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Low level flight solutions for civilian missions

FILIAS FRANÇOIS-XAVIER[1], GILLET MARIANNE[2], PIRE RICHARD[3]

[1]Eurocopter Francois-xavier.Filias@eurocopter.com
[2] Eurocopter Marianne.Gillet@eurocopter.com
[3] Eurocopter Richard.Pire@eurocopter.com

ABBREVIATIONS

ADC	Air Data Computer
AFCS	Automatic Flight Control System
AHRS	Attitude and Heading Referential System
CFIT	Controlled Flight into Terrain
DAL	Development Assurance Level
DMAP	Digital Map
DTED	Digital Terrain Elevation Data
EMS	Emergency Medical Service
EVS	Enhanced Vision System
FMS	Flight Management System
GNSS	Global Navigation System Situation
GPS	Global Positioning System
H/C	Helicopter
HMI	Human Machine Interface
HTAWS	Helicopter Terrain Awareness and Warning System
HTT	All-weather helicopter
HUD	Head-Up Display
H/W	Hardware
IAS	Indicated Air Speed
IMC	Instrument Meteorological Conditions
LIDAR	Light detection and ranging
LLF	Low-Level Flight
MFD	Multi Functional Display
OCL	Obstacle Contour Line
OWS	Obstacle Warning System
RA	Radio Altimeter
SVS	Synthetic Vision System
S/W	Software
TCAS	Traffic Collision Avoidance System
V&V	Verification and Validation
VMC	Visual Meteorological Condition
WPT	Waypoint

I. INTRODUCTION

This paper addresses state-of-the-art advances in the field of efficient algorithms enabling to compute obstacle contour line (OCL) [1] and flight path for a manually-flown or automatically-flown rotorcraft unit flying a low-level trajectory [2][4].

Low-altitude and terrain following flights are needed for both civil and military rotorcraft.

In Emergency Medical Services (EMS) missions, it is sometimes necessary to fly as low as possible in order to minimize pressure variation for the wounded passengers.

Consequently, pilots are under a lot of stress and must be quick in order to avoid accidents with close terrain and obstacles.

Carrying out such tasks in poor visibility (whether in daylight, at night or in bad weather conditions) and at low altitudes can be hazardous. Low altitude flight is more difficult and stressful for pilots, requiring extra focus, quick thinking and reflexes in order to avoid accidents. It can be hazardous, especially when visibility is poor. Studies have shown that Controlled Flight into Terrain (CFIT) [4] accidents and obstacle strikes have been a major concern for civilian missions [5].

Thanks to research programs, avionic navigation solutions have been identified with different objectives.

To perform low level flights, two major solutions exist (today used alone):

- Use of navigation data (GPS, FMS, etc.) and databases
- Use of an active sensor which provides 3D images in front of the carrier (LIDAR, RADAR, etc.)

This paper provides an overview of some of the state-of-the-art low level flight solutions, developed by Eurocopter with information about their shortcomings, advantages as well as possible improvements and future solutions. For each proposed solution as it is, an algorithm/system description is made, the use concept is detailed, strengths and weaknesses are shown and a regulation status is established.

II. FMS3D+T FOR LOW LEVEL FLIGHT

An experimental FMS 4D was developed during HTT (all weather helicopter programs) in order to test 3 Dimensions + Time (3D+T) capabilities.

