

ASSISTED LANDING FOR HELICOPTERS IN CONFINED AREAS

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ABSTRACT

This paper describes the implementation of a computer-based approach planning for manned helicopters in confined areas. The algorithms developed consider the procedures of pilots during the approach planning. Thus approach trajectories are generated which not only regard flight limitations, obstacles, terrain and airspace restrictions but also the pilot's individual preferences and approach criteria. These factors depend on the flight missions and/or the pilot's experience for instance. To get an idea which criteria are important and have to be regarded by the approach planning, a comprehensive survey among 80 air rescue pilots was conducted. Based on the results different types of approaches were identified which still have to be adapted to meet each individual requirement of the helicopter pilot. This adaptation can be conducted by the current pilot or the operator of the helicopter. The generated approach trajectories are evaluated by pilots.

1. INTRODUCTION

Due to its versatility a helicopter is particularly suitable for air rescue. In a multitude of SAR missions, however, the pilot cannot draw upon ground-based navigation and landing aids resulting in limited operational readiness in poor visibility conditions. Since in 70% of all cases a rescue helicopter is requested in bad weather situations or at night a variety of missions cannot be flown or has to be aborted. To encounter that problem numerous institutions focus their attention on the development of the all weather capability of helicopters.

The project ACTIME (Active Control Technology for Improved Mission Effectiveness) of Eurocopter dealt with control law development to increase handling qualities ratings to level 1. It was shown that controllers alone could not reach the goal [1]. The project HACT (Helicopter Active Control Technology), a US Army Aviation Applied Technologies Directorate financed program, used right hand side sticks to control the aircraft and flight controllers to enhance mission effectiveness and all weather capabilities [2]. Within the DLR project PAVE (Pilot Assistance in the Vicinity of Helipads) an assistance system to land on helipads has been developed [3]. Here the path planning and design of the visual displays were of primary interest. Related work was done in the PILAS (Pilot Assistance System) project [4], in which a planning and guidance system for HEMS (helicopter emergency medical service) missions has been developed. The project used advanced displays and a 4-axis autopilot to display the planned path and fly it automatically. Besides this project a lot of work is done in the field of unmanned aircraft. All of these projects have in common that they deal only with a single part of the overall assistance.

The DLR internal project ALLFlight (Assisted Low Level Flight and Landing on Unprepared Landing Sites) combines all the different methods for pilot assistance. It deals with the development of an assistance system

which allows the intuitive operation of a manned helicopter from start to landing on unprepared landing sites and an intermediate low level flight in the presence of obstacles in a degraded visual environment. To achieve these requirements the research helicopter FHS (flying helicopter simulator) is equipped with several sensors to collect environmental data [5]. Thus, a 3D earth surface model can be generated so that this online-generated map can be used within trajectory planning. Upper mode control laws and autopilot functions will enable the pilot to stay on the planned trajectories even in adverse weather conditions. Different human-machine interfaces like displays, helmet mounted displays and/or active control sticks provide the information required using visual and haptic perception.

Since approach and landing are the most critical parts of air operation (54% of all aircraft accidents in bad weather conditions occur during landing situations [6]), the initial focus of the ALLFlight project is on the approach phase. This paper deals with the development of a helicopter-based automatic landing aid and focuses on the generation of the approach trajectory. The algorithms for the trajectory calculation have to respect the procedures of a pilot during the approach planning and accomplishment. Hence, the planning tool has to generate an approach path which is equivalent to an approach defined by the pilot in consideration of any given boundary conditions (terrain, obstacles, atmospheric conditions and the flight mechanical limits).

To meet these requirements the path planning is based on the results of 80 interviewed pilots flying for air rescue organisations, police and armed forces in Germany. The area of inquiry regards air-path inclination angles and types, crosswind conditions, flight limitations, risk tolerance, obstacle avoidance and further pilot-dependent requirements.

The results of the survey reflect a wide variety of approach strategies between different pilots. Therefore the planning algorithms have to be very flexible

to satisfy every pilot's demands. To achieve an individual adaptation of the planning tool to any pilot's specification the planning tool can be adjusted by the current pilot.

This paper introduces the strategy of the automatic approach planning, the algorithms used and the trajectories generated by the planning tool. The generated approaches are evaluated. Chapter 2 outlines briefly standard and confined area approaches. Some interesting results of the survey among the rescue pilots are discussed in chapter 3. Chapter 4 focuses on the path planning strategy. A rough overview of the path planning concept is given before the algorithms used are discussed in detail. In chapter 5 the performance of the path planner with varying boundary conditions and weighting factors is analysed and discussed. Finally, a summary and an outlook are given.

2. APPROACH PROCEDURES

The method of the automatic approach planner is derived from the approach procedures performed in civil and military aviation. A brief introduction into these approach procedures is given to clarify the method of operation of the path planner described in chapter 4.

The approach is defined as the transition from traffic pattern altitude to either hover or ground. The approach should terminate at the hover altitude with the rate of descent and groundspeed reaching zero at the same time. In the context of this paper approaches are categorized in standard and confined area approaches according to the boundary conditions of the landing site. These conditions may include obstacles and size and surface of the landing area. Further relevant factors affecting the approach planning are density altitude, wind direction and speed, and available engine power.

2.1. Standard approach procedures

It is well known that a standard approach uses an air-path inclination angle γ_a of between -8° and -12° starting at approximately 300ft above the helipad elevation (AHE) with the recommended approach speed (approximately 60kn indicated airspeed - IAS). The air-path inclination angle remains constant during the entire approach. The rate of descent (R/D) must not exceed 500ft/min to avoid any risk of entering the vortex ring state.

Generally, takeoff and landing should be made into the wind to obtain maximum airspeed with minimum groundspeed and to minimize crosswind conditions.

During the approach the airspeed is reduced at a constant rate in such a way that speed above ground meets 0kn at the intended landing spot. In this respect particular attention is to be paid to the current wind conditions.

Throughout the approach, performance instruments are also to be monitored as well as the flight instruments to detect any discrepancies in the approach procedure at an early stage. In doubt of a safe landing the approach has to be bailed. In this case the pilot has to accomplish a safe climb at takeoff safety speed (V_{TOSS}).

Figure 1 depicts a standard approach profile with the parameters stated above at the approach entry point. The wind is illustrated with a three-arrowed wind vector marked W/V.

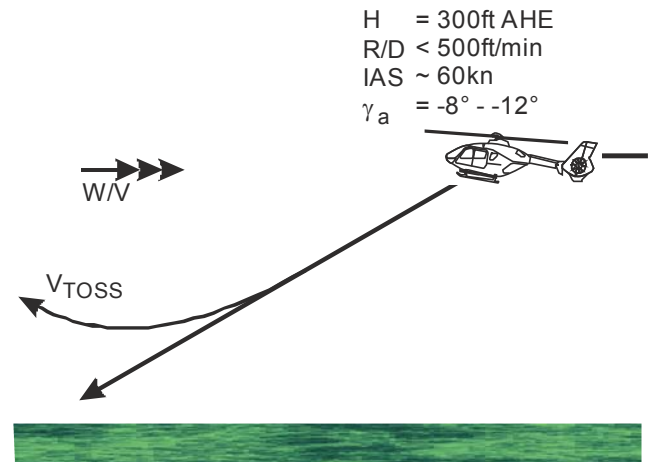


FIG 1. Standard approach procedure

2.2. Confined area operations

A confined area is an area where the flight of the helicopter is limited in some direction by terrain or the presence of obstructions. For example, a clearing in the woods, a city street, a road, a building roof, etc. can each be regarded as a confined area.

