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Near-Term Flight Path Adaption for Tilt-Wing Aircraft Obstacle Avoidance

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Abstract Current research projects within RWTH Aachen University investigate unmanned tilt-wing applications to support rescue forces within rescue missions. To meet the practical challenges of such missions, integration into civil airspace and along with it avoidance of obstacles is necessary. Consequently, the flight path planning requires adjustments during flight to perform obstacle avoidance maneuvering. As obstacles are typically detected on short notice the flight path needs to be adapted in the near term. This work describes the generation of near-term horizontal avoidance paths that satisfy all flight dynamic constraints of a tilt-wing aircraft: Due to the tilt-wing's significant airspeed variation from hover to fast forward flight these constraints depend on the current flight speed and need to be adapted to the current flight situation. For avoidance path generation varying flight dynamic constraints are explicitly considered and estimated during flight. The paper presents a geometric approach for avoidance of static obstacles during any flight phase. This approach and the interaction between flight path controller, estimation of constraints and the path generation are discussed in detail. The overall flight guidance system was evaluated by simulations of selected mission scenarios. Simulation results indicate good performance and applicability of the overall system.

1 Introduction

Tilt-wing aircraft are characterized by their ability to perform efficient high-speed cruise flight as well as hover flight, also enabling vertical take-off and landing (VTOL). Therefore, the hybrid tilt-wing configuration combines the advantages of the fixed-wing configuration and the rotary-wing configuration. Due to these advantages, a tilt-wing aircraft was chosen for the research project "FALKE" [2] that

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focuses on the support of rescue forces. The development of the utilized tilt-wing aircraft is presented in [9]. An outline of the ”FALKE” project is shown in Figure 1.

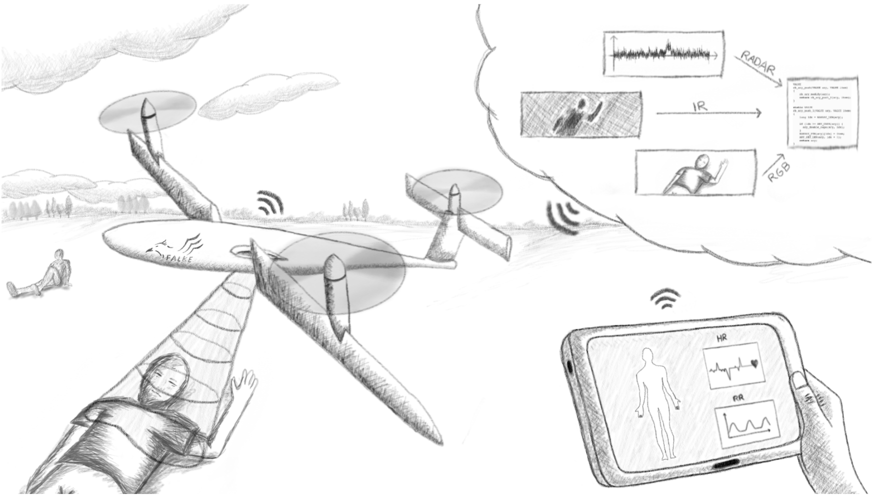

Fig. 1 FALKE mission scenario

Within this project, the aircraft is used to gather information about a mass casualty incident focusing on the health condition of patients involved. These tasks lead to various requirements on the flight guidance system. A challenging fact is that the flight mission is not pre-plannable. The mission changes constantly during flight e.g. by the scene coordinator requesting for a repeated analysis of a distinct patient. Another challenge for the flight guidance system is the integration of the used tilt-wing aircraft into civil airspace. To also enable a full integration of the aircraft at the area of operation during a rescue mission the aircraft needs to avoid collisions with obstacles, e.g. light towers that are needed for the rescue mission. The existing flight path needs to be adjusted in order to avoid obstacles without neglecting flight dynamic constraints. These constraints arise out of the current flight speed which is not feasible with all turn radii. Aside from satisfying flight dynamic constraints, it is important that the adjusted flight path proceeds in close proximity to the previously planned path in order to minimize information loss about the current rescue mission. This paper will focus on the implementation of an obstacle avoidance method in order to fulfill the requirements mentioned above.