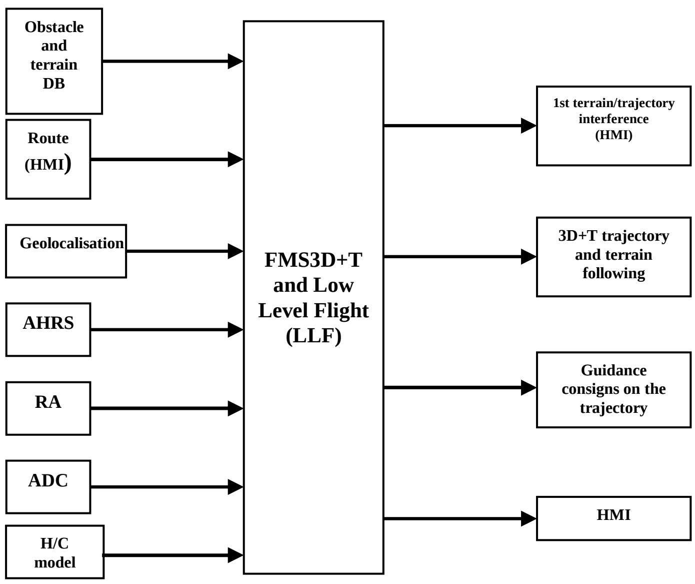

Figure 1: FMS3D+T and LLF architecture

The FMS3D+T makes it possible to have a fully defined 3D flight path with altitudes and time [3]. Thanks to performances models linked to H/C type and H/C altitudes, this flight plan takes into account H/C capability to fly above the terrain. Trajectories could be flown with AFCS or not with different anticipation times to avoid delay when a trajectory is manually flown.

Basic use concept

On a mission preparation MFD: Multi Functional Display (on a DMAP), an operator builds a horizontal 2D flight plan with waypoints (figure 2). He can choose one leg (or more) with a LLF (or contour flight) attribute.

He can also define:

- a vertical climb speed
- a vertical descent speed
- the sub leg duration
- the expected Indicated Air Speed (IAS)
- the height margin

Some of these parameters can be set automatically and the pilot can choose between three flight types :

- smooth (with little vertical speeds and longer duration of leg flight)
- medium (with classical vertical speeds and medium duration of leg flight)
- hard (with high vertical speeds and short duration of leg flight)

Thus, the algorithm [6] (if possible) parses each leg into sub legs (figure 3) according to the input parameter used.

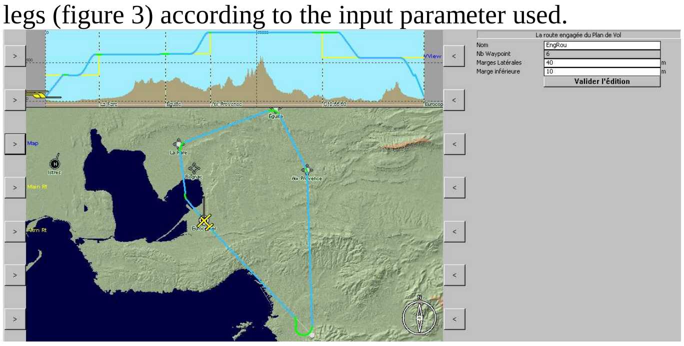

Figure 2: Classical flight in 3D+T debug interface without contour flight

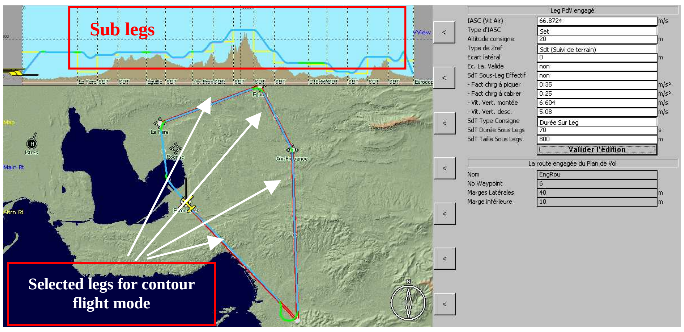

Figure 3: 3D+T debug interface with vertical contour flight activated

During the flight he has the possibility to display the vertical profile of his predictive flight path.

Algorithm description

In the first stage of the algorithm, each parsed sub leg is attributed a length and a minimum height (also called margin):

- the length is based on a duration and calculated thanks to the indicated air speed, the wind (actual and/or to come) and the expected IAS on the sub leg,
- the height could be given by the pilot and be limited by safe margin (dedicated for each helicopter type or triggered by regulation requirements)

We obtain a skeleton of the trajectory (figure 4).

