CEAS-GNC-2024-097

EuroGNC Bristol, UK June 11th-13th 2024

Advanced Flight Control Architecture for Safe BVLOS Drone Operations

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ABSTRACT

This paper presents a flight control architecture for safe BVLOS tilt-wing operations. The control architecture is based on a cascaded structure including attitude and velocity control with a defined interface to the MPC-based path controller. To meet the requirements of BVLOS operation, a robust LQR-based attitude control design is applied over the entire speed range of the tilt-wing aircraft. In order to achieve safe and reliable BVLOS operation of the aircraft, even in the event of a failure, a safety concept has been developed that provides various functionalities operating at different layers of the flight control architecture. For this purpose, these safety functionalities include actions to continue the flight under specified restrictions, abort the flight mission and land at a pre-defined safety point, and degrade malfunctioning controller components for immediate safe landing. During an extensive flight campaign in Saxony, Germany, the reliability of the safety functions were proven and demonstrated, especially in the case of an elevator failure and in dealing with an intruder. Thus, the developed flight control architecture laid the foundation for consistently safe operation of the tilt-wing aircraft throughout the entire campaign.

Keywords: Flight Control Architecture, BVLOS Operations, Safety Concept

Nomenclature

BVLOS	=	Beyond Visual Line of Sight
LQR	=	Linear Quadratic Regulator
OP	=	Operating Point
Φ, Θ, Ψ	=	Euler angles (roll, pitch, heading)
$u^h_{a,c}$	=	Horizontal aerodynamic velocity
$w^h_{a,c}$	=	Vertical aerodynamic velocity

1 Introduction

The implementation of Germany's so far largest Beyond Visual Line of Sight (BVLOS) flight campaign poses significant safety challenges in operating tilt-wing aircrafts. The highly challenging requirements of the missions are reported in [1]. With numerous flight missions, predominantly BVLOS, the campaign requires extended flight hours. In addition to automatic flight execution, the flight control architecture must allow the integration of safety functions to allow the tilt-wing aircraft to safely operate BVLOS. These safety functions are either exectued automatically by the tilt-wing aircraft, or initiated remotely by a safety or remote pilot through communication channels with the tilt-wing aircraft, as described in [2].

To achieve safe flight control, two major task areas must be integrated. Firstly, automatic flight operations need a reliable flight control system and secondly, the architecture must include an extensive safety concept that ensures safe operation in case of software or hardware failures, and environmental factors. To fulfil this goal, an existing flight control structure was adjusted, so that the safety concept could be integrated into the architecture through intervention capabilities and functionalities.

In this paper a flight control architecture with a safety concept that ensured the safe operation of a tilt-wing aircraft during the BVLOS flight campaign in Saxony, Germany, is presented. Therefore, a cascaded architecture was developed for the flight state controller, which interfaces with the trajectory controller from [3]. This approach enables individual controller components to be clearly separated. The division of controller components establishes the foundation for incorporating the safety concept, enabling the degradation of individual controller components in the event of software or hardware malfunctions. The safety concept include various stages to respond according to the the severity of the issue. Safety functions were designed to cope with different failure scenarios without defining individual strategies for each possible failure. As a high level of complexity in the safety concept itself represents a safety risk, minimizing complexity was a key design principle. When the safety functions are activated, they allow the mission to be continued with specific limitations, to safely abort the mission with landing at pre-defined safety points, to degrade individual flight control components, or finally, an immediate landing at the current location. The safety functions have three possible triggers, including automatic triggering under certain conditions and intervention by the remote or the safety pilot. The flight control architecture described in [2] offers communication channels for remotely initiated safety functions. Moreover, a safety pilot can activate safety functions with a transmitter within receiving range. The developed architecture safely executed flight missions with a total of 140 flight hours during the flight campaign in Saxony, Germany. The efficiency of the safety concept was demonstrated in scenarios of elevator failures and in the event of an intruder along the flight path.

The paper is structured as follows: Initially, criteria for safe BVLOS procedures are established according to the regulatory framework and planned flight missions for the campaign. Then, the developed hierarchical flight control architecture is introduced. Subsequently, the safety concept, comprising distinct escalation stages, is elaborated in detail and each individual safety function is addressed. Finally, the individual flights of the flight campaign, in which the safety concept ensured safe handling of failures, were evaluated. In the end the handling of an elevator failure, in which a safe landing occurred at a pre-defined safety point is examined.

2 Requirements for BVLOS Operations

For the safe operation of a tilt-wing aircraft in BVLOS scenarios, the system must meet high requirements. To systematically consider these requirements, they are categorized into three areas: flight control, flight performance, and safety. Additionally, specific safety requirements have been derived for the BVLOS flight campaign in Saxony based on its missions. These requirements are in addition to the mandatory requirements for the operation of tilt-wing aircraft. In the following sections each area is addressed separately.

