open science

# Dynamic autonomous decision-support function for piloting a helicopter in emergency situations 

Konstanca Nikolajevic

## To cite this version:

Konstanca Nikolajevic. Dynamic autonomous decision-support function for piloting a helicopter in emergency situations. Modeling and Simulation. Université de Valenciennes et du Hainaut-Cambresis, 2016. English. NNT : 2016VALE0008 . tel-01468013

## HAL Id: tel-01468013 <br> https://theses.hal.science/tel-01468013

Submitted on 15 Feb 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Thèse de doctorat
Pour obtenir le grade de Docteur de l'Université de
VALENCIENNES ET DU HAINAUT-CAMBRESIS
Discipline, spécialité selon la liste des spécialités pour lesquelles l'Ecole Doctorale est accréditée :

## Informatique

Présentée et soutenue par Konstanca, NIKOLAJEVIC.
Le $03 / 03 / 2016$, à Valenciennes
Ecole doctorale :
Sciences Pour l'Ingénieur (SPI)
Equipe de recherche, Laboratoire :
Laboratoire d'Automatique, de Mécanique et d'Informatique Industrielles et Humaines (LAMIH)

## Système décisionnel dynamique et autonome pour le pilotage d'un hélicoptère dans une situation d'urgence.

## JURY

## Président du jury

- Rezg, Nidhal. Professeur. Université de Lorraine.


## Rapporteurs

- Billaut, Jean-Charles. Professeur. Université François Rabelais Tours.
- Sevaux, Marc. Professeur. Université de Bretagne-Sud.


## Examinateurs

- Rezg, Nidhal. Professeur. Universite de Lorraine.
- Terrasse, Isabelle. Professeur chargée de cours à l'Ecole Polytechnique de Paris, Expert Executif Airbus Group.


## Directeur de thèse

- Artiba, Abdelhakim. Professeur. Président de l'Université de Valenciennes et du Hainaut-Cambresis.

Co-encadrant industriel : Belanger, Nicolas. Docteur. Responsable des programmes innovation avionique, Airbus Helicopters
Co-encadrant : Duvivier, David. Maître de conférence, HDR. Université de Valenciennes et du Hainaut-Cambresis
Co-encadrant : Ben Atitallah, Rabie. Maître de conférence, HDR. Université de Valenciennes et du Hainaut-Cambresis

## Membres invités

- Bestaoui, Yasmina. Professeur. Université d'Evry Val d'Essone.


# PhD Thesis <br> Dynamic Autonomous Decision-Support Function for Piloting a Helicopter in Emergency Situations 

Konstanca Nikolajevic
Airbus Helicopters
University of Valenciennes and Hainaut-Cambresis

A mes parents,

## Remerciements

Mes remerciements s'adressent tout d'abord à Airbus Helicopters et l'Université de Valenciennes et du Hainaut-Cambresis qui ont rendu ce travail de recherche possible.

Je tiens à remercier mon directeur de recherche ainsi que mes nombreux encadrants qui ont su me laisser une marge de liberté suffisamment importante afin de mener à terme ce grand projet de trois ans. Je les remercie de m'avoir accordé du temps dans les moments les plus insolites.

Une pensée particulière pour David Duvivier et pour son acceuil chaleureux lors de mes déplacements au labo (les boites de chocolat et de bonbons qui m'attendaient sur mon bureau :), sans compter celles qu'ils gardait en réserve dans son tiroir). Vivent les mi-chocos !! Je remercie David d'avoir passé un temps précieux y compris en congés et en weekends à travailler avec moi sur cette thématique de recherche car il n'a pas toujours été facile de nous synchroniser pour travailler à distance pendant 3 ans.

J'addresse également ma profonde gratitude à Nicolas Belanger, mon encadrant de thèse industriel chez Airbus Helicopters. Nicolas a su me mettre à l'épreuve durant ces années de thèse; cela a renforcé ma motivation et mon profond intérêt pour ce travail. Je le remercie tout particulièrement pour sa confiance et son soutien inconditionnels, ainsi que pour les moments qu'il a consacrés à me former sur des sujets de recherche innovants pour Airbus Helicopters.

Je tiens à remercier mon jury de thèse pour l'intérêt qu'il a porté à ce travail de recherche.
Je remercie chaleureusement les équipes du bureau d'études d'Airbus Helicopters et en particulier l'équipe du département Innovation dans lequel $j$ 'ai fait mes premiers pas en tant qu'ingénieur et en tant que chercheur.

Je remercie également Marc Greiller et Patrick Pezzatini du département flight safety, Stéphane Morel du bureau d'études et enfin Aurgustin Dupuis, Hervé Jameyrac et Didier Delsalles du département des essais en vol d'Airbus Helicopters pour leur aide précieuse en ce qui concerne le choix des cas d'études qui ont été traités dans ce travail ainsi que leurs retour d'expérience sur les accidents opérationels abordés dans cette étude.

Enfin je tiens à saluer les personnes qui de près ou de loin ont contribué à la concrétisation et à l'achèvement de ces travaux, dans le cadre de ma thèse de doctorat. Merci à Marko Mladenovic pour les cartes qu'il a générées et qui ont servies à effectuer la plupart des tests mentionés dans cette étude.

Merci à mes amies Farah, Iris et Morgane sur lesquelles j'ai pu compter pour me changer les idées dans les moments les plus difficiles!

Pour terminer je tiens à remercier ma famille, mes parents et mes deux petites soeurs, qui n'ont cessé de me soutenir pendant toutes les étapes importantes de ma vie. J'ai toujours pu compter sur eux et je sais que je leur dois beaucoup.

Un GRAND MERCI à tous et à bientôt $;$
Konstanca

## List of Tables

4.1 List of parameters extracted from the Flight Data produced in the simulation environ- ment and necessary to the construction of the analytical model ..... 74
4.2 Total curvilinear abscissa of flight trajectories with and without a turn ..... 96
5.1 Warning rules as risk indicators for the system ..... 121
6.1 Criteria description and influence ..... 135