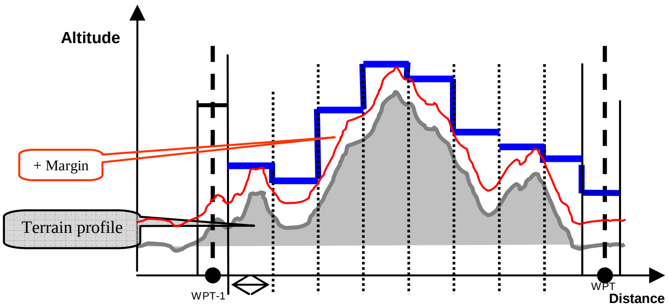

Figure 4: Skeleton of the trajectory colored in blue

In the second stage of the algorithm, position and size of these sub legs, and thus the skeleton are optimized. The following formula is used (figure 5) (figure 6):

$$\int_{T_0}^{T_f} \delta(x)dx = \int_{T_0}^{T_f} Ztdc(x)dx - \int_{T_0}^{T_f} Zt(x)dx$$

x is the curvilinear abscissa of the flight path;
$Ztdc(x)$ represents the altitude of the trajectory;
$Zt(x)$ represents the height of the overflown terrain;
T_0 represents the beginning of the main leg;
T_f represents the end of the main leg in question, and
$\delta(x)$ is the height above the terrain (figure 5)

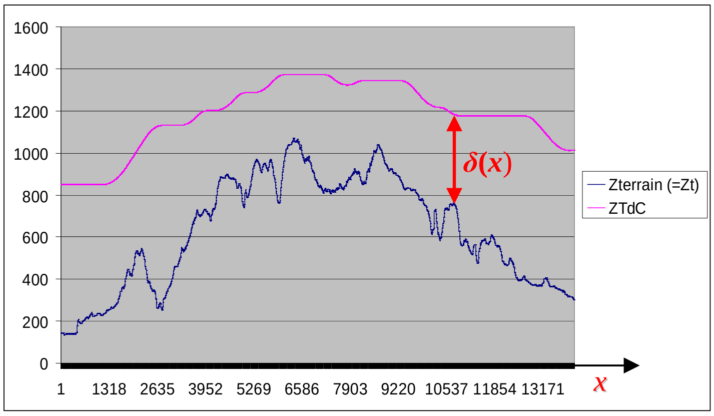

Figure 5: Trajectory above the terrain example with δ function.

Then by moving sub waypoints, we intend to have the lowest height above the terrain with the result of: $Min\left(\int_{T_0}^{T_f} \delta(x)dx\right)$

On the example bellow (figure 6), we reduce by ~5% the height above the terrain. The gain is between 5% and 15% depending of the terrain relief.

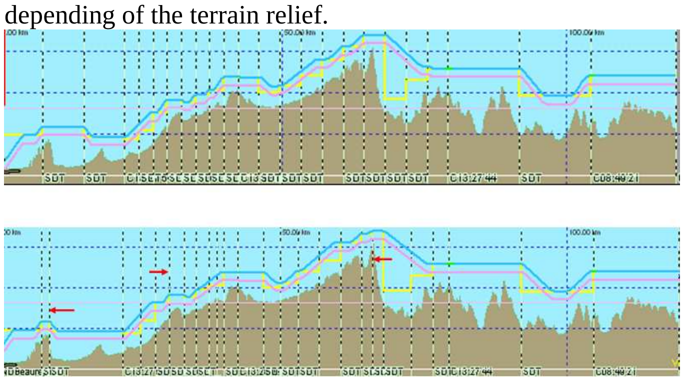

Figure 6: Position optimization example (blue line is the trajectory and pink one a protection margin)

In order to minimize the duration on the highest points of the LLF path, an algorithm is used in order to reduce the sub leg size at these points (figure 7).

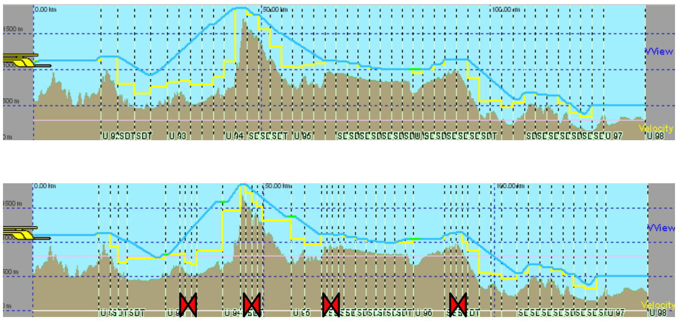

Figure 7: Highest sub leg reduction example

Operational advantages and limitations

The main goal of this system is to fly at constant altitude on sub legs, using the lowest altitudes possible regarding H/C capabilities given by the FMS [3] (figure 3).