Various methods for collision avoidance systems are described in literature. In general, they are categorized into sensing and detection and into collision avoidance maneuvering. One sensing method to obtain information about obstacles is using sensor systems, e.g. cameras or radars [8, 1]. After detecting an obstacle, the collision avoidance system needs to determine if there can be the possibility of an upcoming collision. In literature, various different collision detection approaches are presented. Most commonly used approaches are trajectory calculation and distance estimation. In those approaches, collision is considered to occur if the distance between the aircraft and an obstacle is lower than a given threshold [11, 7] . With these information about obstacles and collision detection results, a maneuver path needs to be applied in order to ensure that the obstacle will be avoided. In contrast to preplanned flight paths, replanning methods use simple formulas to react in the near term in order to hold low demanding computational resources. Two most commonly applied methods are potential field methods and geometrical approaches. The former methods utilize forces that either push the aircraft away from an imminent obstacle or attract it toward a predefined target [3]. The latter methods deal with information about among others location, velocity and heading of the aircraft and obstacle and then calculates a maneuver trajectory based on a limited set of geometrical elements [10].

Within this paper, a geometrical approach is proposed due to its low demand for computational resources as well as its deterministic computation. The difficulty consists in applying this approach on a tilt-wing aircraft with its wide range of speed, wherefore flight dynamic constraints play a significant role. Since an avoidance in vertical direction is often not sensible, considering the low possible rates of climb and descent of the tilt-wing aircraft in comparison to those in the horizontal plane, the geometrical collision avoidance is presented on 2D paths.

Section 2 presents the structure of the flight guidance system which enables obstacle avoidance. Here, the focus is laid on the interaction between the path planning and the path controller which imposes flight path constraints. Methods for collision avoidance path calculation are described in section 3. There validation in mission scenarios is presented in section 4.

2 Architecture for Tilt-Wing Obstacle Avoidance System

In this section, the environment for the collision avoidance system is described in detail. First, the architecture of the flight guidance system is presented, that is necessary to enable on-board path replanning. Then the interaction of the path controller and the path planning is described, which is indispensable, since the path controller provides flight dynamic constraints that need to be satisfied by the path planner. In the end, the collision detection is presented.

2.1 Structure of Flight Guidance System

The flight guidance system (see Figure 2) consists of various components that are arranged in a cascading structure with the flight management component ”Mission Control” at the outer layer and the aircraft at the inner layer.

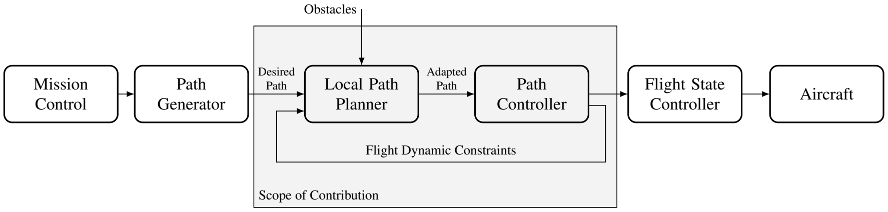

Fig. 2 Flight guidance system

The mission control is a state machine connected to a user. It schedules different kinds of flight tasks, needed for a rescue mission like exploring an unknown area or heading to certain patients to obtain information about their health condition. The user is always allowed to add or delete flight tasks or to change its order. The current flight operation is passed from the mission control to the following component with the name ”Path Generator”. In this component, the flight task information is transformed in the desired flight path, which consists of straight line and circular segments. The generated path remains unchanged until a change in the flight task is detected. In this case, the path needs to be changed in strict accordance with flight dynamic constraints. The aim of the following component ”Local Path Planner” which obtains the previously generated path is to adapt the path in order to avoid upcoming obstacles and proceed in close proximity to the previous path. The new adjusted path is generated due to information on upcoming obstacles from sensors as well as path constraints that are provided by the following component, named ”Path Controller”. The path controller calculates path constraints, e.g. minimum turn radius and passes them to the path planning components. The last controller component with the name ”Flight State Controller” provides control surface deflections being necessary to capture the commanded acceleration values and passes them on the aircraft.