## List of Figures

1.1 U.S. IHST Accident Rate Reduction Goal and Progress - taken from [96] ..... 21
1.2 Worldwide Civil Helicopter Accidents/Year - taken from [96] ..... 21
1.3 Standard Problem Statements - taken from [96] ..... 22
1.4 Accident Causes - taken from [11] ..... 23
1.5 A Layered Approach to the Problem Statement ..... 25
2.1 Status of technology deployment and remaining challenges [70] ..... 31
2.2 Framework for the Design and Evaluation of Autonomous Systems [70] ..... 32
2.3 Concept of a Work System [38] ..... 34
2.4 Organisational Structure of Conventionally i.e. Hierarchically Automated Human- Machine Systems taken from [38] ..... 34
2.5 Work System with a unit par of the Operation-Assisting Means[38] ..... 36
2.6 Work System in configuration "Co-operative Automation" [38] ..... 37
2.7 A grid of waypoints in front of the vehicle reachable by motion primitives taken from [58] ..... 38
2.8 Examples of the path-planner [58] ..... 39
2.9 Avoidance trajectories to collision threat [19] ..... 40
2.10 "Generation of motion primitives: (a) A reachability tree for a fixed-wing UAV stopped at the third depth (b) Precomputed motion primitives at different starting states" [58] ..... 43
2.11 Pre-computed motion primitives taken from [80] ..... 43
2.12 Example of Dubins path in 3D taken from [78] ..... 44
2.13 Example of path planning [58] ..... 45
3.1 Accident loop made up of undesirable events $E_{1}, E_{2}, E_{3}, E_{4}$, etc provoked by an undesirable event $E^{\prime}$ ..... 51
3.2 CFIT Accident Causes - taken and translated from [1] ..... 56
3.3 RAMSES functional architecture ..... 58
3.4 Classifier functional bloc - detailed view ..... 62
4.1 RAMSES functional architecture - focus on the Trajectory Generation functional bloc ..... 68
4.2 From the Helicopter's Simulated Flight Loop to the Mathematically Computed Tra- jectories ..... 70
4.3 The three degrees of freedom actioned by the Basic Flight Loop ..... 71
4.4 A space curve; the vectors $\mathbf{T}, \mathbf{N}$, and $\mathbf{B}$; and the osculating plane spanned by $\mathbf{T}$ and $\mathbf{N}$ ..... 73
4.5 An avoidance trajectory is composed of three sequence manoeuvres ..... 75
4.6 Sets of alternative avoidance manoeuvres to the current path, low and strong solicita- tion, equally oriented in the three-dimensional space frame. ..... 75
4.7 One typical trajectory of the immediate environment reachable by the aircraft in 30 seconds of flight ..... 76
4.8 Envelope of avoidance trajectories with three different sections composed of motion primitives ..... 76
4.9 Curvature profiles obtained from simulation data, with Bezier curves smoothing - results computed for different roll angles ..... 77
4.10 Framework of the curvature distribution for a lateral trajectory as a function of the curvilinear abscissa ..... 78
4.11 Results for a lateral trajectory during 30s of flight - simulation (red) and computed trajectory (blue) ..... 78
4.12 Curvature profiles obtained from simulation data, with Bezier curves smoothing for climb trajectories at different vertical speeds ..... 79
4.13 Diagram of the curvature distribution for a climb trajectory ..... 79
4.14 Results for a climb trajectory on 12 seconds ..... 80
4.15 Distribution of the curvature $\kappa$ for oblique trajectory with $1000 \mathrm{ft} / \mathrm{min}$ vertical speed and 20 degrees roll angle ..... 81
4.16 Diagram of curvature $k$ and remaining climb angle $\theta$ distributions for the three- dimensional spiral transition ..... 82
4.17 Framework of the design of the 3D spiral transition as a series of infinitesimal spirals (blue), top view ..... 82
4.18 Framework of the oblique trajectory with the three-dimensional spiral transition (blue) connected to the helicoidal path (red) at point $P$ ..... 83
4.19 Change of torsion on a cylinder for the 3D spiral transition (red curve) with curvature constant along the transition and equal to $k_{\max }$ ..... 84
4.20 Three-dimensional spiral transition ..... 85
4.21 Three-dimensional view of the problem ..... 86
4.22 Two dimensional top view of the problem ..... 87
4.23 Finding plane $(\mathscr{P})$, the link between $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ with $A P_{1}<B P_{2}$ - top view ..... 89
4.24 Cylinder $\left(\mathscr{C}_{1}\right)$ with the helix spiral and the 3D transition spiral connecting $M$ ..... 89
4.25 Framework of the curvature along the three-dimensional trajectory between A and B given by the thick black polygonal chain ..... 89
4.26 Connecting two different flight levels with a three-dimensional trajectory ..... 92
4.27 3D Trajectory computed with the Dubins gliding symmetry conjecture ..... 93
4.28 Finding plane $(\mathscr{P})$, the link between $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ with $A P_{1}<B P_{2}$ - top view ..... 94
4.29 3D Trajectory computed without pivot ..... 95
4.30 3D Trajectory computed with and without pivot ..... 95
5.1 RAMSES functional architecture - focus on the Trajectory Evaluation and Risk As- sessment functional blocs ..... 99
5.2 Danger zone computed 150 meters above the ground (yellow) and terrain elevation data (white) ..... 101
5.3 Mesh of a the terrain elevation matrix (white) and the three coordinate mapping of the helicopter path (turquoise) ..... 102
5.4 Example of a safe flight situation with respect to the Danger Zone, the trajectories are all above the danger zone ..... 102
5.5 Example of a dangerous flight situation with respect to the Danger Zone ..... 103
5.6 Reduction of the number of points of the trajectory in order to estimate the collision risk ..... 103
5.7 Focus on a cell of the danger zone mesh ..... 104
5.8 Safe flight situation with many safe (green) trajectory solutions available ..... 105
5.9 Less safe flight situation, the safe (green) trajectory solutions start to disappear ..... 106
5.10 Not safe flight situation, the safe (green) trajectory solutions are all gone ..... 106
5.11 Drop in the total number of safe trajectory solutions when the aircraft flies straight to a danger zone ..... 107
5.12 Drop in the total number of safe trajectory solutions when the aircraft flies close to a danger zone and moves away ..... 107
5.13 Helicopter flies towards a cliff ..... 108
5.14 Drop in the number of remaining trajectory solutions when the helicopter flies towards a cliff ..... 109
5.15 Transfer of cardinal between the different sets of trajectory solutions with steps $\mathbf{1}$ to 3 from Fig. 5.14 ..... 110
5.16 Helicopter flies over a cliff ..... 111
5.17 Drop in the number of trajectory solutions when the helicopter flies over a cliff ..... 112
5.18 Helicopter flies towards a cliff and moves away ..... 112
5.19 Drop in the number of trajectory solutions when the helicopter flies towards a cliff and moves away ..... 113
5.20 Framework of a trajectory composed of four sections ..... 115
5.21 Example of a TAWS function display, dedicated to the Helicopter flight, manufactured by Sandel Avionics - http://www.sandel.com ..... 118
5.22 Density of trajectories (dsol1 to dsol8) - exploded view in the three-dimensional frame linked to the terrain ..... 119
5.23 Case where the aircraft goes close to the cliff and moves away - illustration with low soliciting trajectories ..... 122
5.24 Case where the aircraft goes close to the cliff and moves away - density of solution ..... 122
5.25 Case where the aircraft goes close to the cliff and moves away - display of the time to obstacle of the extrapolated trajectory of the current state ..... 123
5.26 Case where the aircraft goes close to the cliff and moves away - simulated HTAWS alarms ..... 123
6.1 RAMSES functional architecture - focus on the Classifier and the Decision Making functional blocs ..... 128
6.2 Preference function: linear shape ..... 129
6.3 Preliminary use case where the helicopter goes towards the terrain and moves away ..... 138
6.4 Preliminary use case where the helicopter goes straight towards the terrain ..... 140
6.5 Preliminary use case where the helicopter goes straight towards the terrain with best ranked trajectories ..... 140
7.1 Helicopter path smoothed using the Bezier curves - 3D view ..... 144
7.2 The three-dimensional test environment rendered with the OpenGL API with the 3D flight position coordinates ..... 145
7.3 The danger zone 150 meters above the ground with low soliciting trajectory solutions intersecting it ..... 146
7.4 Example of the best avoidance trajectory solution ranked by PROMETHEE II for successive 3D positions ..... 147
7.5 Time to obstacle given for the extrapolated trajectory of the current flight state, given with respect to a danger zone computed 200 meters above the terrain elevation ..... 148
7.6 Distribution of the density of solutions in the 3D frame for directions described in Fig. 5.22, for the danger zone computed 200 meters above the ground ..... 148
7.7 Results of alarms given by the simulated TAWS during the flight, by analysis of col- lision with a danger zone computed 200 meters above the ground ..... 149
7.8 Distribution of the density of solutions in the 3D frame for directions described in Fig. 5.22, for the danger zone computed 50 meters above the ground ..... 149
7.9 Time to obstacle given by the extrapolated trajectory 10,20 and 30 seconds before the impact with the danger zone situated 50 meters above the terrain ..... 150
7.10 Display of the top 5 trajectory solutions ranked by PROMETHEE II for successive positions along the path in the Type special CFIT configuration ..... 152
7.11 Focus on top 5 trajectory solutions ranked by PROMETHEE II for 30 (cyan) and 20 (yellow) seconds time to obstacle of the extrapolated trajectory (magenta). The danger zone is computed 50 meters above the terrain elevation data. ..... 153
7.12 Diagram of the positions with directions before the crash (occurred at point C) ..... 155
7.13 One possible trajectory connecting the three last positions known of the aircraft before the crash ..... 156
A. 1 Three-dimensional spiral transition with linear curvature and parabolic torsion ..... 176
A. 2 Three-dimensional Euler spiral, with linear curvature and torsion. ..... 177
A. 3 Space curve computed with increasing torsion. ..... 178
A. 4 Analysis of path-planning recordings for the Dubins Gliding Symmetry curve fitting ..... 179
A. 5 Analysis of the helicopter path of the use case developed in Chapter 7 ..... 180
B. 1 Case when the simulated TAWS detects a danger while the extrapolated trajectory of the current state does not encounter a collision threat ..... 182
B. 2 Case when the simulated TAWS does not detect a danger threat while the extrapolated trajectory of the current state enters in collision with a danger zone ..... 183