This solution offers a good comfort of flight and has the advantage to be prepared interactively before or during flight.

Nevertheless, with these straight trajectories, the H/C is not very close to the terrain and wind variation is not easy to take into account. Additionally, the H/C position has to be robust and potential threats and terrain collision shall be taken into account.

Now the third dimension (and fourth: the time) is strongly expected at FMS level in order to allow flying above the terrain thanks to continuous and defined 3D+T flight paths inline with H/C capabilities.

The DO-236 [7] requires high altitude flight level (thanks to air control inputs) but without any predictive terrain reference for en route phases. This regulation is oriented towards airlines and H/C specific cases need to be addressed. Low level flight is not needed for transit or regular flights but more for EMS or to secure H/C in sudden bad weather conditions.

In front of regulation evolution, in order to achieve this goal, following assets would be mandatory:

- Have a dual (or tri) FMS with continuously calculated trajectories based on Height Above Terrain
- Ensure the continuity and the integrity of the position. Thanks to multi GNSS sources well monitored (with inertia and/or position matching with Radio Altimeter and terrain database)
- Have accurate and robust databases with obstacles [10] [11]. DTED® (at least level 2) [12]
- Secure the H/C in front of unprepared aircrafts (TCAS) and/or obstacles with an Obstacle Warning System
- Define adapted DAL (Development Assurance Level) [8][9]regarding expected security level of the function

III. OBSTACLE CONTOUR LINE TO FOLLOW THE TERRAIN

To perform LLF with navigation system, Obstacle Warning System and HUD (Head-Up Display) for flight (simulation testing), a new architecture was designed (see figure 8). Firstly the term of Safety Line (SL) is sometimes used, but in order to avoid any misunderstanding with aeronautic safety items, the wording Obstacle Contour Line (OCL) is preferred.

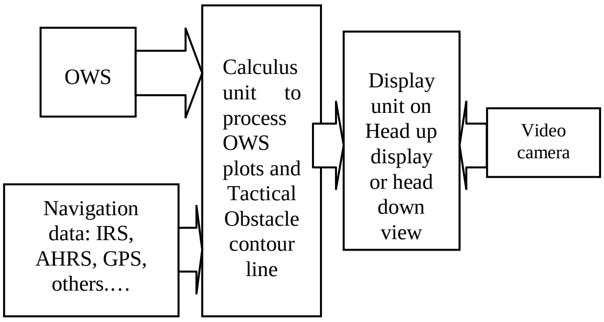

Figure 8: System architecture overview

Definition of the Obstacle Contour Line [13]:

A hypothetical curve is calculated, in regards to the aircraft and associated with an optimal trajectory for clearing an obstacle in a vertical plane. The field in front of the aircraft is subdivided into angular sectors and, for each one, the following steps are performed (see figure 9):

a) All obstacles located in a search area are identified;

b) The obstacle peaks are compared with the theoretical curve;

c) An obstacle is defined as dangerous if a top point is located highest with respect to the hypothetical curve; and

d) The coordinates of the top of this dangerous obstacle are communicated (and displayed).

The way to compute the obstacle contour line is very challenging. An efficient OCL algorithm should allow:

- *Good rendering of terrain imaging*
- *Natural stability without filtering*
- *Clearance of any approaching obstacle*
- *Dependent on aircraft speed and related characteristics*
- *Real-time computation time on an embedded H/W (dedicated computer or MFD partition)*
- *Precise trajectory control*

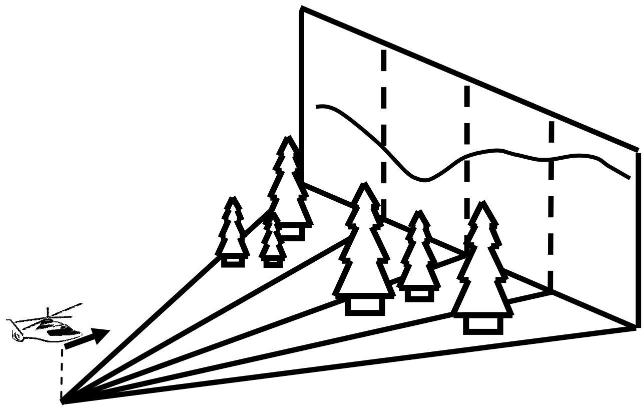

Figure 9: Obstacle Contour Line construction

Basic use concept of terrain following with obstacle contour line [1] [14]