The fundamental objective of the flight state controller for the tilt-wing aircraft is to maintain stable flight states throughout the entirety of the flight envelope [4, 5]. Tilt-wing aircrafts have a wide range of speeds, leading to a noticeable variation in flight mechanical characteristics based on horizontal velocities [6]. To be able to fly a large flight envelope, a flight state controller capable of managing the varying aerodynamic flow conditions and flight mechanical stability, and of stabilising and controlling the aircraft in a consistent manner, is required. Additionally, it has to be robust against disturbances arising from wind effects, caused by the various weather conditions encountered during the flight campaign.

As outlined in [7], the flight missions involve narrow flight corridors and complex altitude profiles. Based on these tight flight corridors, the requirement for a large speed range is necessary to ensure that trajectory planning can accommodate geometrically complex flight missions that the aircraft can safely execute. Additionally, [7] notes that the complex altitude profiles are based on aircraft's height above ground. To comply with these altitude requirements, the climb and descent rates of the aircraft must meet strict standards.

Overall, the flight state controller requirements aim to optimise aircraft performance across the entire flight envelope, including high dynamics with significant horizontal and vertical accelerations. This foundation is crucial for achieving high flight performance, particularly during the flight campaign's missions, which require extensive operational ranges and efficient operation of the tilt-wing aircraft. Since the aircraft has higher energy consumption in thrust-borne flight states compared to wing-borne states [8], reducing flight time in the inefficient regions of the flight envelope is recommended. Highly dynamic operation enhances flight performance by enabling quick transitions between thrust-borne and wing-borne states. Thus, operational dynamics prioritize efficient approach and departure of the aircraft to maximize its flight range.

For the BVLOS flight campaign, operational safety is of utmost importance as the aircraft's safety concept must minimize ground risks and avoid endangering populated areas. The safety requirements are categorized into two groups. On one hand, safety protocols for managing software and hardware malfunctions are essential. On the other hand, it is necessary to address environmental factors to guarantee safe operation of the aircraft.

Safe operation of the tilt-wing aircraft requires properly functioning hardware and software to avoid uncontrolled flight states and ensure smooth operation. It is essential to maintain reliable hardware and software for the safe operation of the tilt-wing aircraft. If any component fails, the aircraft must be designed to respond accordingly. Examples of hardware failures include failures in individual control surfaces or servo actuators, propulsion system failures, sensor failures or failures in the accumulator. Additionally, the safety concept must also be equipped to handle diverse failure cases on the software side. The focus lies on managing failures in trajectory planning and control, as such failures can lead to leaving the flight area in case of an emergency, which poses a significant risk to the ground and should be cautiously avoided. Staying in the permitted flight area is also required in order to comply with the operating permit of the tilt-wing aircraft.

Lastly, environmental factors require additional considerations for the safety concept. General aviation aircraft, gliders, paragliders and rescue helicopters, may enter the flight area, posing a risk to planned operations. Dealing with intruders is crucial and must be included in the safety concept [9]. To interact with intruders safely, the detection of other aircraft is essential, alongside safety functions that can prevent conflicts.

The complex requirements of the tilt-wing aircraft pose a considerable challenge in terms of technological and control solutions for safe and efficient operation. The safety concept, in particular, demands careful attention. The successful realization of the BVLOS campaign in Saxony hinges on a flight state control system with an architecture that aligns with the safety concept to meet the multifaceted requirements.

3 Flight Control Architecture

The primary objective of the flight state controller for the tilt-wing aircraft is to control and stabilize specified flight states throughout the flight envelope while achieving necessary accelerations [4, 5, 10]. The controller operates across the whole speed range of the aircraft, in both horizontal and vertical directions.

In the subsequent section the structure of the flight state controller, including its distinct components and interfaces is outlined. To manage the large speed range of the tilt-wing aircraft, a gain scheduling approach is implemented in terms of control technology. The approach means that the components are designed depending on the operating point (OP). [11–15]. In this instance, scheduling is carried out solely based on longitudinal motion, which is dependent on the aerodynamic horizontal and vertical velocity [4]. Figure 1 illustrates the architecture of the flight state controller.

