	x,y	100	90	WP 1
Node B	x,y	150	−75	WP 6
Node C	x,y	...		

ized by the need for high precision navigation solution. If necessary, the node points to one of the ALS in close distance, this safety procedure is described in Sect. 4.3.3.

Mission Types Next to each skyport an ALS is located on the ground. A maneuver is related to both nodes pointing in the direction of the mission's route. During daily operations the demonstrator aircraft had to be maintained and checked on a regular basis. Therefore, next to the standard waypoint flight another mission type was introduced for short distance flight. If short distance flight is selected, the mission controller will guide the aircraft to target, conducting hover flight only.

4.3.2 Regular Modes of Operation

The state machine of the mission controller can be summarized as shown in Fig. 9. For accomplishing the mission, the controller works in the following way:

Initialization A operational flight starts with a set of initialization processes before take-off. The operator selects the current skyport as the starting node and the desired as target node, this defines the upcoming route. Additionally the mission type is selected to be 'long distance' or 'short distance' flight. Current wind data of the anemometer of the starting skyport are broadcasted to the GCS. The operator commands the manipulator to turn the aircraft to head into the wind and adjusts the initial aerodynamic speed to compensate the headwind at the moment of take-off.

Take-off After this initiation process, the take-off procedure is started by entering the next state of the mission controller. During the engine ramp up, the mission controller imposes a certain downward-force on the velocity controller to prevent the aircraft from lifting off. Just after the engines reach their final value this force is reset to zero and a constant rate of climb is commanded to ensure a defined liftoff.

Position Control As long as the aircraft is close to the platform, high attitude angles can be avoided by only damping the horizontal speeds and inhibiting the position feedback. Additionally the commanded vertical speed is transferred directly to the velocity controller; the altitude controller is not active in this phase. At a certain altitude, the position controller is activated to ensure the aircraft reaches its end of vertical climb directly above the platform. Short period disturbances like gusts are compensated by roll and pitch angle, while constant wind change cause change in heading or forward airspeed via the integrators.

Departure Maneuver After reaching the starting waypoint, the mission controller activates the departure maneuver controller. The direction of the maneuver is taken from the node attribute 'maneuver heading'. As the maneuver works identically for any given wind condition, the aircraft simply starts its procedure of accelerating and turning. As soon as the airspeed reaches cruise speed, the maneuver control loop resembles the control law of the waypoint controller for straight flight. That way the pitch command is faded out, as there is no need for longitudinal position adjustments at higher airspeeds. Additionally the maneuver controller alters the lateral command variable from roll angle ϕ_c to heading's rate of change ($\dot{\Psi}_c$). Thanks to this gain scheduling no discontinuities occur during switching.

Waypoint Flight After reaching cruise speed, the mission controller activates the waypoint controller. During cruise flight a combination of waypoints define the route. The mission controller identifies the upcoming waypoint and changes the waypoints during the turn at the correct time. As the gateway waypoint already includes a reduced 'airspeed' attribute, on the leg to the gateway waypoint the airspeed is reduced and the target is locked. The maneuver controller has to schedule the approach maneuver on the gateway leg, therefore the current wind condition at target has to be updated.

Approach Maneuver After reaching the gateway waypoint, the waypoint controller remains active. The maneuver controller is activated by the mission controller at a certain distance to target, located on the gateway leg. The maneuver controller initializes the start of deceleration adjusted to the maneuver length for the current wind condition. The aircraft starts decelerating and heading into the wind until the groundspeed along the track to target is zero. At this moment the mission controller allocates control authority to the position controller to compensate residual displacements or overshoots. The position controller guides the aircraft to the landing waypoint.

Landing When reaching the landing waypoint at certain tolerance, the vertical landing procedure is started. Thanks to the capability to adjust the wing angle and heading to the current wind condition, the tiltwing is able to approach the platform even at high wind speeds without need for high attitude angles. During vertical landing the mission controller commands a constant descend rate directly to the velocity controller. After touchdown detection, the engines are shut down and the aircraft is prepared for the turnaround process. Therefore the wing is tilted in a pre-defined position and the aircraft is moved by the manipulator to the center of the platform for unloading.

4.3.3 Operational Procedures

Next to scheduling the operational procedure, another task of the mission controller is to allow for operator and safety pilot overwrites. Additionally, the mission controller performs automated checks and activates different safety procedures, if necessary.

Operator The operator is responsible and in charge of operation during the whole flight. He uses the GCS to observe the flight and has the permanent authority to interrupt. During default procedure the operator has to confirm the start procedure before the engines are run up. During the run up of the engines the start can be aborted. After take-off the operator has different possibilities to activate or confirm safety procedures. An operator overwrite causes the mission controller to change the state, according Fig. 9. During operational flights the operator never had to overwrite the default procedure.

Automated Checks Before take-off a number of initialization processes and automated checks are performed to ensure safe flight. The navigation solution has to provide a minimum precision. The position of the aircraft has to match the selected starting node. The aircraft's heading and measured indicated airspeed have to be adjusted to the wind condition measured by the anemometer.