To land within a confined area the air-path inclination angle, the flight direction or both have to be altered during the approach manoeuvre. Another possibility is a steep approach with an air-path inclination angle of less than -15° . Whichever approach strategy is best suited in the current scenario is at the discretion of each pilot. It becomes obvious that a confined area approach diverges from any standard approach procedure and therefore makes high demands on the pilots' skills. To conduct a safe approach a sound reconnaissance of the landing zone and a conscientious planning of the whole approach procedure have to be performed prior to the approach.

The most significant aspects influencing the approach planning are described in the following.

First the Pilot has to determine if the area is suitable for a landing at all. Size of the landing spot, legal allowance to perform a landing or if the helicopter is a nuisance to people are to be considered for example. A further important factor is the texture of the surface concerning the soil's stability to carry the weight, surface inclination, loose objects which may damage the helicopter and dust or snow causing brown-/whiteout.

A second important point refers to the identification of anything that has to be avoided along the approach path. This could be physical objects such as mountains, tall towers or buildings, wires, but also non-physical barriers such as noise-sensitive areas or some kind of restricted or prohibited airspace.

After evaluating these aspects a flight path is determined which is the best solution to the given situation. Besides the approach itself also a flight path for the departure has to be defined prior the touchdown.

When planning the approach path many factors have to be considered. The wind is only one small part of figuring out the approach. Parameters that should be considered as well are performance limits, emergency landing areas, areas of high turbulence, the height of obstacles which will have to be cleared on approach and the annoyance factor of the people on the ground.

To gather the required information for the approach planning the pilot performs a high recon (high reconnaissance), which is often done by overflying the landing zone at 500 feet. While overflying the landing spot, the pilot checks the points described above and defines an approach strategy. Once the approach path is determined, the pilot can figure out his relation to that approach path and fly a standard traffic pattern which will align the helicopter with the final approach path.

In the framework of this paper, different strategies of confined area approaches will be considered. These include steep, double angle and curved approaches.

An air-path inclination angle of less than approximately -15° is regarded as a steep approach. This type of approach is used primarily when there are obstacles in the approach path that are too high to allow a normal approach. A steep approach permits entry into most confined areas and is sometimes used to avoid areas of turbulence around an obstruction. Entry into the vortex ring state or crossing the deadman's curve of the H-V-diagram are hazards that must not be neglected. The advantage of this approach is a constant air-path inclination angle during the whole procedure.

In small confined areas, the so called double angle approach technique may be necessary. Initially the air-path inclination angle is as normal until the landing spot is visible. After this the air-path inclination angle is steepened aiming at the landing spot. Since two different air-path inclination angles have to be flown this approach requires more situational awareness than a constant angle approach.

Figure 2 shows an approach profile of a double angle approach. The approach begins at about 200ft above the obstructions.

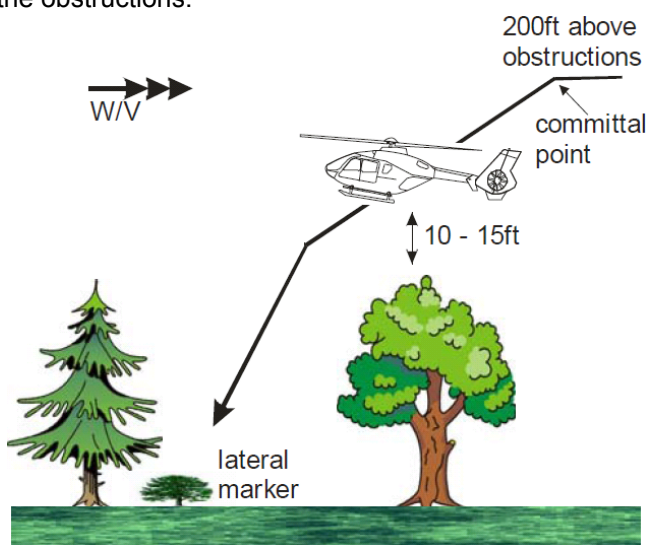


FIG 2. Double angle approach

The pilot decides if the approach is feasible prior to reaching the committal point. The final approach is

initially carried out to the front edge of the clearing aiming for more than 10ft minimum obstacle clearance at a slow walking pace. When steepening the air-path inclination angle, the pilot should make use of lateral markers to maintain a clearance between rotors and obstacles.

A rather challenging but timesaving manoeuvre if carried out correctly is a curved or turn approach. Obstacles are avoided laterally enabling the pilot to maintain a rather constant air-path inclination angle. A turn approach can be flown from nearly any position. Thus the approach might be initiated directly out of an en-route flight. Since turn approaches are manoeuvres used to change flight direction to establish an aircraft inbound on final approach course, heading changes up to 180° are possible.

The point at which the turn may be commenced and the type and rate of turn, speed and air-path inclination angle are left to the discretion of the pilot. But the approach should be set up in such a way that the heading of the helicopter is into wind direction below an airspeed of 40kn. A discrepancy of $30^\circ - 40^\circ$ is acceptable subject to the current wind conditions. The height above the landing spot at this point should be 200ft – 300ft and the rate of descent not more than 300ft/min.

The reconnaissance of the landing area is accomplished during the approach manoeuvre which saves even more time making this approach quite suitable for rescue missions. A high mental workload of the crew during this approach is to be valued as disadvantageous.

Figure 3 shows a scenario of a typical rescue mission in a confined area. The helicopter enters the turn approach with en-route flight parameters having 10kn tailwind at this stage (W/V $90^\circ / 10kn$). The approach path is depicted with a black dashed line. The red dot marks the airspeed passing 40kn during the approach.

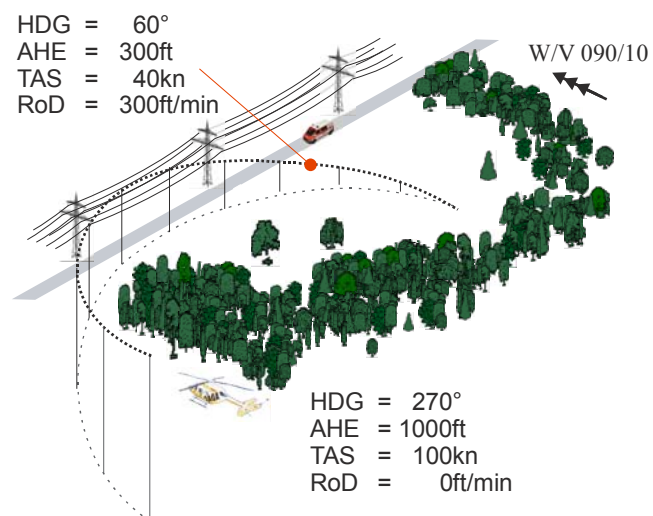


FIG 3. Turn approach

The prevalent approach procedures described above will be implemented in the algorithms for the computer-based approach planning. To decide which type of approach is to be preferred in the current situation and to adjust these algorithms in detail several pilots

were interviewed about their behaviour concerning approach procedures. Some results of the survey will be presented in the following.