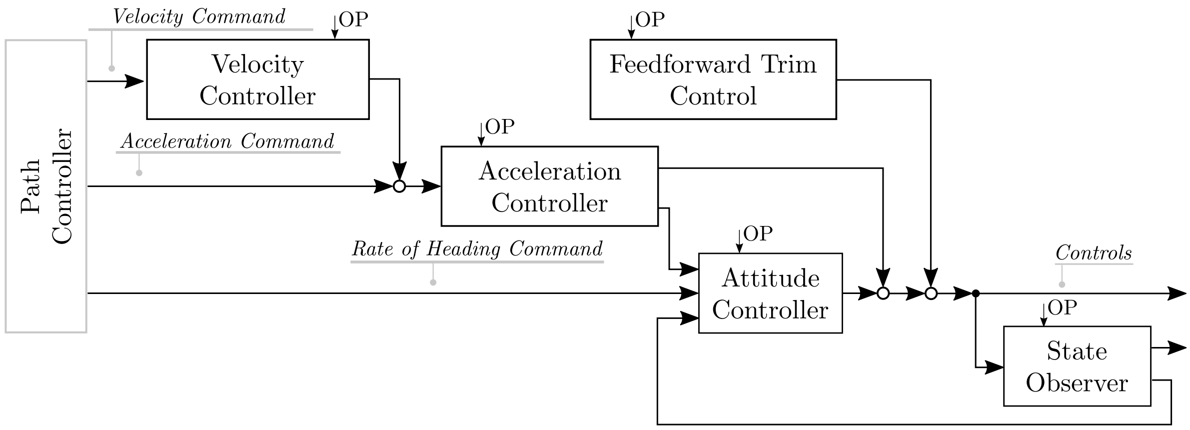

Fig. 1 Architecture of the Flight State Controller

The flight state controller's input variables are determined by the higher-level trajectory control, as outlined in [3]. This specification dictates the reference variables in the form of a flight state, defined by the aerodynamic speeds in the horizontal system and the associated accelerations. Additionally, for coordinated curve behavior, the lateral acceleration and rate of change of direction are specified. The output variables of the flight state controller are the control variables of the til-wing aircraft.

The flight state controller has been separated into attitude and velocity control, as figure 1 shows, and represents an established structure for tilt-wing aircraft [4, 5, 12, 16]. The flight state controller's control variables comprise a superposition of control variables from both the attitude controller and feedforward trim controls. The attitude controller controls the necessary attitude angles $\vec{\omega}_c = (\Phi_c, \Theta_c, \Psi_c)^T$, which are specified by the acceleration controller. Additionally, a reduced state observer from [17] estimates unmeasurable states for full state feedback. The acceleration control comprises the acceleration command from the trajectory controller and the command from the velocity controller. The velocity controller manages the aerodynamic velocities specified by the path controller and provides accelerations to compensate for any deviations.

3.1 Velocity and Acceleration Controller

The aim of the velocity controller is to follow the translational flight state that is computed by the trajectory controller via the horizontal speed $u^h_{a,c}$ and vertical speed $w^h_{a,c}$. Any divergence from the intended flight state that is caused by disturbances or errors in the velocity and vertical rate models is adjusted. The velocity controller consists of two PI regulators for both horizontal and vertical airspeed. The control component issues translational corrective accelerations, which are then passed on to the acceleration unit.

Acceleration unit comprises two main components. Firstly, the acceleration unit converts the commanded lateral acceleration into curved flight by using curve coordination. Secondly, a control allocation takes place, which translates the required accelerations into controls [5]. Lateral accelerations in the tilt-wing aircraft can be transformed by turning the lift vector, which establishes a bank angle [4]. The control allocation is the second component of the acceleration control system. It serves to distribute the necessary acceleration to the control variables and regulates the pitch angle input, which acts as a command variable for the attitude control.

3.2 Attitude Controller

The objective of attitude control is to stabilize the aircraft's attitude. However, the act of feed-forwarding trim controls alone via gain scheduling does not guarantee that the flight state will remain near the operating point. Deviations caused by external disturbances, such as wind turbulence, along with model inaccuracies in controller design, are compensated by the attitude control [5].

The attitude control's commands comprise the roll and pitch angle from the acceleration unit and the rate of change of the azimuth from the path controller. The longitudinal and lateral motion of the tilt-wing aircraft require separate attitude control designs. A multivariable controller utilizing the LQR approach was chosen for attitude control, designed based on trim points [6].

To ensure correct reference tracking in tilt-wing aircraft attitude control, relying solely on proportional feedback is inadequate. Thus, [18] recommends combining state feedback with integrating feedback. This involves providing feedback on the integrals of the attitude angles, as depicted in Figure 2 and implemented in the LQR position controller structure. The design of the attitude control and the

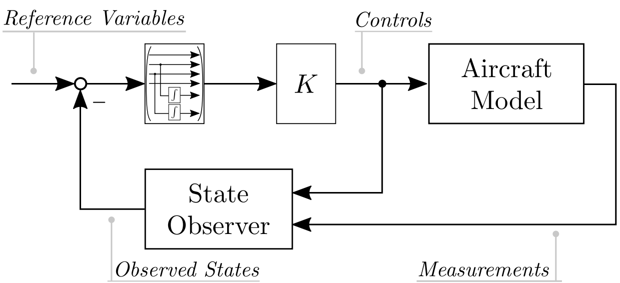

Fig. 2 Structure of the attitude controller

determination of an optimized trim path is described in [6].