2.2 Flight Path Constraints

Flight Dynamic Constraints Requiring Flight State Planning

In general, planning a flight path for an aircraft requires consideration of flight dynamic constraints. At first sight, the constraints for tilt-wing aircraft are very relaxed. Due to the tilt-wing’s ability to perform hover flight, which is a flight state with almost zero velocity with respect to ground, it is possible to follow an arbitrarily shaped flight path. This is different from fixed-wing aircraft. The minimum possible air-speed of fixed-wing aircraft and a maximum magnitude of possible lateral acceleration (or maximum bank angle, respectively) define geometric constraints on the flight path, e.g. a minimum turn radius. For tilt-wing aircraft, the same holds true if the flight is performed with higher velocities compared to hover flight. Of course, higher flight speeds are desired in general because of mission requirements and because wing-borne fast forward flight has a much better energy-efficiency than that of thrust-borne hover flight. Hence, flight path planning for tilt-wing aircraft has to consider constraints as well.

As this contribution looks at horizontal flight path planning only, the following explanation focusses on the minimum turning radius constraint. When taking into account a constant limiting value of bank angle or lateral acceleration, the minimum radius increases with increasing forward speed. A similar dependency can be found for other dynamic constraints like the maximum heading's rate of change. That is why local flight path geometry limits the maximum speed locally. Additionally, while moving along the flight path, the speed along the path may change. This speed gradient should be limited because a change of speed along the track implies a change of corresponding flight states. This flight state change has to satisfy constraints, too.

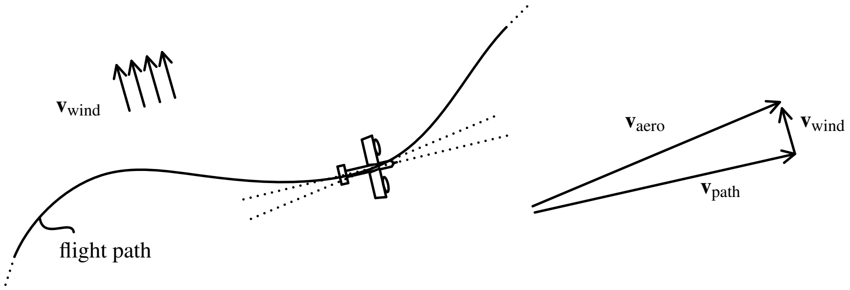

Fig. 3 Correspondence between different speeds during flight along path [6]

Provided that the angle of sideslip is negligible and the aircraft follows a flight path, there is a relation between the inertial speed along the path and the flight state, which is dependent on the local flight path geometry and the current wind situation (compare Figure 3). For fixed-wing aircraft, presuming that the average wind speed is always much smaller than the average airspeed, small changes of the speed along the path lead to small changes of the corresponding flight state only. During the flight of a tilt-wing aircraft, airspeed or speed along the path may be of the same magnitude as wind speed. Thus, small alterations in speed along the path may require extensive flight state modifications. Figure 4 shows an example situation. The aircraft follows a linear flight path from left to right. In the situation shown left, it maintains a speed along the path that is only marginally below the wind speed. Therefore, its heading directs against the wind direction and airspeed is low. In the situation shown on the right, the speed along the path is only slightly different, a bit higher than the wind speed, and the heading has changed by 180°. Such flight state changes are typical for low-speed maneuvering of tilt-wing aircraft and have been discussed in detail in [4]. As possible rates of flight state change are limited (see [5]), these changes must be considered for flight path control. The flight path controller needs to plan the future speed along the path to allow sufficient time for extensive flight state changes. As the correspondence between speed along the path and flight state is dependent on the wind situation, this planning cannot be performed pre-flight but has to be performed during flight. Please note that this speed planning should not be confused with planning the flight path geometry.