## Contents

1 Introduction ..... 19
1.1 Context ..... 20
1.2 Problem Statement and Objectives of the Study ..... 23
1.2.1 A layered approach to the Problem Statement ..... 24
1.2.2 Expectations and work hypothesis ..... 24
1.3 Contributions ..... 26
1.4 Structure of the document ..... 27
2 State of the Art - Discussion around the Related Works ..... 29
2.1 Introduction ..... 29
2.2 "Autonomy is a capability" [70] ..... 29
2.2.1 Framework for the design and evaluation of autonomous avionics systems ..... 29
2.2.2 Autonomy versus Automation ..... 33
2.3 Rendering the aircraft's future states ahead of the current position ..... 37
2.3.1 Approach by Motion Primitives for Short-Term Navigation Safety-Monitoring ..... 37
2.3.2 Dubins-like three-dimensional path-planning ..... 44
2.4 Dynamic Decision Making and notification of alarms reflecting the operational reality of the flight ..... 45
2.5 Conclusion and positioning ..... 47
3 RAMSES Functional Architecture ..... 49
3.1 Introduction ..... 49
3.2 Methodology of research ..... 49
3.2.1 Understanding the Accident Loop ..... 49
3.2.2 Positioning within Airbus Helicopters ..... 52
3.2.3 Definitions - Glossary ..... 52
3.3 Limits of the present study - Hypothesis ..... 54
3.3.1 Set of assumptions ..... 54
3.3.2 Objectives of the thesis ..... 54
3.4 Validation of the concepts ..... 54
3.5 The RAMSES Functional Architecture ..... 57
3.6 Bloc Diagram Definition ..... 59
3.6.1 Trajectory Generation Functional Bloc ..... 59
3.6.2 Trajectory Evaluation functional Bloc ..... 59
3.6.3 Risk Evaluation Functional Bloc ..... 60
3.6.4 Classifier functional Bloc ..... 61
3.6.5 Decision Making Functional Bloc ..... 63
3.6.6 Interfaces ..... 64
3.7 Conclusion ..... 65
4 RAMSES: Trajectory Generation Functional Bloc ..... 67
4.1 Introduction ..... 67
4.2 From the dynamic model of the aircraft to the mathematical characterization of the flight ..... 69
4.2.1 Process mapping - Using a Helicopter Flight Loop in a Simulated Environment ..... 69
4.2.2 Smoothing of the Flight Data Collected in Simulation ..... 72
4.2.3 Construction of the Trajectories Composing the Physical Environment, Image of the Helicopter's positions extrapolated to 30 seconds of Flight ..... 74
4.3 Trajectories Extracted from the simulation model ..... 77
4.3.1 Design of Lateral Trajectories ..... 77
4.3.2 Design of Climb trajectories ..... 78
4.3.3 Design of Oblique trajectories - focus on the three-dimensional spiral transition ..... 79
4.3.4 Extrapolated trajectory to 30 seconds of flight ..... 85
4.4 Computing an efficient three-dimensional trajectory between two positions for a heli- copter flight ..... 86
4.4.1 Positionning of the problem ..... 86
4.4.2 Finding the plane containing the straight line between $S_{2}$ and $S_{3}$ with the Dubins gliding symmetry conjecture ..... 88
4.4.3 Finding the final torsion distribution on $\left(\mathscr{C}_{2}\right)$ ..... 90
4.4.4 Connecting two different flight levels with a three-dimensional trajectory ..... 90
4.4.5 Comparison with the "3D Dubins-like path" ..... 92
4.4.6 Finding a three-dimensional trajectory with no turn ..... 93
4.5 Conclusion ..... 96
5 RAMSES : Identifying localized risk of collision in-flight ..... 97
5.1 Introduction ..... 97
5.2 Danger Zones ..... 100
5.3 Trajectory Evaluation ..... 101
5.4 In-flight Diagnosis of the Risk ..... 105
5.4.1 Trajectory Patterns - the disappearance of the reachable helicopter's environ- ment ..... 105
5.5 Multi-dimensional risk of collision assessment - Interpretation of the preliminary use cases ..... 114
5.5.1 Set of independent performance criteria ..... 115
5.5.2 Time to obstacle coupled to the minimum distance along the path ..... 116
5.5.3 Time to non solution ..... 116
5.6 Proposal of new warning rules conveying pilots experience in operational emergency situations that could lead to a crash ..... 117
5.7 Conclusion ..... 124
6 RAMSES : Decision Making ..... 127
6.1 Introduction ..... 127
6.2 Trajectories sorting and ranking ..... 129
6.3 Interview with flight test pilots and experts, Questionnaires and Experimental Initiatives ..... 130
6.3.1 Weighting of criteria ..... 130
6.4 Interpretation of Airbus Helicopters flight test pilots and experts interviews ..... 130
6.5 Criteria chosen for parametrizing PROMETHEE II ..... 131
6.6 Criteria valuation and influence ..... 133
6.7 Results on preliminary use cases ..... 135
6.8 Conclusion ..... 141
7 Practical application of the RAMSES avionics function ..... 143
7.1 Introduction ..... 143
7.2 First use case: RAMSES avionics function test along a helicopter path leading to a crash ..... 143
7.2.1 Accident Context and positioning of the problem ..... 143
7.2.2 Assessing the current flight situation ..... 144
7.2.3 The CFIT (Controlled Flight Into Terrain) accident scenario ..... 146
7.2.4 Conclusions on this accident scenario ..... 154
7.3 Path-planning - reconstruction of the last two minutes of an accident of the Airbus Helicopter fleet with 3D Trajectory Generation algorithms ..... 155
7.3.1 Accident context and positioning of the problem ..... 155
7.3.2 Reconstitution of an estimated path between the three last known waypoints before the crash ..... 156
7.3.3 Conclusion on this accident scenario ..... 156
8 Conclusion and Perspectives ..... 159
8.1 Outline of the study objectives ..... 159
8.2 Review of the contributions and findings ..... 160
8.3 Perspectives and future works for in-flight and ground applications ..... 161
A Approaching the curvature and the torsion ..... 173
B TAWS Bench ..... 181

## Résumé

Dans un contexte industriel aéronautique où les problématiques de sécurité constituent un facteur différentiateur clé, l'objectif de cette thèse est de répondre à la problématique ambitieuse de la réduction des accidents de type opérationnel. Les travaux de recherche s'inscrivent dans le domaine des systèmes d'alarmes pour l'évitement de collision qui ne font pas une analyse approfondie des solutions d'évitement par rapport à la situation de danger.