4 Safety Concept

The aim of the safety concept is to respond appropriately to failure cases, allowing safe continuation of flight and the ability to initiate an abortion of flight missions with a landing at a previously defined safety point. The main focus is on reducing ground risk associated with the aircraft and avoiding personal injury or damage to property during flight or on the ground. As outlined in [2], safety functions can be activated autonomously through a communication channel by a remote pilot, or manually by a safety pilot. The developed control architecture provides interfaces and options to respond appropriately to various failure scenarios. Firstly, an overview of the safety concept's escalation stages is presented, demonstrating how the safety functions are arranged hierarchically. Subsequently, the safety functions are discussed in further detail.

4.1 Overview

The safety concept aims to minimize the number of safety functions needed for all possible failure cases, instead of implementing separate safety functions for each case. The figure displays all safety functions categorized by escalation stages.

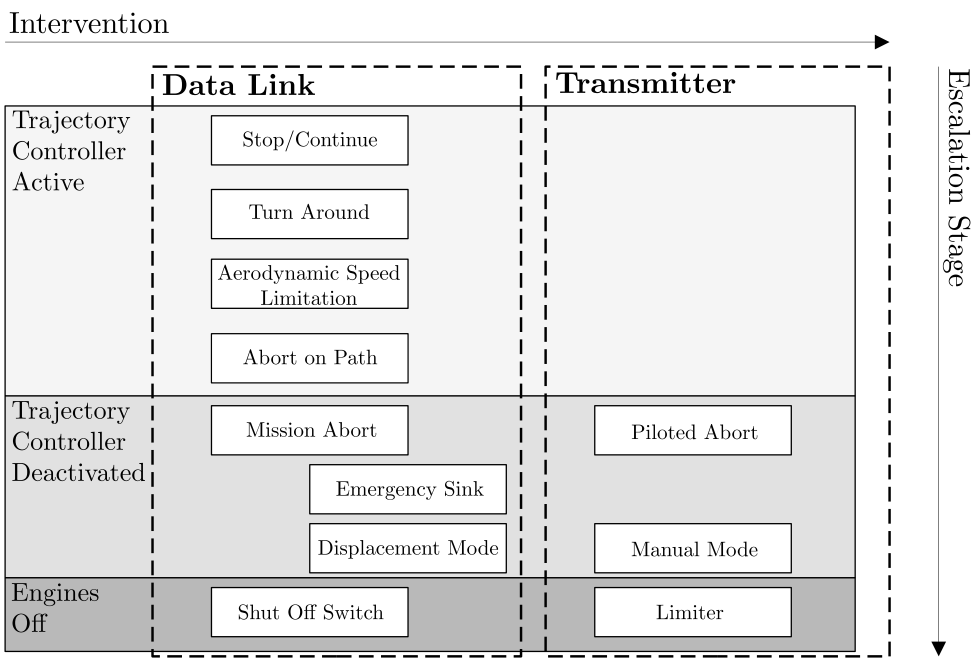

Fig. 3 Safety functions in different escalation stages

The safety functions in figure 3 are assigned according to intervention possibilities through the data link and safety pilot transmitter. The figure also shows which control components are active within each safety functions. It is important that further escalation of the safety functions is also possible at any time.

4.2 Safety Function

The subsequent sections present safety functions separately. These include safety functions that enable the flight mission to proceed under specified limitations. Before discussing aborting the mission without a trajectory controller specifically with a constricted flight control system, it is described how the flight mission with an active trajectory controller is aborted. Lastly, manual intervention by a safety pilot and immediate aircraft shutdown is examined. The safety functions are structured in the following five different categories and are addressed separately.

- Continuation of flight mission with restrictions
- Abort flight mission with trajectory controller
- Abort flight mission without trajectory controller
- Intervene with safety pilot
- Aircraft shut down

4.2.1 Continuation of Flight Mission with Restrictions

There are three safety functions for continuing the flight mission under certain restrictions.

4.2.1.1 Stop/Continue

This safety function operates at the highest level of the cascaded controller structure in which the trajectory controller is active. Via the data link, an intervention in the planned mission can be carried out. This safety function commands the trajectory controller to decelerate and hover for a pre-defined time without leaving the planned trajectory. Subsequently, the aircraft can continue the flight mission as planned. Within the safety protocol, a pre-defined time interval is implemented to automatically resume the flight and elicit an automatic response from the aircraft in cases of communication loss.