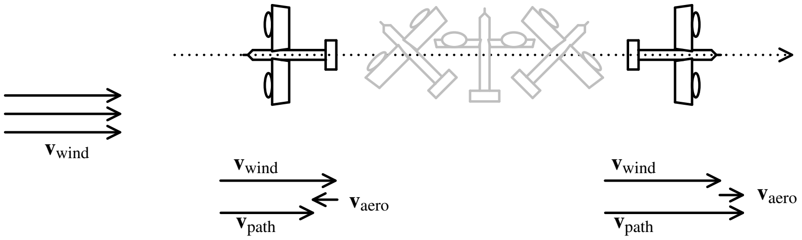

Fig. 4 Small changes of speed along path results in significant flight state change [6]

Path Controller with Speed Planning

To perform the speed planning during flight, advanced flight path controllers for tilt-wing aircraft utilize the concept of receding horizon control [6]. Within receding horizon control the future progress of speed along the path (or flight states, respectively) is optimized over a limited part of the upcoming flight path (planning horizon). Optimization starts at the current position, considers the current speed of the aircraft and ensures that the speed progress satisfies all dynamics constraints. Additionally, the optimization ensures that the flight is performed as fast as possible within the defined maximum allowed speeds. After optimization, the first part of the resulting progress of flight states is applied to the flight state controller. Subsequently, the optimization is repeated and reinitialized with the updated current position and speed of the aircraft. The majority of the previously planned flight states are discarded.

Repeated planning is necessary because the wind situation continuously changes during flight. Due to the stochastic nature of the atmosphere, these changes can-not be predicted. Each planning has to rely on the current wind situation. The speed planner has to react to changing wind by an updated planning. Nevertheless, each planning must take into account a larger portion of the upcoming flight path than covered by the traveled path during the update period. The planning algorithm must consider any upcoming path segment that requires slow speeds (e.g. small turn radii) and with that requires extensive flight state adjustments. On the contrary, it is not necessary to plan flight states for the overall upcoming flight path. Any segment that enters the planning horizon influences the planned flight states. Depending on the geometry of the flight path segment, this influence propagates from the end to the front of the planning horizon. The length of the horizon should be chosen such that the influence cannot reach the beginning of the horizon, which matches the current flight state. If the influence would reach the beginning, applying the updated planning would change the current flight state discontinuously, which is not possible. Depending on the expected maximum average wind speed, the maximum allowed airspeed and flight performance characteristics of the aircraft, e.g. maximum acceleration, the aircraft is always able to come to a stop within a limited amount of time or within a limited flight distance. If the length of the planning horizon equals this maximum stop distance, the influence of path segments entering the planning horizon is guaranteed not to reach the current flight state, because a full stop is the most influential speed change possible. According to this, the planning horizon in [6] has a length of 500 m.

Constraints on Flight Path Adjustments

As seen before, there are no general constraints on preflight flight path planning for tilt-wing aircraft. But path planning should be aware of dynamic constraints, if a higher speed is anticipated, e.g. provide sufficient turn radii during cruise flight.

If the flight path is modified during flight, for example on purpose of performing a collision avoidance maneuver, there are no additional constraints, as long as the flight path changes only affect parts of the flight path that are not covered by the current planning horizon and thus cannot affect the current flight state. However, depending on aircraft performance, intruder situation and safety margins initiation of the avoidance maneuver might be necessary within the horizon. If so, the adjusted flight path has to satisfy geometric constraints. The definition of these constraints is based on the same condition that was used for choosing the length of the planning horizon. Any flight path change within the horizon must not change the current flight state. One possibility to satisfy this constraint is to check the adjusted flight path in terms of an optimization run and correct the flight path adjustment iteratively, as long as the check fails. Due to limited computational resources, this contribution is based on another approach. As said before, geometric flight path constraints arise from the speed along the path. Therefore, the path controller calculates not only the nominal progress of speed that is used in nominal flight but also a second variant that reduces the upcoming speed along the path as fast as possible. The progress of that minimum speed along the path corresponds to minimum radii that are possible for the adjusted flight path. The minimum radius has its maximum value at the current aircraft position and reduces for more distant path segments. It reaches a value of zero at the latest in a distance that equals the length of the planning horizon. This progress of minimum radii defines the geometric constraints for adjusting the path within the horizon. A new flight path that exploits these constraints will lead to an immediate deceleration of the aircraft but not to a discontinuous flight state change. Because any flight path adjustment needs time to be calculated, the flight situation evolves between calculating the current path constraints and a flight path change becoming effective. Therefore, the decelerating variant of the speed planning assumes that deceleration does not start immediately but two seconds after the start time of planning. That allows for appropriate calculation time to plan an avoidance maneuver. Calculation of general-purpose constraints for path adjustments is not possible because constraints depend, like the speed planning itself, on the current wind situation.