En effet, les situations d'urgence en vol ne bénéficient pas à ce jour d'une représentation et d'un guide des solutions associées formels. Bien que certains systèmes d'assistance existent et qu'une partie de la connaissance associée aux situations d'urgence ait pu être identifiée, la génération dynamique d'une séquence de manceuvres sous fortes contraintes de temps et dans un environnement non connu à l'avance représente une voie d'exploration nouvelle.

Afin de répondre à cette question et de rendre objective la notion de danger, les travaux de recherche présentés dans cette thèse mettent en confrontation la capacité d'évolution d'un aéronef dans son environnement immédiat avec une enveloppe physique devenant contraignante. Afin de mesurer ce danger, les travaux de recherche ont conduit à construire un module de trajectoires capable d'explorer l'espace en $3 D$. Cela a permis de tirer des enseignements en terme de flexibilité des manouures d'évitement possibles à l'approche du sol. De plus l'elicitation des connaissances des pilotes et des experts d'Airbus Helicopters (ancien Eurocopter) mis en situation d'urgence dans le cas d'accidents reconstitués en simulation a conduit à un ensemble de paramètres pour l'utilisation de la méthode multicritère PROMETHEE II dans le processus de prise de décision relatif au choix de la meilleure trajectoire d'évitement et par conséquent à la génération d'alarmes anti-collision.

## Mots-clés:

- Aide à la décision;
- Méthodes multi-critères;
- PROMETHEE (Preference ranking organization method for enrichment evaluation);
- Génération de trajectoires sous contraintes;
- Robotique aérienne mobile;
- Evitement de collision;
- Primitives de mouvement;
- Fonction avionique;
- Optimisation;
- Simulation.


#### Abstract

In the aeronautics industrial context, the issues related to the safety constitute a highly differentiating factor. This PhD thesis addresses the challenge of operational type accident reduction. The research works are positioned and considered within the context of existing alerting equipments for collision avoidance, who don't report a thorough analysis of the avoidance manoeuvres with respect to a possible threat.

Indeed, in-flight emergency situations are various and do not all have a formal representation of escape procedures to fall back on. Much of operational accident scenarios are related to human mistakes. Even if systems providing assistance already exist, the dynamic generation of a sequence of manoeuvres under high constraints in an unknown environment remain a news research axis, and a key development perspective.

In order to address this problematic and make the notion of danger objective, the research works presented in this thesis confront the capabilities of evolution of an aircraft in its immediate environment with possible physical constraints. For that purpose, the study has conducted to generate a module for trajectory generation in the 3D space frame, capable of partitioning and exploring the space ahead and around the aircraft. This has allowed to draw conclusions in terms of flexibility of escape manoeuvres on approach to the terrain. Besides, the elicitation of the Airbus Helicopters (former Eurocopter) experts knowledge put in emergency situations, for reconstituted accident scenarios in simulation, have permitted to derive a certain number of criteria and rules for parametrising the multicriteria method PROMETHEE II in the process for the relative decision-making of the best avoidance trajectory solution. This has given clues for the generation of new alerting rules to prevent the collisions.


## Keywords:

- Decision aid making;
- Multi-criteria methods;
- PROMETHEE (Preference ranking organization method for enrichment evaluation);
- Trajectory generation under dynamic constraints / path-planning;
- Aerial mobile robotics;
- Collision avoidance;
- Motion primitives;
- Avionics function;
- Optimization;
- Simulation.


## Chapter 1

## Introduction

Improvements related to Safety and Security of passengers constitute a highly differentiating factor in the aeronautics industry. This is why this issue remains one of the top priorities of the Airbus Group and of Airbus Helicopters. Airbus Helicopters fosters a working policy based on reactivity and transparency in case of accidents or incidents by collecting events having an impact on the fleet safety, the protection of occupants; and by cooperating with Investigation Boards and communicating with operators on protective measures to take in order to improve safety [11]. Conscious of accident rates helicopter operators are more and more concerned about the safety and they are demanding innovative solutions to prevent accidents.

The stakes covered by the dynamic autonomy of an aircraft represent a crucial technological challenge of tomorrow's helicopter and may refer to a wide range of development axes including accident reduction. The very concept of Autonomy may refer to various subjects such as Regulation, Air Traffic Management, Communication with the ATC ${ }^{1}$ or other stakeholders, Failure detection or Maintenance; but also to aircraft's dynamics properties centred issues such as Navigation, Automatic Pilot instruction handling, flight-ground transition and short-term long-term trajectory control. Improvements on these topics are highly engaged through serious academic and industrial research projects in collaborations with aeronautical groups like Airbus, as is the case of this study. Indeed, the work detailed in this PhD thesis is the result of a collaboration between the Innovation department of Airbus Helicopters in Marignane and the LAMIH (Laboratory of Industrial and Human Automation control, Mechanical engineering and Computer Science) of the University of Valenciennes and Hainaut-Cambresis. Due to the plurality of disciplines concerned in this study and due to the technological and research requirements necessary to conduct the design of a first demonstrator, in line with the industrial expectations, a collaboration with an academic entity, studying complex systems and their interactions, was essential.

The attitude to significant enhancement of complex autonomous systems is a key issue for many industrial and academic research entities. In this context, the Airbus work group RTG12 includes advanced research topics related to autonomy, to the delegation of tasks between several decisionmaking bodies based on negotiations between agents, on a multicriteria basis in line with the current situation of the flight. The discussions lead the way to perspectives around securing the aircraft in degraded flight conditions in which discharging the pilots with specific tasks may be useful for the

[^0]good progress of the flight. Indeed, the challenge of distributed intelligence between decision-making bodies interacting within a same system constitutes a strong research axis and a key development perspective for a thorough positioning on the safety and security business key differentiator sector over 2015-2016 year horizon.

To address this challenge, it seems important to understand what happens in flight when the accident scenario is taking place; how the difficulties start and grow into successions of undesirable events leading to the crash. Considering degraded in-flight situations confers an additional complexity to this study and implies a thorough understanding of emergency situations and their part in accident scenarios. Unfortunately, emergency situations in-flight are various and do not all have a formal representation of escape procedures to fall back on. Much of operational accident scenarios are related to human mistakes. An unique and proper solution in avionics, for reducing accident rates, is not yet available, and the problem has to be taken gradually and separately for each possible emergency situation or undesirable event. The first thoughts when designing an avionics decision-support function for piloting a helicopter in emergency situations with real-time ${ }^{2}$ constraints, proper to the flight, have lead us to consider that the study would probably need to focus on a limited corpus of representative accident causes. Due to the significant variability of the context related to the in-flight safety management, it seems necessary to position the study in relation with actual helicopter accident rates and causes, and more specifically towards the current technology in use.

### 1.1 Context

International Helicopter Safety Team (IHST) ${ }^{3}$ [96], and the European Helicopter Safety Team ${ }^{4}$ [51] provide an overview of the top factors in standard problem statements playing a role in helicopter accidents. It appears that "Pilot judgement and actions" and "Safety Management" take the lead (Fig. 1.3). Besides, recognizing that the rate of helicopter accidents were too high, the IHST committed to an ambitious program [96] aiming at reducing the worldwide helicopters accident rate by $80 \%$ in 10 years (by 2016) as shown in Fig. 1.1.