3. RESCUE PILOT SURVEY

Besides the flight limitations specified in the respective flight manuals there are many more criteria affecting the approach planning of the pilots. These criteria are mainly based on the operating experience of the respective pilots. It is in the discretion of the pilot to decide whether an obstacle is to be avoided laterally, vertically or in a combination of both for instance. Furthermore it is important to know how much crosswind is accepted by pilots and how this depends on the surrounding obstacles. Whether crosswind is preferred from a specific side is a question that has to be answered, as well.

These and other parameters are to be considered in the computer-based approach planning. For this reason a questionnaire was developed in cooperation of "Deutsches Zentrum für Luft- und Raumfahrt" (DLR) and the "Universität der Bundeswehr" Munich investigating the different behaviour patterns of pilots [7]. The questionnaire consisted of 35 questions concerning flight experience, missions flown, flight parameters for high recon, low recon and approach, accepted wind conditions, dealing with obstacles etc. This questionnaire was handled by 80 pilots flying for civil air rescue companies, German Forces, German Police or German Border Police and others. In order to detect differences in the behavioural patterns within the different occupation groups stated above, the pilots were grouped into four categories, namely "Air Rescue", "Forces", "Police" and "Others". Each of the first three groups represents about 30% of the questioned pilots leaving 10% forming the category "others" which are mainly VIP transport and test pilots.

In addition to the questionnaire interviews with about 15 pilots out of the group mentioned above were conducted, each lasting several hours. A lot of valuable additional information about factors affecting the decision making process in the approach planning was gained in these interviews.

The flight experience of the participating pilots was mainly between 100 and 300 flight hours annually with a mean experience of more than 10 years.

In the following some of the gained results are reported briefly. Some pilots did not answer all the questions, therefore the sum of votes is below 80 in some cases.

Pilots were asked to evaluate the following factors concerning their influence on the approach planning: availability of an emergency landing site, approach into wind, approach with maximum obstacle clearance, heading changes during approach and maintaining a constant air-path inclination angle. They had to weight each criterion according to its priority by distributing 20 points between the five criteria mentioned above. The higher the priority the more points are to be given.

Figure 4 shows the spread of the voting points broken down according to the employer of the pilots. The votings of all pilots show a similar pattern prioritising

available emergency landing areas, approach into wind and obstacle clearance. A constant air-path inclination angle and minimal changes in heading are rather minor factors.

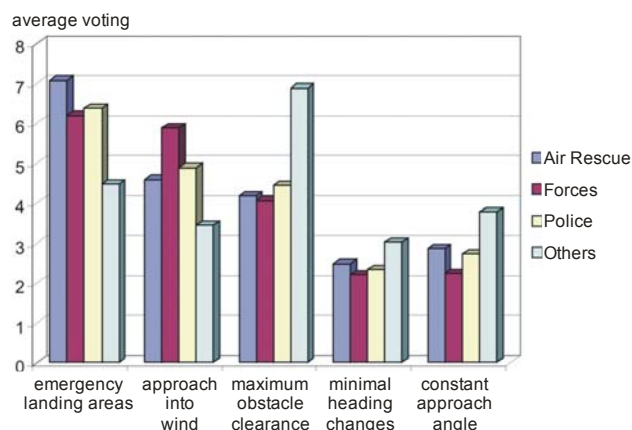


FIG 4. Criteria affecting approach planning

Considering the maximum amount of heading (HDG) changes during a curved or turn approach, the survey revealed that more than 50% of the pilots will accept changes up to 180° which is more or less a complete U-Turn during the approach. Even 84% of the pilots are accepting heading changes up to 90° during an approach.

The following three figures are dealing with the handling of the wind conditions during these turn approaches. The indicated airspeed below which the nose of the helicopter should be directed into the wind is stated to be in the range of 36kn-45kn by nearly 50% of the pilots (Figure 5). This fact coincides with the statement of chapter 2.2 (IAS < 40kn = HDG into wind) which is extracted from aviation school documents [8].

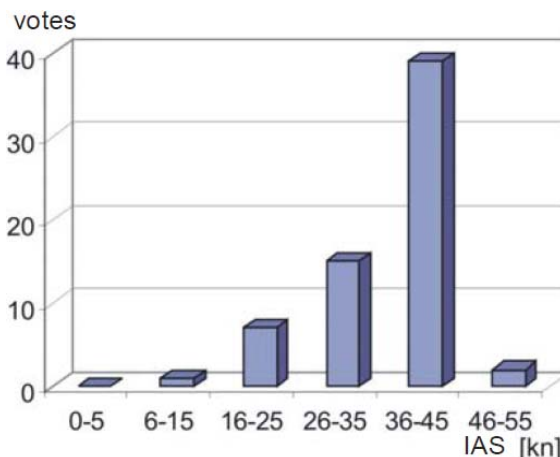


FIG 5. Minimum IAS for heading into wind

The term heading into wind implies an angular tolerance between the longitudinal axis of the helicopter and the wind direction. The size of this angle accepted by the pilots is depicted in Figure 6. It is visible that less than one third are accepting angle differences up to 30° between heading and the wind direction. The answers of one half of the questioned pilots are located between 31° and 90°. Hardly, any clear conclusion can be drawn due to this distribution.

The given answers to the question about the maximal accepted wind for minor heading changes are

distributed from 6 to 30kn (Figure 7). Most answers were given in decades explaining the low values of the columns representing 11-15kn and 21-25kn.

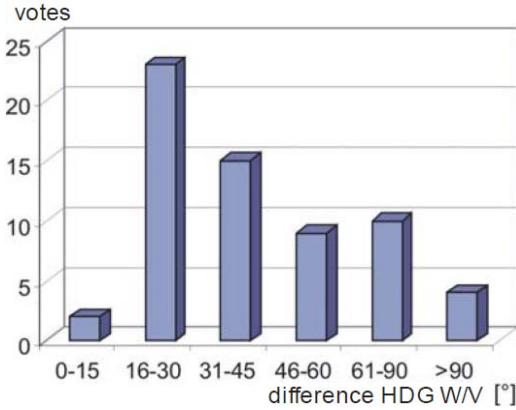


FIG 6. Maximum difference of the angle between HDG and wind direction

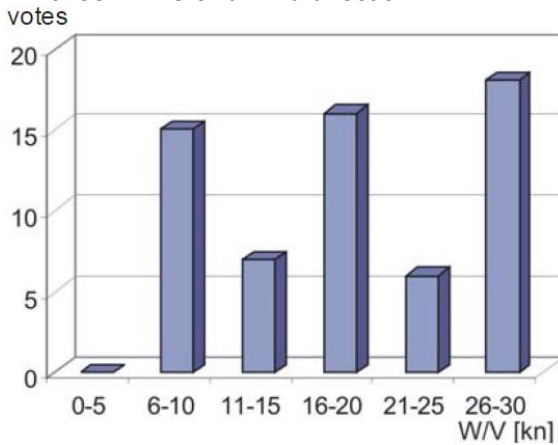


FIG 7. Maximum wind for small HDG changes

The evaluation of the question if pilots consider the adherence to limitations given in the H-V-diagram reflects hardly any clear indication (Figure 8).