2.3 Obstacle Detection

In this paper, we assume that sensors will acquire information about the surrounding environment during flight. Obstacles that may occur within the ”FALKE” mission are for example trees and light towers as used for rescue support. Detection of upcoming obstacles is not part of this work. Therefore, we assume that the position of an obstacle is always known within a certain distance to the current position of our aircraft.

3 Near-Term Path Adaption

All near-term path adjustments are performed by the local path planner. The desired path of the path generator only needs to be modified if a possible collision is detected. Therefore, the local path planner consists of a collision detector and a path replanner that is only enabled if a collision is detected. The structure of the local path planner can be seen in Figure 5. Hereafter the components are described in detail.

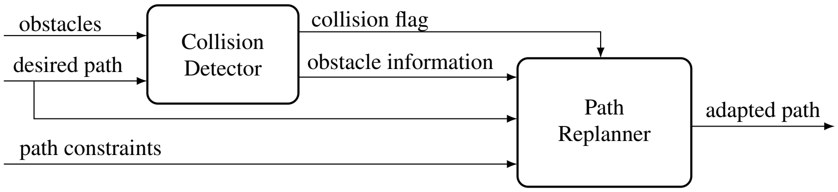

Fig. 5 Collision detection system

3.1 Conflict Geometry

Once information on an obstacle is received, it needs to be determined if there is an imminent collision. To perform this collision detection, trajectory calculation is used. First, the closest point of approach (CPA) and the shortest distance d between the obstacle and the flight path needs to be calculated for all upcoming path elements. The calculation method depends on the kind of element, which can be either straight or circular. The distance d of all upcoming elements is then compared with a predefined safety distance around the obstacle that forms a safety zone and should not be entered. If this distance is smaller than the safety radius, a collision is detected and an avoidance path needs to be initiated.

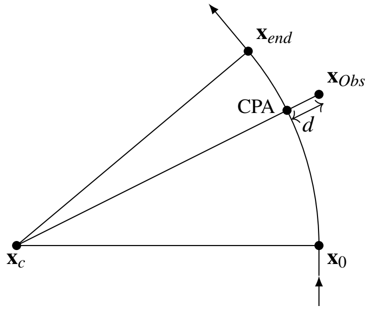

Fig. 6 Collision detection scheme on a circular element

3.2 Methods for Avoidance Path Generation

Before starting with avoidance strategies, we specify some chosen terminology. The position of the aircraft at the time of collision detection is called "detection position" and the first available position to start an avoidance path is called "earliest possible reaction position". The location where the desired path is left is called "actual reaction position" and the one where the desired path is reattached "reattaching position". The area around an obstacle, which has to be avoided, is the "safety zone". All terminology can be seen in Figure 7.

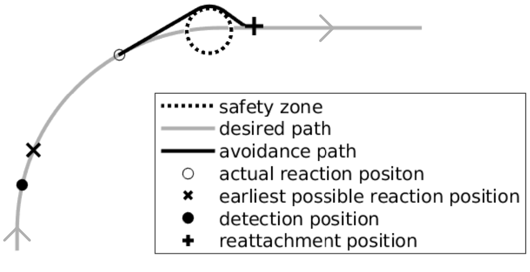

Fig. 7 Terminology for avoidance path generation

The type of elements, which can be either a straight line or circular, on which the actual reaction position is located, influences the avoidance path generation. The following sections describe methods for avoidance path generation depending on the type of element.