An improved Obstacle Contour Line featuring a static guard curve which has been determined as a function of the H/C performances and obstacle position, has been developed, in order to optimize the calculation of all possible wide field of use trajectories, so as performing (with the help of an obstacle detector device and/or database's) some contour flights.

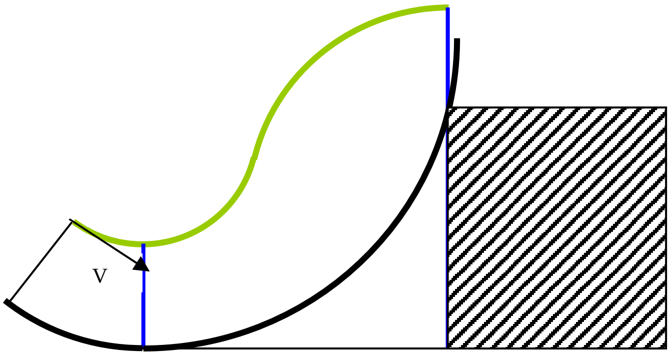

Figure 10: Static guard curve (safe margin in blue)

In order for the pilot to follow the best possible trajectory in a vertical plane relative to the ground relief ahead of him, an Obstacle Contour Line is computed as a function of the aircraft capabilities.
The pilot can select and/or parameterize:

- height of the safe margin
- load factors (with limits inline with H/C model)
- caution and warning times (with limits linked to HTAWS regulations standards [4] [15])

The information displayed from the OCL can act as a "flight director" to the pilot and must inform him whenever it is necessary to either to go up (pull up) or down (pull down) in order to fly as closely as possible to terrain and obstacles considering a given safe margin on guard height. Then the pilot has only to pay attention to maintain his speed vector on the OCL and choose his heading regarding where he wants to go.

Algorithm description

A first guard curve (see figure 10) is determined, referred to as a "static" guard curve, as a function in particular of a pull-up radius of curvature and of a pull-down radius of curvature. It comprises a first circular arc of radius equal to the sum of the curvature pull-down radius plus the guard height relative to the ground, and a second circular arc tangential to the first circular arc, the tangent being horizontal and of a radius equal to the sum of the curvature pull-down radius plus the curvature pull-up radius.
These two radii are respectively determined as a function of a pull-up and a pull-down load factor; and also as a function of the aircraft velocity modulus.
The OCL algorithm then computes distance *D* (figure 11) between the static guard curve and the terrain by calculating the distances between said curve and each of respective corresponding points of the terrain profile having coordinates that are calculated from the coordinates of plots delivered by a telemeter or databases (terrain and obstacles when available) and from aircraft position information delivered by a navigation system, and then determining the smallest of said distances, and attributing its value to said distance *D*.

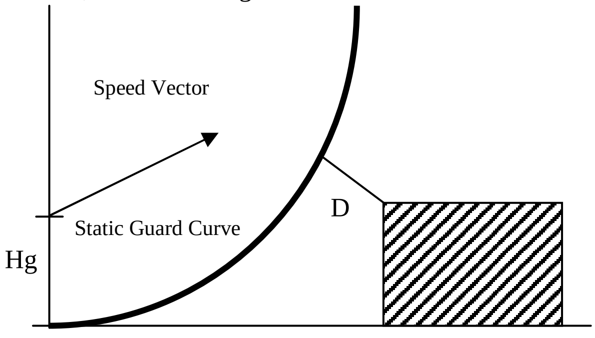

Figure 11: static guard curve

The pull-down or the pull-up order is also a function of the aircraft approach velocity at which the terrain profile and/or the obstacles is/are approaching the static guard curve. The approach speed being calculated using the formula:

$\frac{\Delta D}{\Delta t}$ where:

ΔD: is the variation in the distance *D* evaluated between two successive time markers (or instants), and

Δt: is the time that elapses between these two time markers.