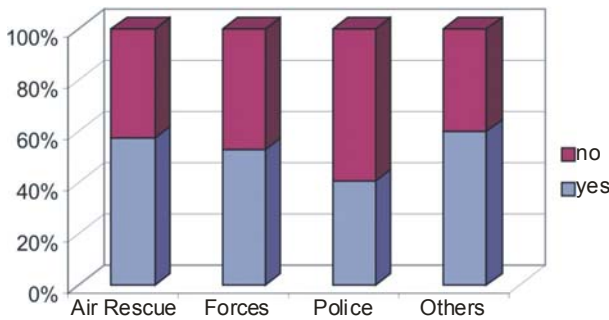


FIG 8. Adherence to H-V-diagram

However, the overall results concerning accepted cross- and tailwind, flight parameters during the approach or air-path inclination angles for example were more distinct.

But the main lessons learned from the questionnaire and the interviews were that any type of approach that is possible from the flight dynamical aspect will be conducted by pilots. This flexibility and versatility is also required from the computer-based approach planner making great demands on its implementation. The algorithms developed have to be very adaptive but still absolutely reliable referring to flight safety. These algorithms will be presented in the following chapter.

4. PATH PLANNING ALGORITHMS

The different approach strategies (constant angle, double angle, steep and turn approach and their combinations), including their amount of variations and modifications are implemented into the computer-based approach planner. This chapter describes the computing of the approach flight paths. The final flight path is defined by a number of waypoints. Each of them is characterised by geodetic coordinates, ground speed and the resulting true airspeed, rate of climb and heading calculated with the mean wind. This information can be visualised to the pilot, so that it is possible to fly the computed flight path manually. Alternatively the computed flight path is flown automatically.

4.1. Principle design

The operation method of the path planning is deduced from the planning procedure of pilots. First a high recon is flown to gather the data required for the approach planning via the sensors introduced in [5]. By means of sensor fusion a topographic map is generated which is mapped on the SRTM-data (Shuttle Radar Topography Mission) stored in a database. This map is displayed to the pilot who selects an appropriate landing point. The path planner computes an approach to this landing spot in consideration of the specifications of the current pilot. Any kind of approach that is described in chapter 2 is considered within this approach planner. The calculated path is visualized to the pilot. The pilot can either accept the planned path or initiate a real-time replanning with modified specifications.

The basic idea of the approach planner is to transform the path planning problem into a so called configuration space (C-space) [21]. This in robotics widely used procedure allows a simplified representation of complex, high-dimensional path planning problems. The aim is to reduce the computational effort and thus to reduce the time required for path planning calculations. In the C-space a path map is computed consisting of all approaches that are possible in consideration of flight dynamics. Afterwards the path is retransformed into the “real world” featuring the properties stated above (geodetic coordinates, speed, etc.). After retransforming any discontinuities in the trajectories are smoothed. An approach path that coincides best with the preferences of the current pilot is determined by means of a weighting function. Finally a transfer trajectory from the current position of the helicopter to the approach path starting point is determined.

Chapter 4 is divided into the following sections. For the C-space transformation a surface in space is defined. The courses of the possible approaches have to be on that surface. Obstacles, which intersect with that surface, are to be considered for planning purposes. The calculation of that surface is described in chapter 4.2. The transformation of the planning problem into the C-space is described in chapter 4.3. Chapters 4.4 and 4.5 explain the generation of the approach path map. The turn approach is briefly

discussed in chapter 4.6. The selection of the optimal approach is delineated in chapter 4.7.

4.2. 3D planning surface

The approach to solve the 3D path planning is to generate a surface around the landing spot. This surface is calculated based on wind conditions, the air-path inclination angle and entry height. The approach paths have to stay on that surface avoiding any conflicting objects. Thus obstacles which are intersecting this surface are to be considered for the approach planning. Since the position of the helicopter along the approach is controlled via a global positioning system the air-path inclination angle and thus the surface has to be transformed into a geodetic system. In this way it is guaranteed that the air-path inclination angle, being the relevant factor for flight performance data, is independent of the wind conditions.

Because the approach trajectory can be oriented in any direction depending on the path azimuth χ , the possible approach directions are discretized with $\Delta\chi$. This yields a couple of possible approach directions where each direction defines a vehicle motion problem [20] with the landing point as start node and the approach entry point as destination node. For each approach direction, the standard approach, the double angle approach and the turn approach are considered.

Figure 9 shows the surface which is equal to a cone, the terrain together with obstacles (grey) and the approach trajectories (black). The black equidistant rings mark the distance to the landing spot in the centre. The resolution is 50m. The discretization of the approach direction is $\Delta\chi=10^\circ$. Some radials are deformed by the objects intersecting the surface like streamlines being deflected by a body. For some starting azimuths, however, no trajectories are planned due to flight dynamical limitations.

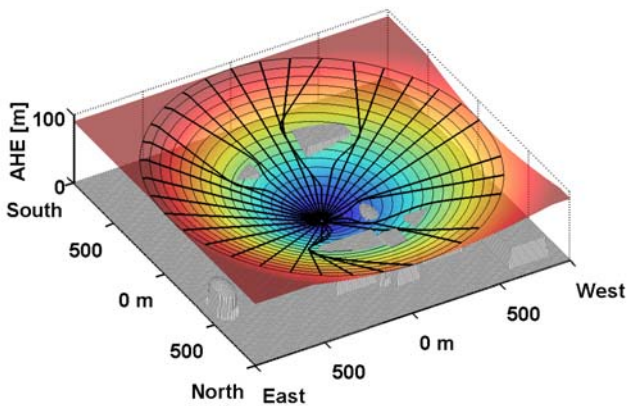


FIG 9. Surface, obstacles and approach trajectories

For double angle approaches the surface is modified to meet the requirements stated in chapter 2. Figure 10 shows this surface for a double angle approach in the geodetic system. The deformation of the upper part of the cone due to the wind is clearly recognisable. The lower part of the surface is defined by the obstacles. Since the surface of a double angle approach depends on the current obstacles in the approach direction only a section of the surface will be computed. The approach has to be within this section or will be discarded

otherwise.