The teams in charge with this project were appointed to analyse accident reports and work with dedicated experts in order to provide recommendations leading to prevention. The Compendium Report of the U.S. Joint Helicopter Safety Analysis Team to the International Helicopter Safety Team, dated from August 2011, provides a discussion and a summary with recommendations on a first study conducted during three years. Fig. 1.2 displays an overview of civil accidents trends worldwide. The Compendium report shows [51] that the trends have remained globally constant over the years and the majority of accidents happen during Day $\mathrm{VMC}^{5}$. In more general terms, the findings of the three years of combined data indicate that there is a need for Aeronautical Decision Making Training and Risk Analysis tools by pilots. In most cases, improving pilot judgement and the ability to safely handle problems may be the best way to improve safety on-board and change the outcome of the sequence of undesirable events that might happen during the mission.

The report also revealed that each accident environment was unique due to the specific constraints related to the flight and the mission at the moment when the accident scenario took place. This was

[^1]

Figure 1.1. U.S. IHST Accident Rate Reduction Goal and Progress - taken from [96]


Figure 1.2. Worldwide Civil Helicopter Accidents/Year - taken from [96]
confirmed by Airbus Helicopters experts during the first phase of the PhD study detailed in this work. Besides, if we look closer at the IHST report, the study revealed that the human factors including the pilot's experience, the pilot's decisions; more generally speaking a bad appreciation of the current situation by the crew represent the highest percentage of accident causes (Fig. 1.3).

A survey on accident trends on the Airbus Helicopters fleet, over a ten years period, initiated for the purpose of this PhD study revealed that the accident trends happen to be similar to those exposed in the IHST report. More precisely, the diagram presented in Fig. 1.4, taken from a presentation of the company dated from 2014, classifies the accident causes of the Airbus Helicopters fleet in three main groups:

Standard Problem Statements (SPSs) Level 1


Figure 1.3. Standard Problem Statements - taken from [96]

- Operational causes representing about $85 \%$ of the fleet accidents,
- Maintenance causes representing about $10 \%$ of the fleet accidents,
- Technical causes representing the remaining $5 \%$ of the fleet accidents.

We notice that the biggest proportion of accident causes appears to be of operational nature. This category mainly involves accidents due to pilot's judgement, a bad appreciation of the current situation and the surrounding environment, or a bad application of in-flight procedures. This, moreover, makes apparent that accidents happening due to a loss of visibility or resulting in a $\mathrm{CFIT}^{6}$ necessitate a special attention because they reveal open technical challenges requiring improvements and further investigations and evaluations. For those reasons, and obviously because they represent a high part of the Airbus Helicopters accident causes in the fleet, the study will focus on a corpus of operational accident causes and more particularly on loss of visibility and CFIT accident causes.

[^2]

Figure 1.4. Accident Causes - taken from [11]

### 1.2 Problem Statement and Objectives of the Study

Despite the existing embedded technologies in use, contributing to operational accident reduction is not a common thing and it requires to get the full point of a typical operational accident scenario, encompassing all the logic there is beyond a simple chain of causes and contributing factors leading to a crash. There are no exact procedures for avoiding a complex undesirable event, be it of operational or technical nature. Of course, models for understanding accidents already exist such as the Reason model, the Domino model, the Swiss Cheese model [83], and there is always a way to reconstruct and understand what happened from the official accident report. However, preventing the accident scenario from happening in-flight is a true challenge and requires a fierce short term risk management and decision making with respect to the aircraft's dynamic capabilities and manoeuvre constraints. In order to prevent the accident scenarios from starting and taking place, it is necessary to have a method for estimating the criticality of the current flight situation before the difficulties start. Indeed, the most important thing is to diagnose, in-flight, the environmental constraint or inappropriate manoeuvre that will make the system (aircraft and passengers) to enter a series of undesirable events composing the danger loop. For that reason it becomes necessary to characterize the current state of the aircraft and translate it into quantitative risk data in order to trigger out alarms and escape manoeuvres when the threat is about to become real.

During their training, the pilots learn how to appreciate the mission risk and take appropriate corrective actions in order to provide a safety management compliant with the mission needs. In case of emergency, the first concern for the crew is to secure the immediate trajectory of the aircraft in order to avoid the collision with the terrain elevation or with the surrounding obstacles. However, "pilots are humans flying machines" and their judgement can be altered [96] due to environmental constraints. For that reason, in this study, we suggest the design of an avionics function with increased autonomy, capable of demonstrating performances to autonomously recover from an operational safety management failure in real-time, on-board the aircraft. Therefore, in addition to the autonomous flight control and the environmental characterization, the study should include the formalization of the pilot's state of mind when the difficulties start. As the pilot remains in the loop constantly, it seems important
to understand why the pilot would take the decision to continue the flight rather than divert to an alternative route.

Main objective: The system concept suggested in this thesis would try to bring a solution for reducing operational accident rates through an autonomous decision-support avionics function for piloting a helicopter in emergency situations.

### 1.2.1 A layered approach to the Problem Statement

The accidents addressed in the study are of operational nature, more precisely CFIT and loss of visibility accident types. In these specific cases, the pilot finds himself in a threatening position. The pilot is not always aware of the gravity of the situation, especially in CFIT accident scenarios where the crew has the feeling to be completely safe. Similarly, when a pilot enters inadvertent IMC ${ }^{7}$, it was his decision to carry on Visual Flight Rules (VFR) while the weather was deteriorating.

The problem addressed in the design of a decision-support avionics function for piloting a helicopter in emergency situations requires a step by step approach because it covers various levels of precision. Therefore, the analysis of the global problem assumes both, skills at the decision-making level and emergency control of the aircraft. For that reason, a layered approach is well suited for dissociating the different levels of detail addressed in this study. Fig. 1.5 displays a diagram of the layered approach to the Problem Statement with three separate levels of detail.

In order to reduce the complexity of the system design and guarantee its implementation modularity, it seems interesting to have a hierarchical system planning, from an upper strategic layer, where the decisions relevant for the mission progress are taken, to a lower operational layer, closer to the execution of instructions from the upper layers. Fig. 1.5 illustrates the layout of the strategic, tactic and operational layers as well as their interactions.

- The Strategic layer encompasses functionalities close to the pilot's perception of the in-flight situation. This layer contains algorithms proper to decision-making in reference to the progress of the mission. The Strategic layer takes into account flight manual regulations, the elicitation of knowledge from the experts, the flight envelope limitations proper to the aircraft.
- The Tactic layer contains the functionalities such as short-term long-term path-planning and more generally computations in line with the current state of the aircraft.
- The Operational layer executes all the primary instructions from the two previous layers like for example the flight control of the current trajectory.


### 1.2.2 Expectations and work hypothesis

The objectives of the study focus on strategic and tactic layers (Fig. 1.5).
The present work aims to increase the autonomy of a helicopter in operational in-flight emergency situations. Moreover, the ultimate goal of the study is to provide a proof of the avionics function concept as a first demonstrator in a simulated flight environment.