A warning time τ is selected and a pull-up order is produced when the sum of the distance *D* plus the product of the warning time τ multiplied by the approach velocity is negative; and in contrast, when the said sum is positive, a pull-down order is produced.
In order to produce a pilot aid curve for each terrain profile (vertical plane), the method comprises the selection of the profile point that corresponds to a maximum pull-up order. When such a point does exist, (i.e. the point for which the absolute value said sum, which in this case is negative) is at a maximum. When said sum S is positive (which corresponds to a pull-down order, or zero, for all of the points of the terrain profile under consideration) it is possible to select the profile point for which the absolute value of said sum is at a minimum, in order to fly as closely as possible to the ground or obstacles. Alternatively, it is possible under such circumstances to select a profile point for which the following formulae T: $-\frac{D}{\frac{\Delta D}{\Delta t}}$ is at a minimum, in order to issue less frequent pull-down orders (figure 12).

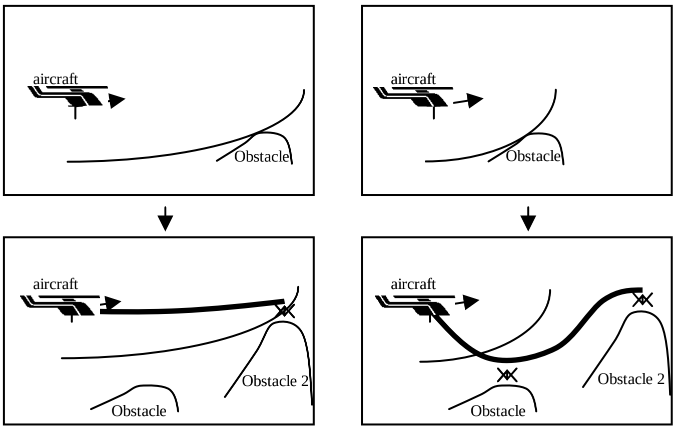

Figure 12: Variation of the warning time examples

By keeping the profile point as selected in this way for each of the terrain profiles corresponding to a lateral angle (e.g. from left to right) of the pilot field of view – or of the aircraft front space– and by producing a graph about this sight and relative bearing angles related to these profile points, a piloting curve is obtained that can be provided to the pilot.
Such a curve is preferably superimposed to the said field of space image, together with an artificial horizon line and a hair cross which represent the aircraft's current velocity vector (figure 14)

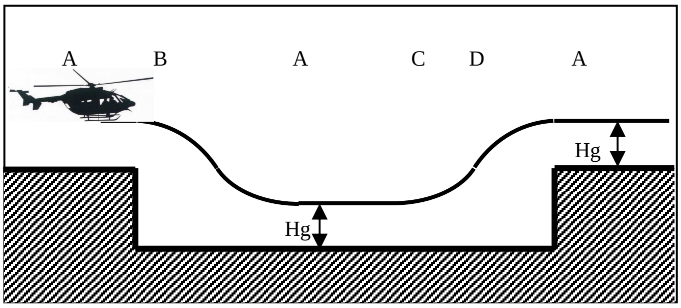

Figure 13: terrain following trajectory in vertical plane

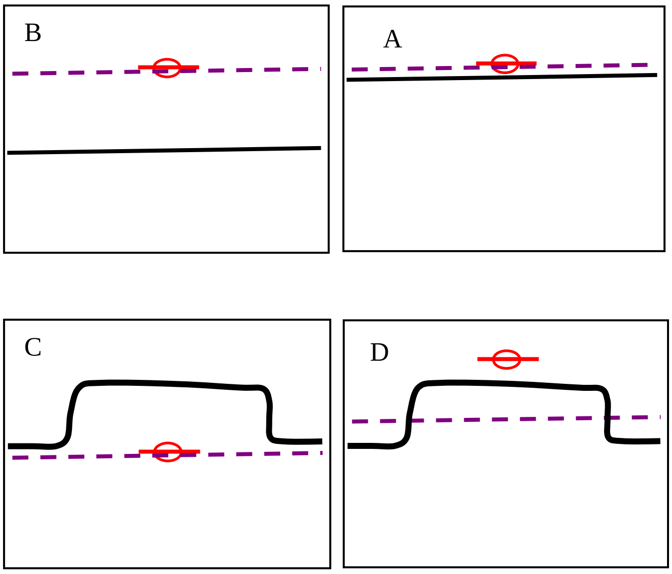

Figure 14: OCL corresponds to respective stages of flight shown in figure 13 (speed vector in red, OCL in black and artificial horizon in purple).