Before descending onto the skyport, the precision of the navigation solution is checked. If the accuracy is not sufficient, the target is changed to the corresponding ALS. The position controller stays active and guides the aircraft to the landing waypoint.

During descend, the mission controller is able to estimate the wind speed. While heading into the wind, the aircraft's airspeed compensates the wind speed to obtain zero groundspeed. The mission controller uses the commanded airspeed to estimates the current wind speed by employing a model of empirical boundary layer data. The estimated wind speed is used to adjust the commanded touchdown point, which increased the precision of the landing. After touchdown detection the engines are shut down automatically.

Safety Procedures The safety procedures include several operations, which need confirmation of the operator. The aircraft is always able to return to the starting point by target change of the operator. Additionally the operator can guide the aircraft to a number of predefined ALS along the route. These ALS also constitute nodes, including maneuver heading. This way a target change to an ALS also simply changes the order of waypoints, leading to the new target.

5 Assessment

The mission control system was designed and tested in a simulation environment. During flight tests the simulation was validated and controller performance could be analyzed. The trial operation proved the suitability for practical use of the entire system.

5.1 Simulation

The simulation consists of a closed loop model of the velocity controller and the aircraft, which is the controlled system. In combination with this model, the different

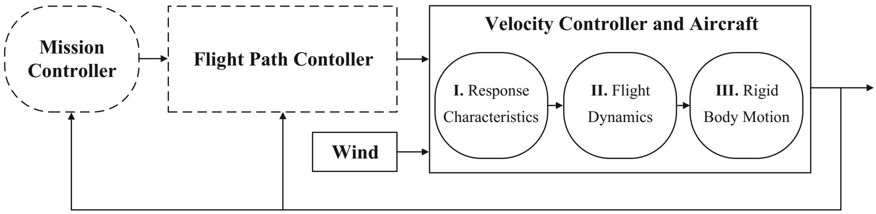

Fig. 11 Overview of the simulation environment

high level controllers could be designed and tested. There was no demand for modeling the flight mechanical variations as they are mainly compensated by the velocity controller. Especially the complex allocation of the control surfaces and forces and moments in the different flight states did not have to be considered.

Simulation Structure Like the controller, also the simulation is implemented in *MATLAB/Simulink*. The model of the controlled system can be divided into three parts, displayed in Fig. 11. The first part describes the different response characteristics of the commanded variables. These characteristics were identified from closed loop flight data as first-order low pass filters with time delays.

The second part addresses the flight dynamics of the closed loop system. The coefficients and derivatives were again identified from previous flight data. The identification was performed at two different airspeeds, 4 and 16 m/s, covering hover and cruise flight characteristics. Thanks to the velocity controller, changes concerning response characteristics between these flight states were remarkable small. In the third part the equations of motion are calculated by a simple kinematic model. Additionally wind is added to the airspeeds to gain velocities in the inertial coordinate system. Therefore high-resolution wind including gustiness was implemented. Wind speed and gustiness can be scaled and rotated as needed. Additionally a boundary layer model was implemented, reducing the wind speed depending on the aircraft's altitude and the roughness of the surface.

Results The velocity controller is able to mask the complexity of the tiltwing aircraft. Because of this feature, the system consisting of aircraft and velocity controller is well accessible to extensive but reasonable simplification. The aircraft's complex flight mechanics could be described in a rather simple simulation. All mission controller parts could be implemented to the simulation. This helped for comprehensive test of the mission control system at different wind conditions. Especially all safety procedures, which may be unsafe to test in flight, could be examined in detail.

5.2 Flight Tests

To validate the simulation environment and test selected aspects of the control system, flight tests were performed near Aachen. For different wind conditions the effect on the aircraft was compared to the simulation results. Also the effect on the maneuver performance could be observed in the simulation very similar to flight tests. In total the closed loop system characteristics are covered by the simulation in all different flight states, which made the simulation an important tool for the design of the controller.

As the higher modes of operation of the mission controller could be tested and validated in the simulation environment, the focus during flight tests was on the analysis of specific controller parts. In particular the precision landing was tested extensively in real flight. Influences of ground effect and boundary layer effects, had significant impact on the performance.

5.3 Parcel Delivery Operation

During the entire operation in the Bavarian Alps all flights were successfully performed in full automation. No operator intervention was necessary and no safety procedure was triggered. The overall unmanned aircraft system worked as expected even under rough weather conditions. Wind speed during take-off and landing at the ground level was 7 m/s at the maximum. Wind speed at flight level was only estimated from measured groundspeed and wind correction angle. The maximum wind speed observed during flights was 13 m/s at a wind correction angle of 31° and a groundspeed of 25.4 m/s.