[^3]Level of Detail


Figure 1.5. A Layered Approach to the Problem Statement

For that purpose the demonstrator constraints to meet are the following :
The demonstrator has to

- Address the development of a new avionics function concept aiming at reducing the number of accidents due to operational causes,
- Cope with the existent technologies and regulations in use at Airbus Helicopters, i.e. existing training programs, maintenance and flight manual instructions and limitations,
- Ensure the compliance of the function with all the helicopters of the Airbus Helicopters fleet,
- Take into account the policies related to the establishment of the Safety Management System (SMS) [2] or make it possible to include specific safety-related constraints in retrospect,
- Render the current environmental constraints proper to the aircraft by quantifying the risk in accordance with the criticality of the in-flight situation,
- Render the current pilot's state of mind in case of undesirable event in order to take safety actions to protect the occupants.

Therefore, the decision-support application is addressing various levels of safety, from a primary level with basic rules to secure the immediate trajectory to the third level when the function evaluated that the collision is unavoidable:

- Primary safety: set of active security actions that could be triggered before the accident occurs, which aim at avoiding the accident, i.e. avoidance manoeuvres and alarms,
- Secondary safety: set of preventive passive actions which intend to minimize the direct consequences of the crash, i.e. the application can predict when the accident is unavoidable in order to trigger protective actions,
- Tertiary safety: When the accident is unavoidable the application can send the vehicle's relevant flight data to rescue teams.

The study was conducted based on a fierce analysis of the company's existing technology in use and the actual technical challenges eager to be improved, on autonomy and avionics topics, by the Airbus Helicopters design office in Marignane.

Based on the current observations of the accident rates, it has been decided that the avionics function concept, focus of the study, should respond the problematic of accident rates reduction.

An internal survey, on the fleet accidents occurred over a period of 10 years revealed that operational accident causes are happening more frequently than others and should constitute an axis of research. Controlled Flight Into Terrain (CFIT) and Inadvertent loss of visibility remain the accident top causes.

### 1.3 Contributions

No matter how advanced a system is, safety remains a deciding indicator in aviation and delegating further autonomy to the helicopter is a challenging matter. Increasing autonomy with the intent of reducing operational accident rates in the Airbus Helicopters fleet through innovative avionics functions is ambitious and it requires an appropriate method for the design and evaluation of the systems.

Yet, this is very closely linked to enhanced safety and thus improvement of risk management inflight. This study is addressing dynamic autonomy issues for the specific case of operational accidents (like Controlled flight into terrain (CFIT) or loss of visibility) through a discussion and positioning over safety and risk management in-flight. Hence, we aim to answer the following research questions:

1) How to ensure a permanent in-flight safety monitoring against collision risk?
2) How to identify the moment when the safety is sufficiently low to trigger avoidance manoeuvres?
3) How the decision to avoid the danger could be taken with respect to the warnings and emergency procedures; without affecting the progress of the mission?

The study suggests four main contributions to answer the problems addressed above:

- The first contribution relates to the functional architecture of the avionics function concept. The global design of the function has been thought in a framework for the design and evaluation of autonomous systems and observation of operational accidents types in order to involve the environmental constraints in the safety monitoring and the decision making process for computing the appropriate avoidance manoeuvre before the collision would occur,
- The second contribution relates to the Dynamic Trajectory Generation functional bloc. This contribution addresses both in-flight emergency trajectory generation to avoid a threat; and path-planning under saturated constraints, compliant with the aircraft's dynamic and kinematic limits; without overreaching the aircraft's flight envelope,
- The third contribution relates to risk quantification in-flight through the Short Term Navigation Safety-Monitoring concept,
- The fourth contribution relates to dynamic decision-making facing a threat on the basis of available escape trajectories; taking into account the current flight situation and state of mind of the pilot characterized by the elicitation of Airbus Helicopters pilots and experts.


### 1.4 Structure of the document

Chapter 2 is a literature review on the scientific and industrial works including a discussion around the related existing industrial technologies in operation.

Chapter 3 exposes the global functional architecture of the avionics function concept though a hierarchical approach for trajectory generation, decision making and risk assessment algorithms. The design framework of the function is though in the idea of autonomous systems and conceived to be generic enough to bring a solution to other operational accident causes.

Chapter 4 details the Trajectory Generation algorithms for emergency manoeuvres and path-planning, in accordance with the aircraft's flight envelope.

Chapter 5 presents the concept of Short Term Navigation Safety-Monitoring in the objective of permanent in-flight safety monitoring illustrated with preliminary use cases of possible operational accident threat; with identification of localised risk of collision in-flight and trajectory evaluation.

Chapter 6 details the decision-support functional bloc, part of the global architecture of the avionics function, focus of this study, and the tools used to characterize the in-flight dynamic pilot's initiative when the difficulties arise.

Chapter 7 presents the results of the algorithms on two operational accidents of the Airbus He licopters fleet. This chapter explores the formal representation of escape procedures, as they are presented and thought in this study to answer the problem of operational accident causes such as CFIT and loss of visibility. The results show the progression of the accident scenario and discuss over the best decision moment to engage corrective actions before the accident would occur.

Chapter 8 is a discussion over the study, its applications and it also presents the perspectives and future works related to the findings.

Beyond the contributions exposed to answer the problems related to the reduction of operational accident causes, this study provides a more general discussion over autonomy in avionics systems for dynamic safety monitoring and adaptable decision making compliant with the current flight situation and operational requirements.

Airbus Helicopters and LAMIH-UVHC

The role of autonomous systems may be various in the aeronautics industry but the interest for autonomy is growing and innovative solutions improving autonomous capabilities of embedded systems, in line with the crew's needs and the operated mission have a significant role to play in real-time risk management. Step by step, formalizing the difficulties a crew may encounter and evaluating the impact of the system solutions designed for that purpose, may lead to a significant increase in autonomy for helicopters flying in emergency situations.

## Chapter 2

## State of the Art - Discussion around the Related Works

### 2.1 Introduction

The objective of this Chapter is to present and discuss a body of scientific and technological contributions related to the questions raised previously. For that purpose, the discussion will be introduced with the concept of autonomy as understood in this study, in order to clear misperceptions limiting its adoption in the design, the development and evaluation of the avionics function concept mentioned in the previous chapter. In a second phase, the discussion will continue in order to enhance the means employed to address the autonomy issue, as part of a Decision-Support function for piloting a helicopter in emergency situations. More precisely, the discussion will support the capabilities making it possible to render the current flight situation to a system for the purpose of a good safety management.

## 2.2 "Autonomy is a capability" [70]

### 2.2.1 Framework for the design and evaluation of autonomous avionics systems

As stated before, the concept of autonomy may refer to many different subjects including air traffic management through the definition of an unique airspace for the insertion of unmanned aerial vehicles into the civil air traffic[62]. Autonomy may also refer to weather detection and protection, automatic take-off and landing procedures, safe recovery systems, secure commands and control systems, autonomous behaviour and so on.

Delegating further autonomy to the aircraft has been addressed in projects such as ASTRAEA II with Separation Assurance and Control and Autonomy and Decision Making ${ }^{1}$. The main objectives of ASTRAEA, started in 2006, are being to design an integrated core avionics system capable of facing barriers, emergencies and pitfalls along with satisfying a high level of safety. Within the project and in a concern of integration of Unmanned Aerial Systems (UAS) in non-segregated airspace, Patchett and al. present in [77] a new avionics system designed to meet these challenges and provide a route selection based on weather forecast. Similarly, project MIDCAS (Mid Air Collision Avoidance System $)^{2}$ has been initiated to allow a better insertion of the Unmanned Aerial Systems into the civilian

[^4]airspace developing functionalities providing the pilot, or the person in charge of the unmanned vehicle with functions of detection of other aircraft and functions maintaining situational awareness of the remotely vehicle. Additionally, if needed the system might propose or execute automatically adapted manoeuvres to restore safety between the UAS and others aircraft. However, it should be made clear that autonomous systems are not "fully autonomous". They are supervised by human operators at some point and autonomy is not an intrinsic property of a system; it should be considered instead in terms of "human-system collaboration" [70]. In this context, autonomous systems complement the operator's capabilities without degradations due to fatigue or lack of attention [70].