Avoidance Path Generation on Straight Elements

On straight elements, the actual reaction position is situated at the earliest possible reaction position and its curve radius is the minimum radius that is obtained from the path controller for the upcoming path (see Figure 8). From this curve, a tangent starting at $\mathbf{x}_1$ is built to the safety zone of the obstacle at $\mathbf{x}_2$. By then the created avoidance path consists of two elements, starting with a circular element and continuing with a straight element, that is tangent to the safety zone.

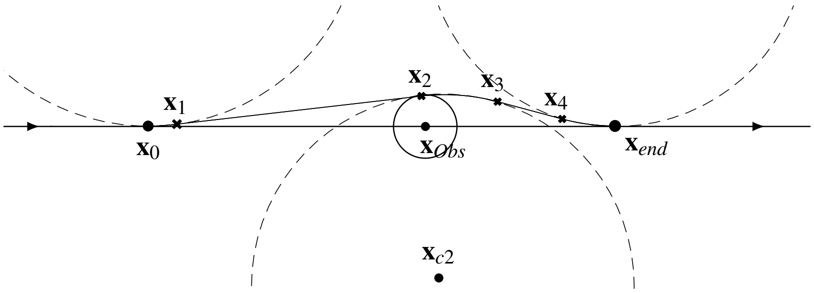

Fig. 8 Avoidance method on straight line element

Once the collision is avoided the aim is to proceed in close proximity to the previously planned path. Therefore, three more elements (two circular elements and one straight element in-between), need to be generated. The center of the second circle $\mathbf{x}_{c2}$ depends on the tangent point $\mathbf{x}_2$ and the obstacle position $\mathbf{x}_{Obs}$ such that we can ensure that the safety region is not entered. In order to reattach as early as possible to the previously planned path, the third and last circle is placed so that inner tangency with the second circle is possible. This is the case if the distance between $\mathbf{x}_{c2}$ and $\mathbf{x}_{c3}$ is greater than the sum of their radii. The completely calculated avoidance path on straight elements will consist of three circular and two straight elements.

Avoidance Path Generation on Circular Elements

Due to the first tangent to the safety region, the reaction position is determined. After having reached the tangency point $\mathbf{x}_2$, the method to reattach to the previous path is similar to the reattachment method on straight line elements. All tangent points can be seen in Figure 9. When examining the two last tangency points the reattachment is done on a circular element and the last element type of the avoidance path must be a straight line in order to accomplish tangency. Because of that, the last two points $\mathbf{x}_3$, and $\mathbf{x}_4$ delimit the line tangent to the curve of the original path where the avoidance path reattaches.

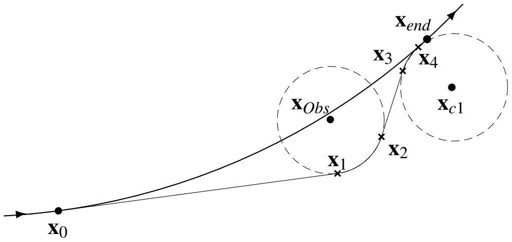

Fig. 9 Avoidance method on circular element

Avoidance Path Generation on Different Elements

It may occur that an avoidance maneuver starts on an element that differs to the one on that the avoidance path reattaches to. The left path in Figure 10 illustrates an avoidance path starting on a straight element and ending on a curve. In this case, for accomplishing a smooth reattachment to the previously planned path on the curve, the last element of the avoidance path needs to be a straight element tangent as well to the curve of the previous path as to the last circular element of the avoidance path. In Figure 10 on the right, the situation of actual reaction position beeing located on a circular element and the reattachment position on straight line element can be seen.

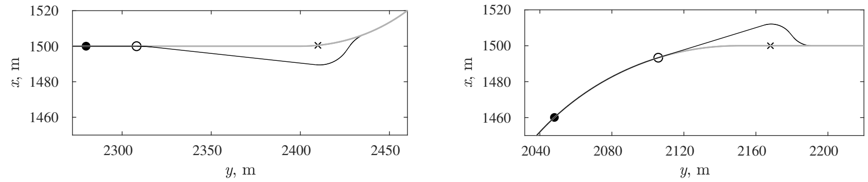

Fig. 10 Avoidance methods on different elements

As a collision may be detected at an aircraft position that is some elements away from the obstacle position, an immediately started avoidance maneuver would lead to a nonoptimal avoidance path since the avoidance path would differ more than necessary from the original (see Figure 11). Considering this, the new avoidance path will always start to be calculated on the first path element where the object is located. In the case of a not possible avoiding path, the calculation will be done for the previous element iteratively. Following this process, the last calculation corresponds to the case where the avoidance starts at the earliest possible reactive position.