The flight time of the operational flights differ in more than 140 s (355 up to 500 s), which indicates the influence of the wind on the flight duration. As the aircraft is controlled to fly at a constant airspeed, the groundspeed during cruise varies between 14 and 29 m/s. The vertical and horizontal track-error during cruise flight stay within the required limits of 10 m. The precision landing mechanism was validated by more than 130 landings. In [1] these precision landings were analyzed in reference to the wind condition. An evaluation of the maneuver controller and its performance can be found in [4]. In general all flights well matched previous simulations, as no unexpected effects could be observed.

6 Conclusion

In this paper a mission control system for fully automated tiltwing operation was presented. The DHL-Parcelcopter delivery operation included vertical take-off and landing and a straight lined maneuver for conversion from cruise flight and vice versa. The overall mission controller design was driven by constraints, such as precision landing on a small platform and flight beyond line of sight.

A design approach, including test flight in line of sight, was combined with a dedicated simulation environment. Controllers for different flight phases and their interaction were presented. The higher level controllers are based on a velocity controller, utilizing the complex flight mechanics of the tiltwing aircraft. The flight path controller consists of three sub-controllers, each operating during a different flight phase. A special focus was set on the mission controller, directing the different controllers during the flight phases. The attributes and procedures of the mission controller were presented in combination with external facilities to ensure safe operations. The mission definition data for standard operations and safety procedures were discussed.

The designed controller allowed automated flight beyond line of sight of the tiltwing aircraft during a 3-month trial operation in the Bavarian Alps. The functionality of the aircraft system was evaluated in a number of different test flights. The robustness and reliability of the mission control system was proven during the flight campaign. All deviations and overshoots stayed within the required limits. The different challenges due to high level of automation and flight in civil airspace were well managed by the control system.

References

1. Dobrev Y, Hartmann P, Schütt M, Moormann D (2016) Entwurf und Validierung eines Präzisionslandesystems für unbemannte Tiltwing-Fluggeräte. Deutscher Luft- und Raumfahrtkongress, Braunschweig, Germany
2. Frost CP, Franklin JA, Hardy GH (2002) Evaluation of flying qualities and guidance displays for an advanced Tilt-Wing STOL transport aircraft in final approach and landing. In: Biennial international powered lift conference, Williamsburg, US-VA. https://doi.org/10.2514/6.2002-6016
3. Hartmann P, Meyer C, Moormann D (2016) Unified approach for velocity control and flight state transition of unmanned Tiltwing aircraft. In: AIAA guidance, navigation, and control conference, San Diego, US-CA. https://doi.org/10.2514/6.2016-2101
4. Hartmann P, Schütt M, Moormann D (2017) Control of departure and approach maneuvers of Tiltwing VTOL aircraft. In: AIAA guidance, navigation, and control conference. US-TX (accepted for publication), Gaylord. https://doi.org/10.2514/6.2017-1914
5. Holsten J, Ostermann T, Moormann D (2011) Design and wind tunnel tests of a tiltwing UAV. CEAS Aeronaut J 2:69–79. https://doi.org/10.1007/s13272-011-0026-4
6. Holsten J, Hartmann P, Schütt M, Moormann D (2016) DHL Paketkopter 3.0 Automatische unbemannte Flüge ausserhalb der Sichtweite zwischen zwei Packstationen mit einem Tiltwing-Fluggerät, Deutscher Luft- und Raumfahrtkongress, Braunschweig, Germany
7. Hrishikeshavan V, Bawek D, Rand O, Chopra I (2013) Development of transition control methodology for a quad rotor-biplane micro air vehicle from hover to forward flight. In: AHS international specialists' meeting on unmanned rotorcraft, Scottsdale, US-AZ
8. DHL-Parcelcopter. http://www.dpdhl.com/en/mediarelations/specials/parcelcopter.html. 20 Oct 2016
9. Ostermann T, Holsten J, Dobrev Y, Moormann D (2012) Control concept of a Tiltwing UAV during low speed manoeuvring. In: Proceeding of the 28th international congress of the aeronautical sciences. Brisbane, Australia
10. Rothhaar PM et al (2014) NASA langley distributed propulsion VTOL Tilt-Wing aircraft testing, modeling, simulation, control, and flight test development. In: 14th AIAA aviation technology. integration, and operations conference, Atlanta, US-GA. https://doi.org/10.2514/6.2014-2999

11. Sato M, Muraoka K (2014) Flight controller design and demonstration of quad-Tilt-Wing unmanned aerial vehicle. J Guidance Control Dyn 38(6):1071–1082. https://doi.org/10.2514/1.G000263
12. Schütt M, Hartmann P, Moormann D (2014) Fullscale Windtunnel investigation of actuator effectiveness during stationary flight within the entire flight envelope of a Tiltwing MAV. In: Proceedings of international micro air vehicle conference. Toulouse, France, pp 77–83
13. Voget N, Binz F, Dobrev Y, Moormann D (2016) DHL Paketkopter 3.0 Auslegung und Implementierung eines Zuverlässigen Kommunikationsnetzes für den Sicheren Betrieb Unbemannter Fluggeräte ausserhalb der Sichtweite, Deutscher Luft- und Raumfahrtkongress, Braunschweig, Germany