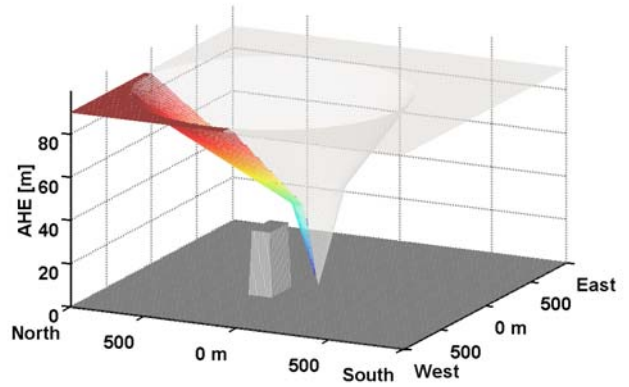


FIG 10. Lower boundary of a double angle approach

4.3. Configuration space

In order to compute the trajectories on the surface of the cone the problem is transformed into the configuration space reducing the helicopter to a mass point which is able to perform a translational motion as well as turns excluding spot turns. The obstacles intersecting the surface are represented by polygons in C-space. The noise in the contour of polygons after the transformation draws upon a lot of unnecessary computational effort. Therefore the noise is eliminated by a modified Douglas-Peucker algorithm introduced in [9] and [10].

Due to smoothing and straightening to obtain a continuous and flyable approach the path diverges from the original obstacle free path computed by the planner in C-space. In order to consider flight dynamical limitations and to provide a collision-free path after the smoothing, obstacle-free corridors are defined. The width of the corridors depends on flight dynamics. The smoothing algorithms are designed in such a way that the courses of the approach trajectories have to stay within these virtual corridors. These virtual corridors are represented by simple lines in C-space. Thus a path planning problem is generated that can be solved by state of the art path planning algorithms [14], [21].

In C-space the dimension of the helicopter including safety margins and the virtual corridors are added to the obstacle representing polygons. The remaining obstacle- or polygon-free space in C-space is available for path planning.

The addition of the parameters described above to the polygons is performed via the Minkowski addition. The standard method for computing the Minkowski sum is to decompose the input polygons into convex sub-polygons and compute the union of the pairwise sums of these convex sub-polygons. To avoid this computational effort, a modification of the Minkowski addition is used. This modification introduced in [11] and [12] is called the convolution method. This method is based on polygonal tracings and computes the contour line of the unified polygons.

Like in [13] only the outer face of the Minkowski sum is needed. Furthermore, the octagonal polygon H, representing the helicopter, safety margins and the

corridors, is convex. Thus the Minkowski sum is built by non-convex polygons O (obstacles) and a convex polygon H (helicopter, safety margins, corridors) with varying dimensions. This fact allows for some simplifications of the algorithms introduced in [12] and [13]. These are that convolution cycles can be identified and removed quite easily. A complex data structure as presented in [13] is not necessary. The removal of the convolution cycles as well as the variation of the size of the polygon H is done on the fly. Figure 11 shows the polygons derived from the obstacles (blue) in C-space. The helicopter dimensions including safety margins added to the obstacles is depicted by the green polygons. The red polygons including the virtual corridors are finally representing the obstacle region in C-space.

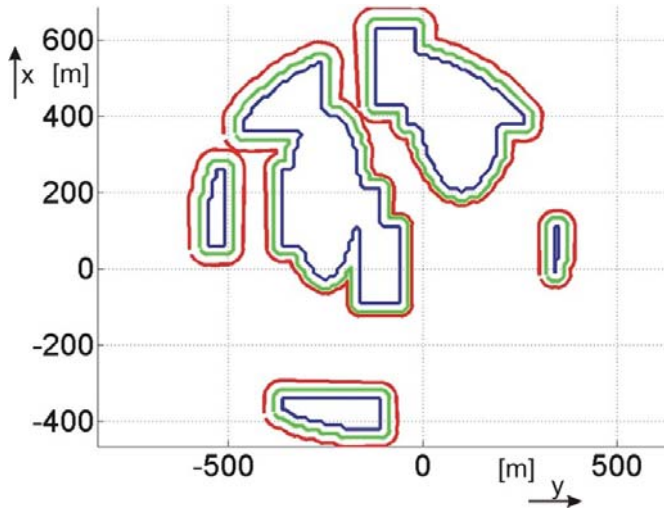


FIG 11. Polygons in C-space

The configuration space created by the measures described above is the basis for the path planning algorithms.

4.4. Visibility graph

The decisive factor concerning the development of the path planner is the certification by the aviation authorities. Therefore the path planner has to be 100% predictable, precise, reproducible and robust. These requirements are fulfilled by a path planner based on a visibility graph. Furthermore the visibility graph always provides the shortest connection with a minimum of direction changes. In the following two sections only one approach path for one single approach direction is considered. All other approach directions, however, are handled analogously.

The visibility graph is a graph of intervisible locations. Each vertex or node in the graph represents a point location, and each edge represents a visible connection between them.

To determine whether two vertices are intervisible each polygon has to be checked if it intersects with the line of sight (edge) between the two vertices. Since a Polygon consists of a large amount of line segments each line segment has to be checked for intersections with the prevailing edge which is rather time consuming [14].

To reduce the computational effort of checking edges and polygon segments for intersections the segments and edges are represented via their minimum bounding

rectangles. The minimum bounding or enclosing rectangle for a point set in two dimensions is the rectangle with the smallest measure which all points lie within. In this case the bounding rectangle is defined by the two points forming the polygon segments or the edges (line of sights). An intersection between polygon segments and edges is only possible if the corresponding bounding rectangles are overlapping. The check if there is an overlap between the two rectangles is less time consuming than the actual collision test of edges and segments. Figure 12 shows the bounding rectangle of an edge (green) with the coordinates x_1, y_1 , x_2, y_2 and the rectangles of polygon segments (red). Overlapping rectangles are shaded. Only the gray shaded rectangles have to be checked for collisions.

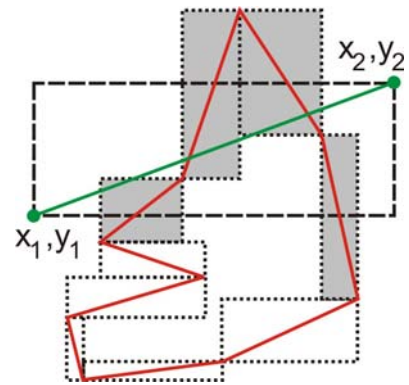


FIG 12. Bounding rectangles

A further reduction of the computational runtime is achieved by an intelligent data management. A data base that is best suited to handle the 4-dimensional data (the two coordinates of the two points forming the line or spanning the rectangle) is the MF-CIF Quadtree presented in [15].

Once a visibility graph is generated, graph search algorithms like Dijkstra or A* are used to find an optimal path within the visibility graph [14], [21].

In this work the visibility graph and the A* algorithm are interacting in a way that the visibility graph only expands towards the destination point. The following section describes this interaction in detail and also presents further methods to expedite the computational runtime.