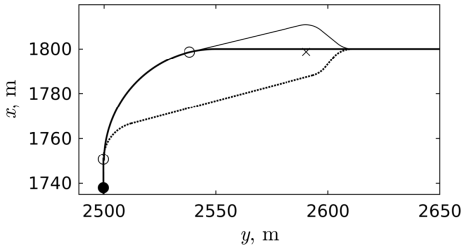

Fig. 11 Actual reaction position with various path elements between obstacle and detection position

4 Validation in Mission Scenario

The tilt-wing aircraft has the capability of low-speed flight. Hence, turns with small radii are feasible. As a result, a collision avoidance path can be generated, that is in close proximity to the desired path. To validate the feasibility of the presented avoidance system, two desired paths, representing two possible mission scenarios with various geometries are created (see Figure 12).

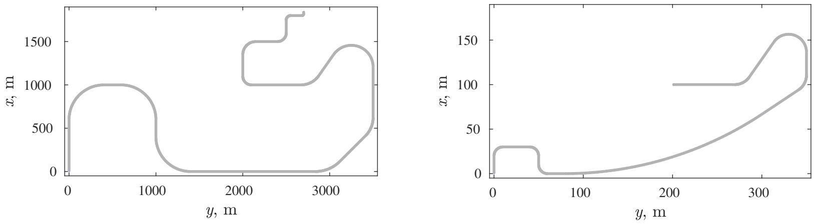

Fig. 12 Mission scenario path I and II

The first path taken into consideration includes a wide range of geometry features such as circular elements with various radii in a range from 2.5 m to 500 m and various segment lengths in a range from 45° to 140°. The different size of the geometric elements challenges the aircraft, demanding a wide speed range of the tilt-wing aircraft. Figure 13 shows the maximum possible velocity with respect to ground depending on the traveled distance. One plot is on the supposition that there is no wind. The other one considers wind, that has a mean speed of 5 m/s.

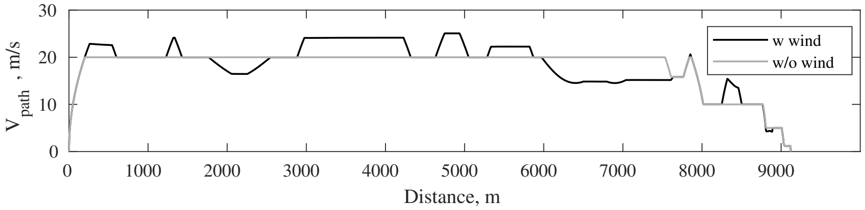

Fig. 13 Speed along mission scenario path I

Figure 14 shows three examples of planned future flight states for the horizon and constrains for path adjustments at various time steps. They obtain a travel distance along the path of 242 m, 881.2 m and 1501.5 m. The dotted line indicates the current flight state. The upper plot shows the resulting future progress of different speeds along the path. The solid black line indicates the resulting future progress of speed for the case that deceleration is initiated. The first possible deceleration starts 2 seconds after the current situation. The corresponding minimum radius at the moment of first deceleration corresponds with the current speed. It is indicated in the lower plot. After deceleration, the planned values decrease monotonously to a full stop or a radius of zero, respectively. The dashed line in the lower plot indicates the future progress of the planned radius without deceleration. The aircraft location at the considered time steps and the corresponding minimum turn radii in deceleration case can be seen in Figure 15.