The decision-support avionics function for piloting a helicopter in emergency situations requires a collaborative interaction with the crew but, at the same time, it must demonstrate autonomous behaviour for monitoring the safety on-board in real-time, based on accurate characterization of the environmental complexity around the aircraft. The avionics function concept must therefore evaluate the criticality of the flight based on the aircraft's and the environment's properties.

In manned aircraft, pilots play a paramount role in the handling of emergency situations in-flight. The operational difficulties encountered by the crew necessitate a good comprehension of the surrounding environment, which means that the design phase of the systems dedicated to assistance in emergency situations should demonstrate ability to cope with the failures and lead to a suitable recovery behaviour satisfying the environmental constraints. In the case of a CFIT (Controlled Flight Into Terrain) or loss of visibility accident cause, focus of this study, the system should report autonomous capabilities in line with the mission requirements and constraints. The specificity of a CFIT accident scenario is that the aircraft is unintentionally flown into the ground, or another obstacle, under the pilot's supervision; which means that the crew is unaware of the collision threat until too late. In the case of a loss of visibility accident scenario, the pilot often loses the visibility inadvertently, and the crew doesn't notice the impending disaster, which happens soon after the meteorological conditions degraded.

According to the U.S. Department of Defence report on the role of autonomy in DoD systems, dated from 2012, "Autonomy is a capability or a set of capabilities that enables a particular action of a system to be automatic or, within programmed boundaries, self-governing" [70]; and it should no longer be considered as scalable with metrics [40], which means that a system is either autonomous or it is not. Moreover, this report provides a status of technology deployment (Fig. $2.1^{3}$ ) and identifies failure anticipation and Replanning, Scenario assessment and understanding as well as situation awareness as niche functionalities in which technology is not yet mature enough and allows open technical challenges for diverse applications.

CFIT and loss of visibility accidents do not require the fulfilment of a given task. They require a system capable of permanently monitoring the environmental complexity while the pilot is performing the tasks related to the mission. The approach on situation awareness, failure anticipation and replanning, and understanding of the in-flight situation are paramount for the study. However, an additional complexity related to the state of mind of the pilot comes into play for the decision-support functionality of the global system architecture. The system must include capabilities to mix initiative and knowledge autonomously at the same time, which is what a pilot does [70]. Moreover, as the system has to render emergency situations, its use must remain instinctive and reduce the nuisance due to warnings.

[^5]
## Missed Opportunities, Needed Technology Developments



Figure 2.1. Status of technology deployment and remaining challenges [70]

The method for characterizing the complexity of the environment has to be adapted to the mission and specifically designed to cope with environmental constraints proper to the aircraft. Additionally, the design framework should include possibilities of reconfiguration and replanning of the mission during the flight, on dynamic and cognitive views as shown in Fig. 2.2. For example, Lampe et al. [63] evaluate robots autonomy based on considerations related to the mission, the environment's complexity and the information the robots have on it. In [95], an automatic ground collision avoidance system is presented to provide a solution in the case of CFIT accident scenario for a fighter aircraft in the form of a recovery trajectory over a virtual terrain map. The system is presented as nuisance-free in terms of warnings rules, which comforts the pilot in the acceptance of the solution and prevents the deactivation of the system during the flight. However, the system provides this information only ahead of the direction of flight.

The corpus of accidents targeted by this study demands that the system concepts imagined to cover the threats demonstrate abilities to "sense" the danger isotropically in the three-dimensional space frame and engage preventive actions to avoid collisions. Indeed, a helicopter flight allows manoeuvres much closer to the terrain, especially in Search and Rescue (S\&R) or Emergency Medical Services (EMS) missions. For that reason, increasing autonomy implies a 3D diagnosis of the current situation criticality or "quantifying the environmental complexity" [103]. In practice, it is about finding a way to characterize the surrounding environment and make it understandable by the system, in order to find an escape to the chain of undesirable events leading to the accident. In [103], Young et al. demonstrate a model-based framework characterizing the impact of the environmental complexity on robot navigation in unprepared and changing terrain. The approach combines knowledge of the

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

terrain (elevation data), input from the sensors and dynamics capacities of the robot to compute the complexity on a navigation task for a ground robot. The system uses the environmental data collected to formalise a situation awareness proper to the problem treated. The approach is given for a twodimensional path-planning problem.

On the same basis, but for a three-dimensional framework, the function, focus of this study, has to give a clear picture of the progressive collision threat of the aircraft in order to make the approach towards the impact incremental, representative with respect to the dynamic capabilities of the aircraft and comprehensible by the algorithms implied in the design framework. In this context only, the system would be able to "sense" the threat and provide an avoidance solution (kinematic, dynamic or operational) in time. A kinematic or dynamic solution could be an avoidance trajectory/manoeuvre; an operational solution could be an appropriate warning rendering the current threat.


Figure 2.2. Framework for the Design and Evaluation of Autonomous Systems [70]

### 2.2.2 Autonomy versus Automation

Given that the pilot remains in the loop in this study, there is a distinction to be made between autonomy and automation. The main difference resides int the fact that automation does not face the unexpected. There is no "reasoning" in automation, no planning. It is designed in order to accomplish a specific task [95] or several tasks separately at the same time.

In this section, the objective is to position the research scope against automatic systems already widely used in aviation, like the auto-pilot, and discuss possible development axes to increase autonomy for the system. We won't go any further concerning ergonomics, cognitive issues or the restitution of information to the pilot even if some specific vocabulary in direct relation with these notions is used. The purpose of this section is simply to situate what we call autonomy, more precisely partial autonomy and why.

In [38], the concepts of co-operation between the human operator and automation are addressed. Hence, the human operator is presented as the user of the technology in place. It is placed in an automated work environment. The fly-by-wire technology is a perfect illustration of this situation: the higher levels of performance involving decision-making and problem-solving are still attributed to the human operator but the system can easily follow a trajectory [38] or reach a certain flight level without involvement from the human operator.

The concept of the work system with the human operator, the work object (here the aircraft) and the operation-assisting means (the automated system) is illustrated in Fig. 2.3. The work system is an ergonomics concept [38] [73], where according to [38]:

- An Operator is usually a human operator (in the traditional view of the work system) being in charge of accomplishing a mission. the human operator takes the final decisions related to the work object and supervises the progress of the mission. It makes the final decisions and solves problems.
- The Work Object comprises the aircraft (a helicopter in our case) and the "progression of the situation over time" [38].
- The Operation-Assisting Means is seen as a container for automation, tools, technology etc. It could be an autopilot, or in our application this could be the means for the avoidance of operational accidents. Usually, the Operation-Assisting Means could be adapted in improved versions to cope with further requirements.

During the mission, the Environmental Conditions can affect the Work System. Using automation, the human operator's role is "shifted towards supervisory control modes" [38].g The monitoring of lower tasks or systems is done automatically. The human operator adjusts the control laws and monitors the situation according to the flight. Hence the relation between automation and the human operators supervising tasks is vertical as shown in Fig. 2.4.