This safety feature is particularly important in situations where intruders cross the planned flight path, as it can prevent a collision. Furthermore, in situations where multiple aircraft are approaching the same landing position in parallel, this feature can be utilized to correct any potentially dangerous closeness between them during approach.

4.2.1.2 Turn Around

With this safety function, the intended flight mission is not fully executed as planned. Instead, intervention via the data link triggers a procedure whereby the aircraft will decelerate, turn-around and fly the previously flown route in opposite direction to return to the take-off position, while the trajectory controller remains active.

This safety feature is important for intruders when the duration of the planned flight route's inaccessibility is uncertain. Such a situation may arise e.g. when another aircraft, such as a rescue helicopter, intersects the flight area of the tilt-wing aircraft's planned mission. Furthermore, this functionality can be used if it is expected that the intended flight operation may not be completed in its entirety and a full return to the take-off location is feasible, thereby negating the need for the aircraft to land at an unsupervised safety point.

4.2.1.3 Aerodynamic Speed Limitation

This safety feature restricts the commanded airspeed of the active path controller. Consequently, the flight mission can proceed along the designated route at a reduced aerodynamic speed. The primary objective of this function is to facilitate a switch to the thrust-borne flight category.

Examples of this safety function's practical application include scenarios where elevators or rudders fail. A transition into thrust-borne flight changes the configuration of the tilt-wing aircraft. As a result, the flight controller allocates a different set of control devices. This way, failed actuators in wing-borne flight may no longer be needed at lower airspeeds and a safe continuation of the mission is possible.

4.2.2 Abort Flight Mission with Trajectory Controller

There is a safety function that aborts the flight mission and initiates a landing at a safety point.

4.2.2.1 Abort on Path

The trajectory controller stays active and initiates an abort of the flight mission to land at a pre-defined safety point due to this safety function, which is triggered via the data link. The safety points can be located on or close to the flight path. If the safety point is positioned close to the flight path, the closest point on the flight path from the safety point is calculated. This calculation is done pre-flight. The trajectory controller will guide the aircraft to this point and hover there, without leaving the initial planned flight route. Subsequently, the aircraft will perform automatic landing at the safety point. The safety point, defined near the flight path beforehand, is approached from hover with a position controller.

This function for ensuring safety is activated when a controlled landing at a designated safety point is appropriate, particularly in circumstances where the remaining battery capacity is inadequate to complete the flight mission and a turnaround is no longer an option or battery abnormalities occur.

4.2.3 *Abort Flight Mission without Trajectory Controller*

There are three safety functions that abort the flight mission without using the trajectory controller.

4.2.3.1 Mission Abort

The safety function is activated by the remote pilot through the data link, leading to degradation of the trajectory controller and terminating the flight mission. Upon activation, the aircraft experiences an immediate deceleration on a straight path of the current heading and ascends to a pre-defined safety height. Subsequently, executing the safety function may cause deviation from the scheduled flight path, resulting in the possibility of the permissible flight area being breached. The deceleration continues until hover flight is attained. The aircraft is then flown from the hover state using a simple straight line path controller to the closest safety point. Throughout, the aerodynamic speed is restricted to $V_A = 16\,\mathrm{m\,s^{-1}}$ to ensure thrust-borne flight. Once the safety point is reached at a safe altitude, an automatic landing is executed.

If any failure occurs in the higher-level trajectory controller, this safety function at lower level ensures a safe landing at the closest safety point.

4.2.3.2 Emergency Sink

This safety function is enabled and is only accessible from within *Mission Abort* mode described in the previous section. It can also be activated by the remote pilot, and it accesses a degraded flight state controller. The function commands an abrupt deceleration to hover when it is activated. After decelerating, the aircraft immediately begins its descent for landing.

This safety feature is particularly important when the battery is running low and an emergency landing must be performed immediately. Additionally, this feature enables the remote pilot to perform the fastest possible automatic landing. The aircraft will land at the current hover location, which may not necessarily be a safe landing position. This increases the risk of landing on unsafe ground since no verification of a reasonable landing area is available.

4.2.3.3 Displacement Mode

The *Displacement Mode* function is accessible only from within *Emergency Sink* mode. The *Displacement Mode* is in place to enable the remote pilot to alter the aircraft's position in emergency situations. For this purpose, the remote pilot can change position incrementally via data link. Within the safety function, once the *Displacement Mode* is engaged, the descent stops, and the current flight altitude is sustained until the remote pilot's designated endpoint is reached. Following this, the *Emergency Sink* mode is initiated for an emergency landing.