4.5. Overview on path planning algorithm

As stated above the visibility graph is only to be generated for regions that are of interest for path planning purposes. To comply with this demand the expansion of the graph is directed by the A* algorithm. Due to the interaction with A* only vertices for the visibility checks are selected, which are in the direction of the given destination point. Thus a graph is generated that expands in a tree like form from the start point towards the destination. In this work the graph starts at the landing spot and expands towards the start point of the approach. This has the advantage that the generated graph for this approach direction can be used for the path planning of further approaches from different directions.

Figure 13 shall clarify this statement. The figure

shows the visibility graph (dark blue) starting in the origin of the coordinate system (landing spot) and expanding towards the start of the approach marked by a dark blue spot at coordinates $y=-450\text{m}$; $x=800\text{m}$. The polygons representing the obstacles are depicted in red. The graph is expanded along the vertices building the polygons (cf. [14]). In this example the approach direction is $\chi=330^\circ$. Most parts of the graph will be identical for approach directions from 310° to 360° degree marked in Figure 13 via light blue spots. In order to benefit from different path search queries already generated visibility graphs are stored in a matrix. For new approach directions the existing visibility graph needs only to be extended towards the new approach starting point. Therefore, path planning from the landing spot towards the start of the approach like depicted in Figure 13 is reasonable.

It is further visible in Figure 13 that the first segment of the path from the centre is towards 330° ending at the coordinates $y=-40\text{m}$; $x=80\text{m}$ and thus is not the shortest path. This modification is installed in order to achieve that the direction of the last bit of the approach is equal to the initial approach direction. This is to guarantee a fine decomposition concerning approach directions in the last part of the approach. In Figure 13 this decomposition is depicted by the light blue paths for approach directions between 310° and 360° . This last part of the approach is the most critical concerning crosswind conditions. A heading directly into the wind is to be preferred. Without this modification all final parts of the approaches with approach directions between 310° and 360° would be from the coordinates $y=-78\text{m}$; $x=223\text{m}$ directly towards the landing spot and the crosswind conditions would be the same for all approaches.

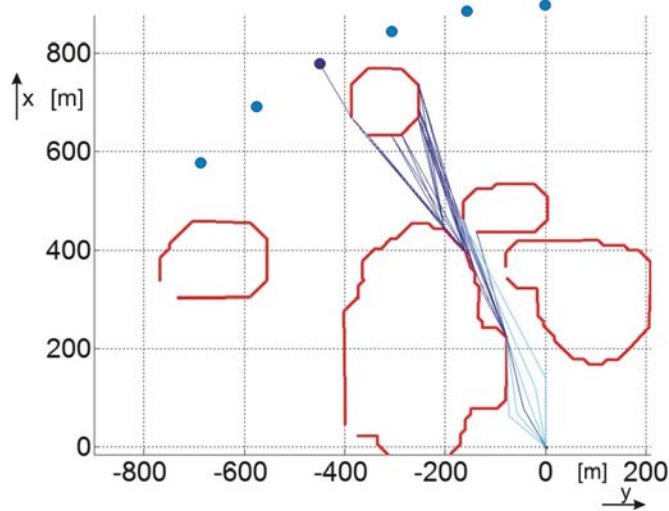


FIG 13. Expansion of visibility graph towards the target point

As stated above the expansion of the graph towards the destination node is performed along the vertices of the polygons. Many vertices will never contribute to the shortest path simply because of their position in the coordinate system. Some vertices that are not reachable due to flight dynamical limitations need not be considered for planning purposes as well. During the generation of the visibility graph all these vertices are ignored reducing the computational effort.

As seen in Figure 13 the generated paths are sharp

edged. To get flyable trajectories the path is to be smoothed. One problem of smoothing a path is that the smoothing alters the obstacle-free path. Therefore a new check for collisions is necessary. To avoid this procedure the smoothing algorithms are given obstacle-free corridors in which the smoothed path might have any course. The width of these corridors depends on flight dynamics. Thus, the path found by the visibility graph is not the actual approach path but the centreline of this corridor. During direction changes of the path or centreline the smoothed path is allowed to cut the corner as long as it remains within the obstacle-free corridor (see Figure 11).

Due to this corridor the space available for path planning is reduced slightly and possible paths might be discarded. But this applies only to paths which are close to obstacles or within narrow gaps. The pilot survey (Figure 4) shows that the maximum obstacle clearance is quite a factor in approach planning and thus the discarded paths are not that relevant.

Due to their properties B-splines are used for the actual smoothing. The convex hull property [16] guarantees that the smoothed path remains within the corridor. The smoothing is done laterally and vertically in case of double angle approaches.

After the path planning and smoothing the path is retransformed into 3D space. To get the approach flight path the speed component is added in such a way that a constant deceleration along the approach is achieved.

Figure 14 shows some possible approaches computed by the approach planner like constant angle (magenta) and double angle (blue) approaches. The discretization of the approach direction is $\Delta\chi=10^\circ$.

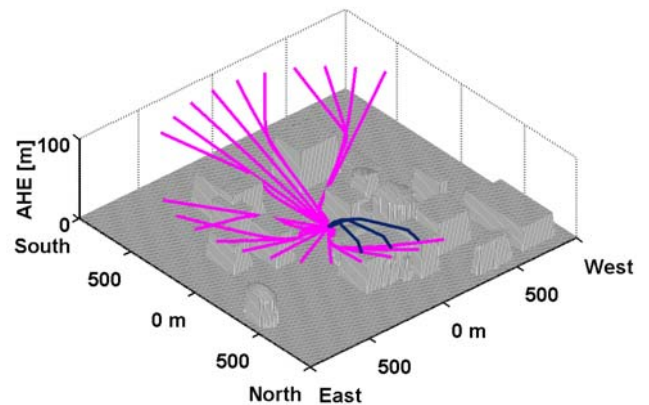


FIG 14. Possible approaches within a confined area

4.6. Turn approach

The turn approach has to meet the requirements described in chapter 2.2 but is very variable otherwise depending mainly on the wind conditions and the position of the helicopter in relation to the landing spot. Initially the approach planner comes up with the shortest path possible accounting for flight limitations and flight safety. A corridor-like surface is generated with the approach path as centreline. This corridor surface is checked for intersections with obstacles and an obstacle-free path within this corridor is

computed with the same methods as described above.

Figure 15 depicts the turn approach corridor starting at the coordinates (300 m South; 200 m West) at 80m above the landing spot. The optimal approach in this example is at the left side of the approach corridor.

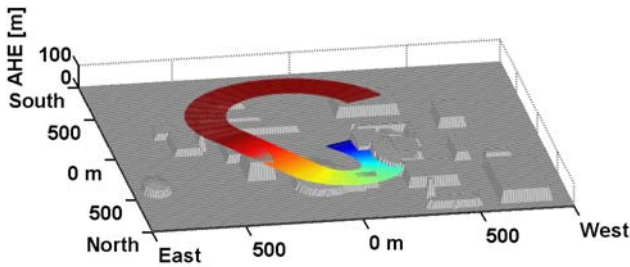


FIG 15. Turn approach

A turn approach is also feasible with the algorithms described above. The only modifications are that instead of a cone-like surface the corridor has to be transformed into C-space.