Operational advantages and limitations

The main advantage of this solution is to allow the pilot to fly close to the terrain with a permanent overview of where he can easily fly with continuous altitude variation during the flight.

With only an approximate idea of the road, without prior knowledge of the way to follow, except an approximate heading, the Obstacle Contour Line displayed on a Head Up Display (HUD) with appropriate symbols helps the pilot to fly safer at low altitude even if he is in bad vision conditions (fog, snow, night …)

Nevertheless, flight incorporating the OCL is not performed automatically (flight mechanic linked with AFCS) today, so it could increase the pilots workload.

Regular altitude variations are well suit to be close to the terrain, but consequently it is not comfortable for passengers (especially for EMS purpose).

Today there is no standard applicable for such solution. As piloting information on a HUD (or head down display) for awareness only, the HTAWS is the closest existing solution. Maybe in a first step this target is achievable, but for the future, we address a piloting help system. In order to develop and integrate such solution for civilian purpose, following points are today mandatory:

- Have a HUD with external view (with SVS/EVS based on Obstacle Warning System if relevant [16])
- Ensure the continuity and the integrity of the position. Thanks to multi GNSS sources well monitored (with inertia and/or position matching with Radio Altimeter and terrain database')
- Have accurate and robust databases, including obstacles. DTED® (at least level 2)
- Secure the H/C in front of other aircrafts (TCAS)
- Use an autonomous Obstacle Warning System in order to detect all obstacles and especially wires. By autonomous we mean independent of the GPS: telemetric coherent solutions or using speed extraction [17]
- Define adapted DAL (Design Assurance Level) regarding expected level of the function

IV. SUMMARY OF PRESENTED METHODS: THE FUTURE?

Each described solution described in this paper can be used in VMC or IMC conditions with advantages and drawbacks.

VMC:

If the pilot really wants to fly close to the terrain, the LLF algorithm could be not sufficient (proximity of obstacles which can not be in data bases) and the OCL use permits to fly as low as possible with the benefit of having external references even if the H/C has numerous altitude variations.

IMC:

Without any external view, following a trajectory such as the LLF one seems more comfortable for passengers and pilot. However, use of the OCL algorithm requires an absolute confidence in the system and lead to a huge workload for the pilot.

The Obstacle Contour Line could be based on databases and/or Obstacle Warning System. With databases, the OCL solution is limited by the accuracy and the completeness of the obstacles database. With Obstacle Warning System, main limits are the sensor's wire detection probability and its all weather capabilities.

The FMS3D+T LLF altitude is only based on terrain database and obstacle database. Even if the height above terrain takes into account safe margins, the only problem is when all wires and/or obstacles are not well stored in the database.

In order to improve and secure low level flight applications, with the LLF algorithm (FMD3+T), a smart idea could be the combination of it with the OCL symbology in order to monitor the margin in front of the H/C, thus made by the help of an Obstacle Warning System (in order to ensure the independence in front of the database) (figure 15)