This safety feature allows the remote pilot to change position during an emergency landing if it is evident from the available mapping data that the location does not provide a suitable emergency landing site due to obstacles or underground with streets or lakes.

4.2.4 *Intervene with Safety Pilot*

The safety pilot can activate safety functions in two ways, as detailed below. These functions are only accessible if the transmitter has connection to the aircraft.

4.2.4.1 Piloted Abort

When triggered, this safety function automatically decelerates the aircraft on a straight line of the current direction until it reaches hovering position, similar to that of *Mission Abort*. While decelerating, the safety pilot can manipulate the altitude of the aircraft through the transmitter. Once the hovering position is established, the safety pilot takes control of the aircraft and can alter both altitude and positioning via the transmitter. One notable aspect is that if the transmitter and aircraft lose connection, the system will automatically enter *Mission Abort* mode, enabling an emergency landing to occur autonomously.

This safety function allows the safety pilot to take control of the tilt-wing aircraft near the take-off and landing position and perform a manual safety landing.

4.2.4.2 Manual Mode

This safety function is the most limited intervention option available to the safety pilot. Upon activation, all control components except the attitude control are degraded, and therefore no automatic position control is available. The function does not use any wind estimate of the aircraft and thus requires the pilot to manually turn the aircraft into the wind. Additionally, the safety pilot commands the aircraft's attitude angle and aerodynamic horizontal speed directly via transmitter for positioning.

This function, representing the most basic and degraded mode of the controller, is used exclusively to bring the aircraft to the ground in a controlled manner and prevent further damage.

4.2.5 Aircraft Shut Down

The ultimate level of escalation is the immediate shutdown of the aircraft.

4.2.5.1 Shut Off Switch and Limiter

This safety feature is only activated in the case of an extreme emergency and leads to an immediate power down of all engines. If this feature is activated during flight, it forces an uncontrolled crash of the aircraft, posing an extremely high ground risk. This safety function can be initiated using two methods. For one, a password pretected shut off command can be sent via data link, which will turn down the engines immediately. Additionally, the safety pilot can always force a shutdown via the transmitter when it is connected to the aircraft. Both alternatives are easily accessible as long as the communication path persists.

This safety function was included in the safety plan to allow the termination of a flight in the case of a fly-away situation, or if the engines or propellers pose risks to individuals. It is imperative to switch off the aircraft right away to prevent harm to property or people.

5 Operational BVLOS Flight

During the flight campaign in Saxony, Germany, four tilt-wing aircraft conducted 290 flight missions, totaling 140 hours of flight time, without any incidents [1]. Further analysis of the flight campaign incidents will provide a more detailed evaluation of the developed flight control architecture and the associated safety concept. During the flight campaign, three elevator malfunctions were experienced in wing-borne flight of the tilt-wing aircraft, leading to safe landings at pre-defined safety points. Additionally, two incidents of responding to intruders were documented and successfully avoided conflicts using the turn around safety feature. Finally, the *Stop/Continue* safety function was employed twice to correct the stagger of approaching aircraft.

5.1 Elevator Failure

The following section outlines the scenario of an elevator failure, derived from flight data collected during the flight campaign. The tilt-wing aircraft experienced unexpected flight behavior, necessitating activation of the *Abort on Path* system along with the *Aerodynamic Speed Limitation* safety function. These controls enabled the aircraft to fly to the next safety point within the flight mission while restricting the aerodynamic speed to $18\,\mathrm{m\,s^{-1}}$. The flight path executed after the safety function was activated is depicted in Figure 4, illustrating the corresponding flight mission. The presented reaction to the