4.7. Selection of a single path

The possible approaches will be evaluated according to flight limitations and requirements given by the pilot building the basis for the final approach computation.

Based on the environment, like topography, obstacles, wind conditions, atmospheric data and airspaces, the path planner generates feasible approach trajectories. These trajectories are evaluated with respect to the pilot’s preferences which lead to a selection of a trajectory that matches the pilot’s specification best.

To determine the optimal approach which complies best with the pilot requirements the approach trajectories are to be evaluated. In this work the following attributes are considered.

- Wind influence along the entire approach

- Curvature of path including bank angle and roll rate
- Rate of descent, air-path inclination angle and difference between set and actual air-path inclination angle
- Adherence to H-V-Diagram
- Airspace restrictions and noise sensitive areas
- Length of transfer flight to approach starting position
- Length of approach and time needed for the approach
- Difference between desired and actual approach speed

Each attribute can be weighted separately according to the pilot’s requirements. Any attributes not included so far might easily be added.

5. ANALYSIS OF THE PLANNED APPROACHES

In this chapter the performance of the path planner with varying boundary conditions and weighting factors is analysed. The assessment of the calculated approaches is done by pilots. Besides flight parameters like rate of descent, approach speed or air-path inclination angle the entire condition of the approach has to meet the pilot’s expectations. For this reason the approaches are evaluated rather qualitatively.

5.1. Standard approach

The first example (Figure 16 – case 1) shows an approach to the apron of the DLR in Brunswick (52,3158°N; 10,5661°E). The wind is 030° / 10kn. The air-path inclination angle is selected to be -3°. The pressure altitude was set to an unrealistic value of 4300ft to artificially increase the influence of the dead-man’s curve.

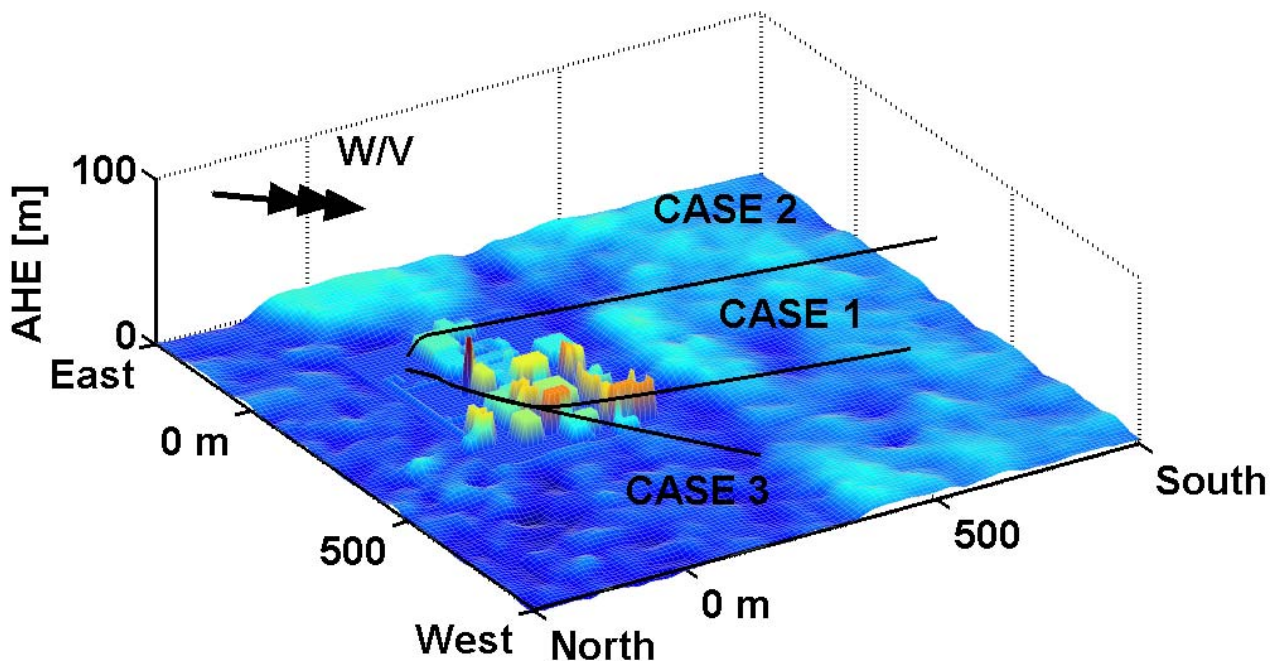


FIG 16. Landing site with approach trajectories

A weighting setting is used that minimizes crosswind and rate of descent at the expense of turns during the approach. Adherence to the H-V-diagram is of minor priority. The calculated approach is shown in black (Figure 16 – case 1). Its routing is windward of the buildings, avoiding possible turbulences. It is visible that the constant angle approach possesses large changes in heading. Figure 17 emphasizes this conclusion. The heading of the helicopter (Ψ -blue) and the track above ground (χ -green) are depicted versus the distance to the landing spot along the approach s . Due to the wind correction angle changes in heading are less profound.

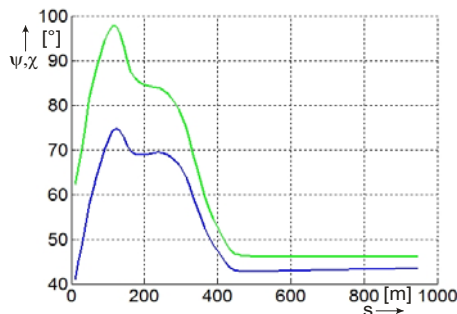


FIG 17. True heading (Ψ -blue) and true track (χ -green) for case 1

Figure 18 shows the crosswind influence during the approach. The strength of the crosswind is depicted in magenta and the headwind in cyan. The distance to the landing spot is s . It is visible that two thirds of the approach are into the wind. 300m in front of the landing spot however, when the helicopter turns towards it, the crosswind is the dominating factor explaining the significant difference between heading and track of 10° - 20° in figure 17.

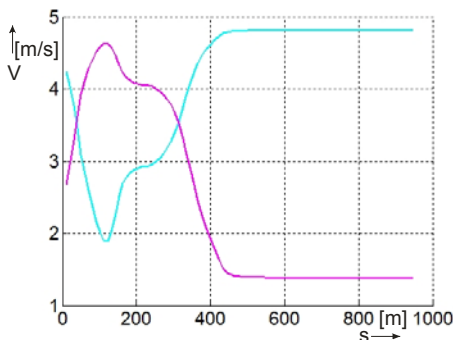


FIG 18. Headwind (cyan) and crosswind (magenta) for case 1

Figure 19 depicts the H-V-diagram as well as the approach profile in the geodetic system (green) and the aerodynamic system (blue). The relevant factor for the dead-man's curve (red) is airspeed. It is visible that the approach profile is within the area which has to be avoided. The fluctuations of the airspeed are due to the changing wind influence during the turns.