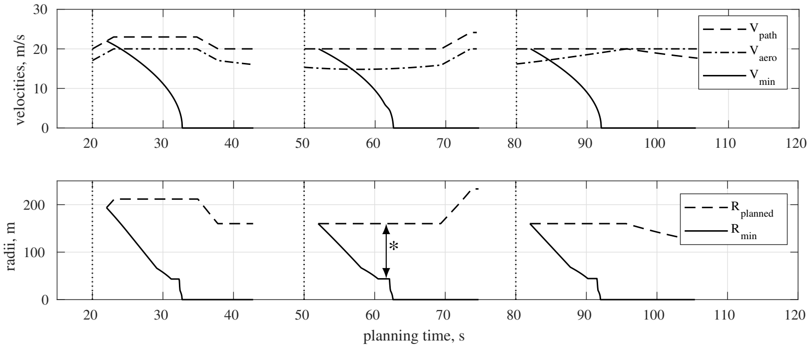

Fig. 14 Flight states and path constraints from path controller

With the aid of those constraints avoidance paths have been generated. We validated the feasibility of the obstacle avoidance system for the presented mission scenario paths by placing obstacles all over the two desired paths. Figure 16 shows

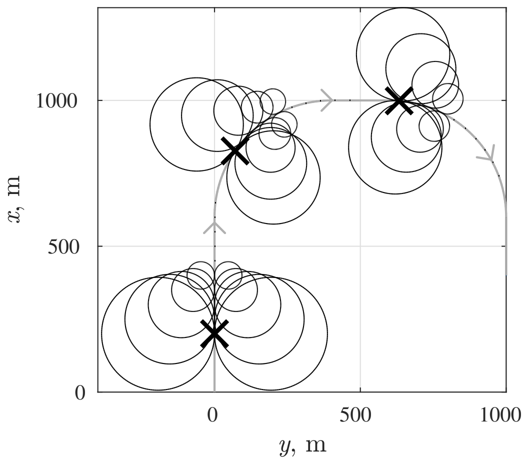

Fig. 15 Position of aircraft at considered time steps and minimum radii

some example avoidance paths for mission scenario path II, which presents in comparison to path I reduced element length and radii, demanding lower speeds.

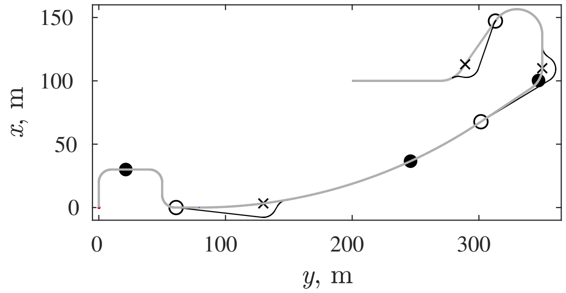

Fig. 16 Avoidance of obstacles on mission scenario path II

The application requires the aircraft to stay as close as possible to the desired path. Therefore all avoidance paths were designed, to reattach to the planned path as soon as possible. This requires a high deceleration from the first possible reaction position to the first tangent point of the safety zone. If energy efficiency and mission time should be considered as well, a weighting factor w can be introduced. Depending on this factor, the radii for reattachment can be determined. A greater radius increases the difference of desired and avoidance path but also reduces the necessary deceleration.

$$R_{reattach} = R_{min} + w \cdot \left(R_{planned} - R_{min}\right)$$
$$w = [0,1]$$

The difference between the future progress of the planned radius $R_{planned}$ and the minimum radius R_{min} can be extracted from the flight path controller, see the marker in Figure 14.

5 Conclusion

In the presented work, a method for horizontal collision avoidance for tilt-wing aircraft including its speed variation has been developed. The method is based on a geometrical approach. In order to implement obstacle avoidance, a flight guidance structure including a local path planner that adjusts a predefined desired path is presented. Those adjustments are subject to flight dynamic constraints that are provided by the path controller. The required constraints for the local path planner for collision avoidance are the minimum allowed radius without deceleration and the minimum allowed radius when starting deceleration immediately. With the help of those constraints, a feasible avoidance path is generated geometrically. The paths ensures not entering the safety zone around an obstacle and reattaching smoothly to the original path. The obstacle avoidance system is validated by showing its feasibility on two possible mission scenario paths.

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