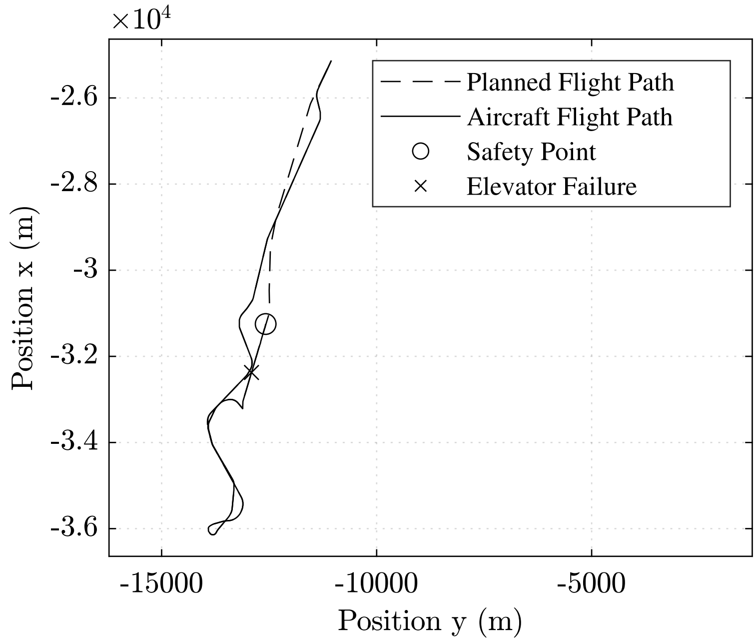

Fig. 4 Approach of a safety point due to elevator failure

flight behaviour illustrated in Figure 5 was fitting. A clear, unmistakable oscillation was apparent in the pitching movement, signifying an issue with the pitch control. The aerodynamic speed limitation aimed to transition the aircraft from an wing-based flight state to a thrust-based flight state, resulting in a distinct pitch control allocation that excluded elevator use. In Figure 5, it is evident that the occurrence of a one-sided elevator failure not only induced an oscillatory behavior in the pitch angle but also introduced a slight oscillation in the bank angle. Moreover, this specific failure scenario resulted in a marginal reduction in altitude, although the aircraft promptly regained and maintained its altitude. Following the implementation of restrictions on the aerodynamic speed, it can be observed that the oscillations in both the roll and pitch axes were successfully attenuated, ultimately restoring a state of safe and controlled flight. Consequently, the pre-defined safety landing location was approached, and a meticulously executed safe landing procedure was carried out.

5.2 Conflict Avoidance due to Intruder

During the flight campaign, two scenarios occurred in which the aircraft avoided a conflict with rescue helicopters by aborting the flight mission by activating the *Turn Around* safety function. Figure 6 shows the scenario. Since the rescue helicopter was flying at low altitude in the region during the mission and crossed the planned flight mission at a distance less than the pre-defined safety distance, the *Turn Around* safety function was activated. Subsequently, the aircraft decelerated to a hover flight state and flew the previously flown flight path back to the take-off position. Since it was not possible to predict how long the rescue helicopter would be in the area of the planned flight mission, the *Stop/Continue* safety function was not an option. Instead, the entire flight region was conservatively cleared for the rescue helicopter to completely avoid a conflict between the tilt-wing aircraft and the helicopter.

6 Conclusion

In this paper, a flight control architecture with an integrated safety concept for a BVLOS use case which achieved safe operation during the largest BVLOS flight campaign in Saxony, Germany, is presented. First, the requirements for the flight state controller as well as the safety concept were