The routing of this rather poor approach contains some changes in heading and thus bank angle leading to an unsteady and bumpy approach. The landing zone is concealed by the buildings at some segments of the approach which conflicts with the requirement of the pilots to have always a good visual contact to the landing zone. The slight violation of the H-V-diagram is rather insignificant.

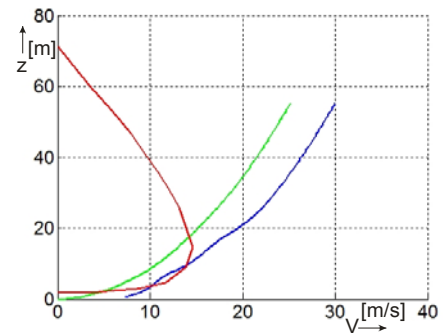


FIG 19. H-V-diagram for case 1

In the second example only the factors for heading changes were modified. The pressure altitude was set to 500ft in order to scale down the dead-man's curve. All other boundary conditions and weighting factors remained unchanged. The approach case 2 depicted in Figure 16 shows a double angle approach directed into the wind.

Figure 20 depicts the flight-path inclination angle (γ -green) and the air-path inclination angle (γ_a -blue) as function of s (distance to the landing spot along the approach). While the flight-path inclination angle rises to -40° the peak of the air-path inclination angle which is the relevant factor for flight performance is -15° .

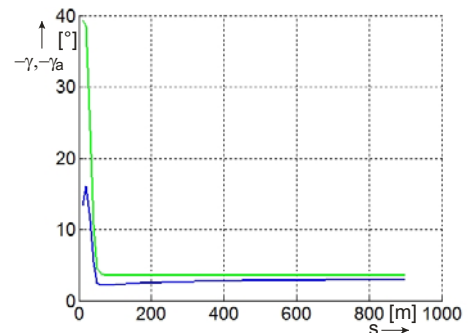


FIG 20. Flight- (γ -green) and air- (γ_a -blue) path inclination angles for case 2

The vertical velocity or rate of descent (blue) is shown in Figure 21. The maximal allowed rate of descent of 300ft/min (2,55m/s) is visualized in red. The approach is planned in a way that the approach is not affected by this limitation. Otherwise the airspeed is changed by the path planner to obey the given limitation.

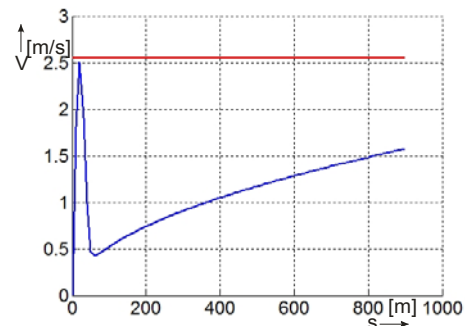


FIG 21. Vertical velocity for case 2

This is a typical double angle approach offering an acceptable solution for the given problem. Negatively is to be said, that the helicopter has to fly over buildings annoying people. Furthermore, the landing spot is concealed by the buildings during the first part of the approach. This approach is rather an option

when experiencing stronger wind conditions than in this example. A realistic approach under these circumstances is shown in case 3.

In the third example the path has to be planned for a heavily loaded helicopter. The weighting factors and wind conditions remain unchanged. Figure 16 visualizes the approach trajectory marked as case 3.

It is obvious that the routing of this approach is steady with a slight change in direction (see also figure 22). The true heading (Ψ -blue) shows quite steady characteristics with heading change into wind at lower airspeeds. This steady trajectory is at the expense of crosswinds all along the approach (Figure 23).

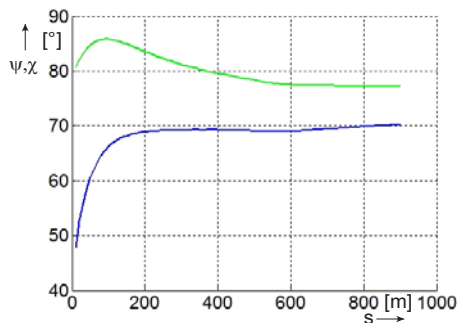


FIG 22. True heading (Ψ -blue) and true track (χ -green) for case 3

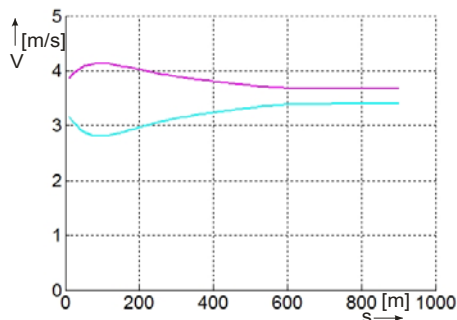


FIG 23. Headwind (cyan) and crosswind (magenta) for case 3

The air-path inclination angle (γ_a -blue) is quite shallow starting at -3° (Figure 24). Due to the reduction of the airspeed the air-path inclination angle is decreasing furthermore. The flight-path inclination angle is constantly at -3.4° . The dead-man's curve is not a factor.

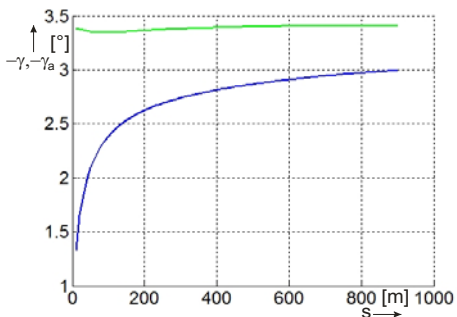


FIG 24. Flight- (γ -green) and air (γ_a -blue) path inclination angles for case 3

This approach is the best solution for the given scenario. Even with more power available this approach meets the requirements of most pilots. Its steady and shallow trajectory comes at the cost of a crosswind, which is acceptable, however.

6. SUMMARY & OUTLOOK

This paper presents a computer-based approach planning which is developed within the frame of the ALLFlight project. The focal points within the design of the approach planner are to reflect the behaviour patterns of pilots and to get certified by aviation authorities. Amongst others the path planner takes into account flight limitations, flight safety regulations, atmospheric data (temperature, pressure), wind conditions, topography and obstacles at the landing zone. The approach trajectory is generated analysing and evaluating these boundary conditions with respect to the pilot's preferences. Different types of approaches are feasible.

Prior to and during the conceptual design of the approach planner behaviour patterns of helicopter pilots regarding approach planning procedures and accomplishment were analysed. For this several pilots from German Forces, air rescue companies and DLR were involved in the development process. To round out the picture a survey involving 80 pilots was conducted.

Due to the variety in the preferences of the pilots the path planner is able to analyse the behaviour patterns of the pilots. These patterns are stored in a database.

The results of the planned approaches were discussed and analysed by pilots.

Further development in the frame of the approach planning contains a local online path planner that considers dynamic objects and comes up with a rerouting instead of aborting the approach like the current path planner.

Furthermore it is planned to evaluate the complete landing area by the path planner. Then, instead of an approach trajectory to a fixed spot, the path planner also determines the best landing spot considering the air-path inclination angle and condition of the surface, infrastructure, etc.

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