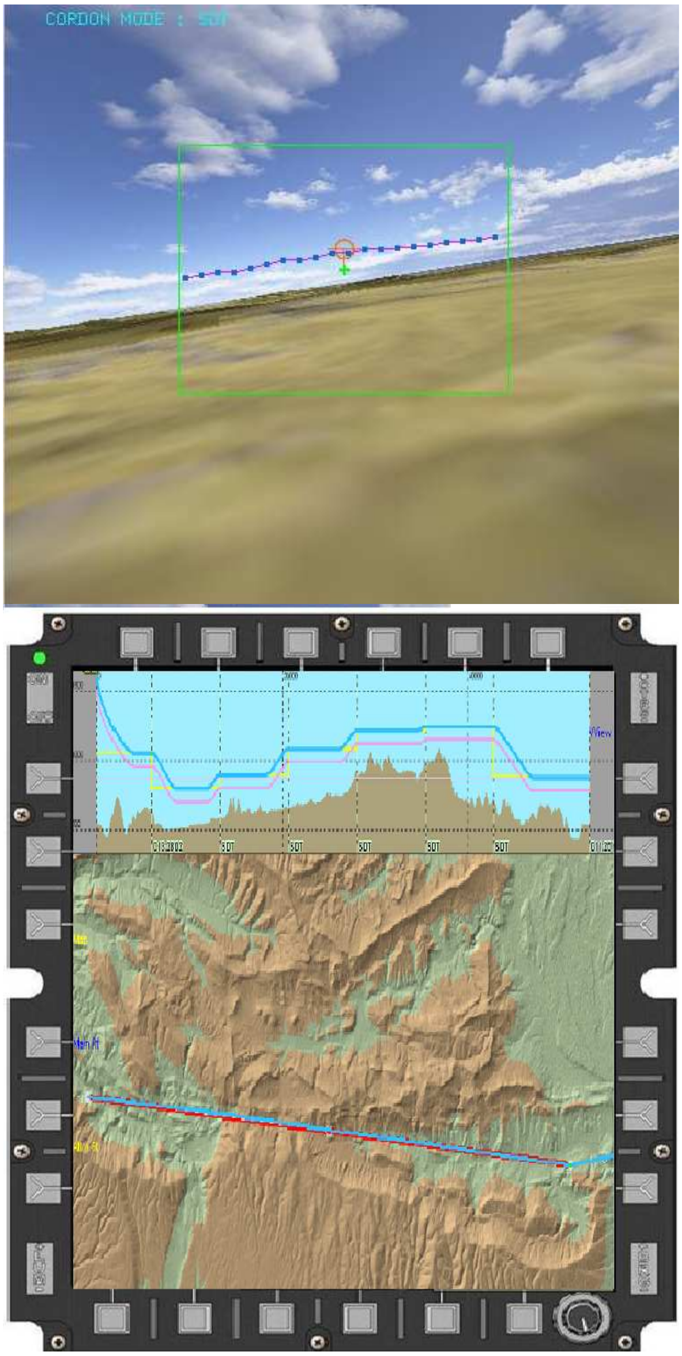

Figure 15: Obstacle Contour Line view on HUD in order to monitor height above the terrain with LLF followed displayed on DMAP Multi Functional Display with vertical view of the flight path.

Some new assets for low level flight solutions have been proposed in chapter II and III. Summarized hereafter are points that need to be addressed in the future in order to allow H/C low level flights regarding our algorithms general design:

- Have a dual (or tri) FMS with continuous trajectories based on Height Above Terrain
- Ensure the continuity and the integrity of the position. Thanks to multi GNSS sources well monitored (with inertia and/or position matching with RA and terrain database')
- Have a HUD with external view (with SVS/EVS based on Obstacle Warning System if relevant [16])
- Have accurate and robust databases [10][11], including obstacles. DTED® (at least level 2)
- Perform regular updates of obstacles databases
- Secure the H/C in front of other aircrafts (TCAS)
- Use of an autonomous Obstacle Warning System in order to detect all obstacles and especially wires. By autonomous we mean independent of the GPS (telemetric coherent solutions or using speed extraction [17])
- Use an all weather (with dust, fog, snow and rain) Obstacle Warning System able to detect all suspended wires with all incidences
- Define adapted DAL (Design Assurance Level) regarding expected level of the function for H/W and S/W
- Define back up altitudes or landing alternatives if possible when H/C problems occur (engine lost, impact …).

In order to develop and commercialize such solutions, an accurate V&V process with specific tools (for S/W an integration aspects) shall be used to fulfill certification objectives.

Minimum aviation (H/C) system performance requirements standards shall be specifically defined for H/C flights with a dedicated part for low level flights.

New legs type definitions for H/C applications continuously defined have to be issued in the third (space) and the fourth (time) dimensions.

There are today several situations when pilots need to fly at low altitude. More than flying at low altitude when it is not needed, our solutions intend to bring safety improvements for unprepared or problematic situations when it would be mandatory to conduct the flight to the end.

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