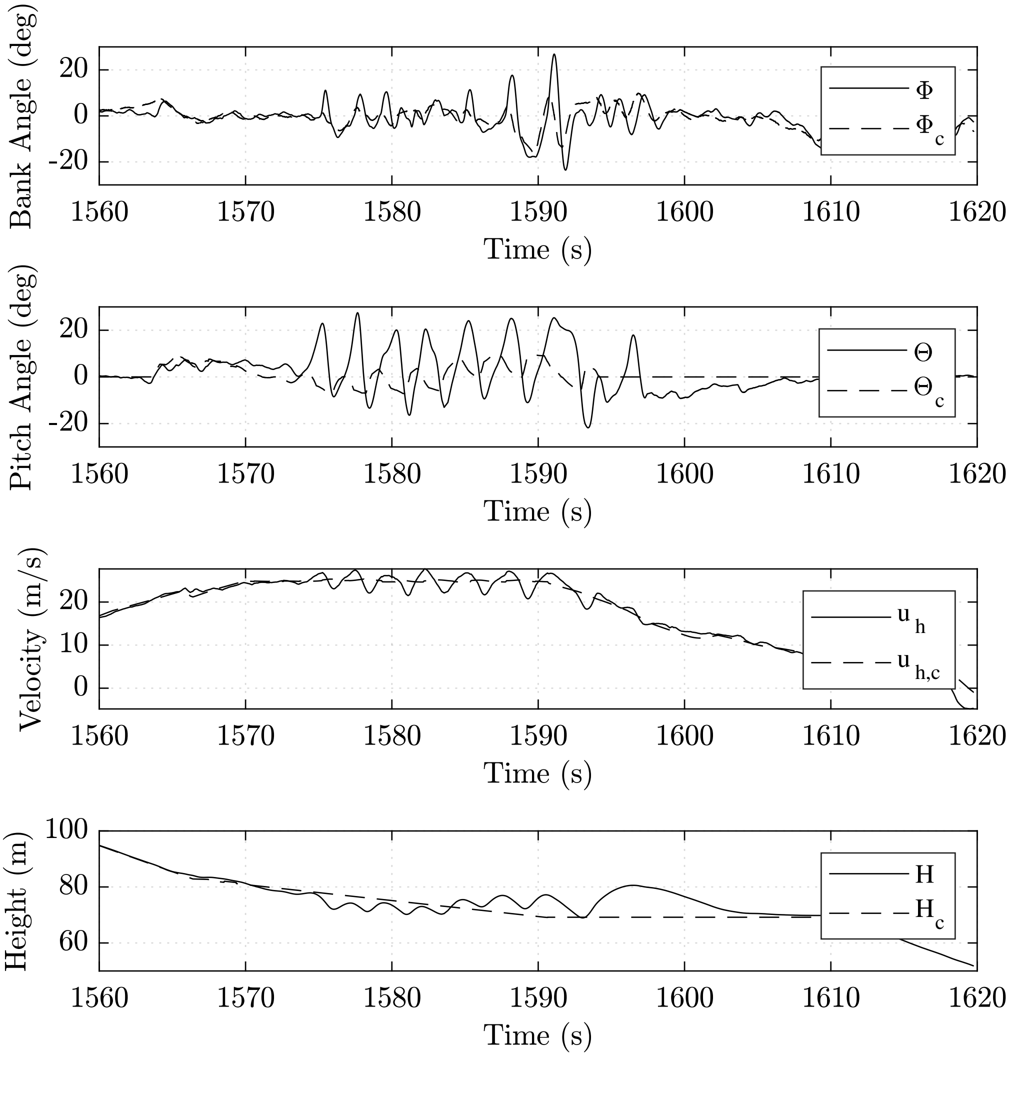

Fig. 5 Flight Data from Elevator Failure

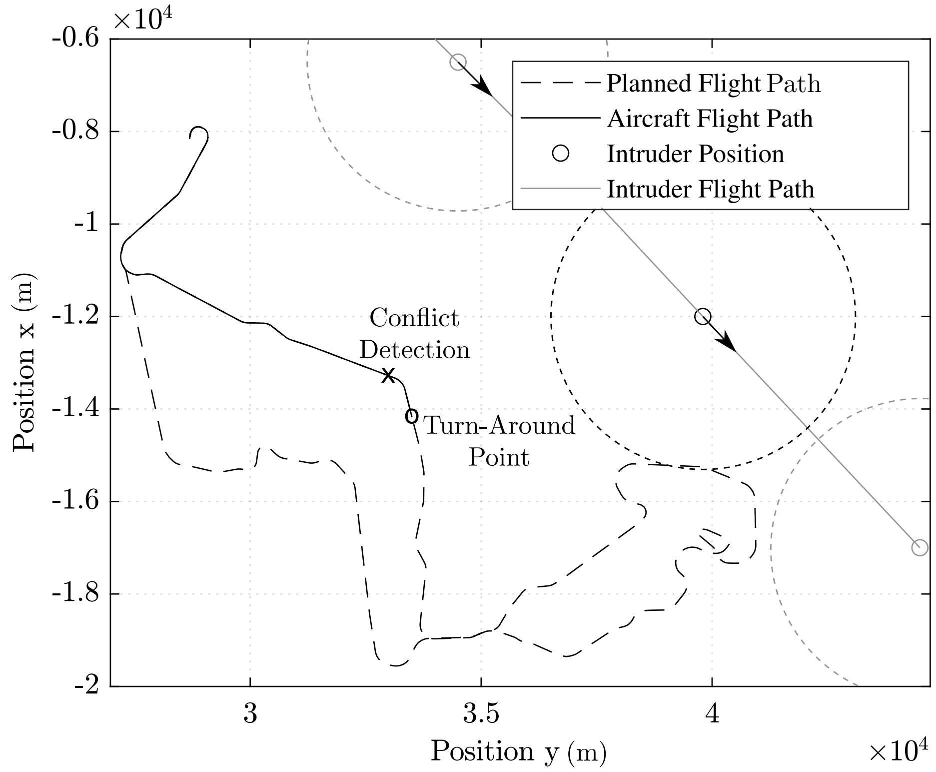

Fig. 6 Conflict Avoidance with *Turn Around*

derived. Then the architecture of the flight state controller was developed and combined with the safety concept. The flight state controller has a cascaded structure, which consists of an LQR-based attitude controller and a separate velocity controller. This architecture provides the foundation for the developed safety concept. It gives the remote pilot as well as the safety pilot the possibility to intervene in the planned mission and permits that individual control components can be degraded in a specific emergency situation. The safety concept creates different intervention options to be able to enable safety functions, which are hierarchically structured into individual escalation stages. For this purpose, a suitable set of safety function was implemented, which could handle failure cases and achieved safe operation during the campaign. The functionality was successfully demonstrated during the campaign for both the elevator failure and the handling of intruders.

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