The introduction of automation could be beneficial in many situations because the human errors are a predominating factor in aviation accidents. However, in other situations the human operators may require additional help or a lower degree of automation. This is not always handled by the current avionics equipments. According to the mission, the human operator could be more or less solicited

externally given
Figure 2.3. Concept of a Work System [38]


Figure 2.4. Organisational Structure of Conventionally i.e. Hierarchically Automated HumanMachine Systems taken from [38]

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

which is not always helpful. As an example, the high rate of false alarms of an over preventive automation is a source of nuisance. In case of emergency, several warnings could be switched on at the same time, which is also a source of nuisance and disturb the mission progress by the crew (human operator).

Of course, there are many examples and each one could be treated separately.
According to [38], "conventional automation will usually not be able to recover from undesired situations induced by malfunctions, faulty operations or just the unexpected", mostly due to a lack of understanding the situation. Hence, the current automation systems are missing "to perform on a supervisory level in order to pursue the overall goals of the work system" [38]. In the example of the autopilot, the system can perfectly capture another flight level, however, it will not take into account the operational constraints and recommendations that go with the manoeuvre like the traffic issues, the collision threats etc. who remain on the supervision of the human operator.

Therefore, the increasing conventional automation is not the answer. In [38], the authors introduce the concept of advanced automation to replace the conventional automation. Indeed, advanced automation keeps the human in the work system and envisages to share the tasks, extended to the supervisory control level, in partnership with the human operator, assuming that the partnership should be adapted to the current flight situation's needs. This idea fits more to a possible solution for avoiding operational accidents. However, we should keep in mind that CFIT accidents happen frequently in perfect knowledge of the crew. For that reason, the system should maybe displace the human from the work system at some point.

In [38], the authors also introduce cognitive automation as part of the operation-assisting means as shown in Fig. 2.5. Furthermore, according to [38] a system can be considered autonomous if it is functioning independently from any human intervention and if it is accomplishing a full work system (an entire mission), not only independent tasks.

In Fig. 2.5, the operation-assisting means is completed with a cognitive unit as an alternative to conventional automation. In this case the operation-assisting means could be able to perform additional verifications when an order is given from the human operator, in order to check the compatibility of the order with the current mission progress, its target and eventually suggest alternative manoeuvres if the order is considered threatening for the work system.

However, this remains problematic in our research goals for the following reasons:

- The operational undesirable events like the CFIT are unpredictable, therefore we require permanent monitoring and analysis of the current situation in-flight, including the case when additional data is given by the human operator to the system.
- In many cases, the accident happens with the consent of the crew (human operator(s)), therefore the system must be able to work independently from the human operator without "polluting" the human operators by suggesting evasive manoeuvres all the time.

Eventually, Fig. 2.6 suggests another configuration : the "Co-operative Automation" where the Human operator and the cognitive unit should be able to perform both all the tasks like team members.


Figure 2.5. Work System with a unit par of the Operation-Assisting Means[38]

This configuration is not fully adapted either to the research problematic because it is able to solve the overall work task which could be a good thing; but if we look closer to the problem the research does not focus on the entire work task.

The work will not attempt to design a cognitive model or unit as an answer to the predominating human errors in aviation. This might be the case in the future and we cannot rule out the possibility that the system suggested in next chapters, as one possible solution to the avoidance of operational accident scenarios, might have advanced cognitive functionalities in improved versions, as a perspective. However, this work aims to focus on the development of partial autonomy as operation-assisting means for a specific task. The system won't be fully autonomous as a UAV could be, however it should provide autonomous capabilities to monitor the danger sight and decide whether the current actions could have one or several undesirable repercussions on the future states of the aircraft, according to the operational application of the system. It appears that the specific knowledge of the targeted application field is of paramount importance, especially for the users to accept the system. For that reason, the system should include data provided by experts as demonstrated in [95].


Figure 2.6. Work System in configuration "Co-operative Automation" [38]

### 2.3 Rendering the aircraft's future states ahead of the current position

In order to characterize the complexity of the surrounding environment and appreciate the distance from the obstacles and the terrain, for the purpose of an autonomous in-flight safety monitoring, it is necessary to evaluate the aircraft's simulated future possible states ahead of the current 3D space position, in terms of collision threat. Simulations relying on helicopter dynamics models raise the problem of computation time. This is particularly true when the problem requires a simultaneous generation of massive set of trajectories ( $>5000$ trajectories covering a given flight period) with a short computation loop (a few milliseconds). In this situation, the use of in-flight embedded computation resources becomes critical. Path-planning solutions based on linearised flight models are in use as shown in [45], where the authors test various avionics suites in order to improve navigation in unprepared terrain. However, linearised models remain less representative of the real flight performances of the aircraft and do not allow a precise vision of the aircraft capabilities in performing strong manoeuvres, close to obstacles. This well-known mobile robotics problem has been addressed by a wide variety of research works in the frame of trajectories kinematics models. If the problem of 2D optimal path for a non-holonomic robot by the use of motion primitives, with bounded derivative of the curvature, is already addressed by performing algorithms [61], the scientific and technical domain of helicopters 3D flight path generation optimization by kinematics motion primitives is currently rapidly moving [99] [102] [75].

### 2.3.1 Approach by Motion Primitives for Short-Term Navigation Safety-Monitoring

Piloting a helicopter in emergency situations requires a good knowledge of the helicopter's dynamic capabilities and its abilities to avoid the incoming obstacles in unprepared terrain as covered in [58] or

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

[67]. Hence, it is useful to know when the piloting manoeuvres are likely to become more aggressive. A rendering and evaluation of the future flight states by simulated characteristic motion primitives ahead of the current position, as illustrated in Fig. 2.7, is a good option as it reports accurately the performances and possible positions of the aircraft "in the future" and it is also a known method used in path-planning to reach a target state with or without imposed constraints [79], be it on speed, acceleration or on kinematic constraints such as the curvature or the torsion.


Figure 2.7. "Control-based action sampling: A grid of waypoints in front of the vehicle at $x_{0}$ is given to a discretized feedback dynamic system $f_{d}(x, u)$ as a set of inputs $\mathcal{U}$. The resulting motion segments comprise the sampled reachable set $\mathcal{R}(, \mathcal{U})$ from the state $x_{0}$ and recorded in a look-up table." [58]

To be more precise, the global problem of navigation safety monitoring is twofold. It addresses both discrete 3D path-planning of the surrounding 3D space, and smoothing of the resulted path (in 2D or 3D) to make it compliant with the aircraft's dynamic and kinematic capabilities.

The discretization of the three-dimensional space frame around the aircraft is commonly used in various path-planning algorithms to provide a safe path, free of obstacles and avoiding forbidden areas [43]. In [93], Souissi et al. compile a survey of path-planning methods and their computation performances, mainly referring to two-dimensional exploring of the space with known obstacles. The paths produced with these methods are not dynamically feasible by a helicopter, even in a 2 D reference frame. They often represent a series of waypoints connected by straight lines, and necessitate an appropriate smoothing [30] taking into account the dynamic and kinematic properties of the aircraft. Some other studies take into account the maximum kinematic constraints of the aircraft in curvature and/or torsion [43], [27], [58], in the 3D discretization of the space around the aircraft, before engaging smoothing procedures. The stakes of having a representative and optimal knowledge of the space around the aircraft, with a feasible path and appropriate transitions between the manoeuvres, is paramount for a good sense and avoid logic in navigation, to the scale of the whole mission. In the short term reference frame, proper Sense and Avoid technologies are widely used for solving navigation and safety related issues for UAVs because they cannot sense and avoid autonomously [42] and because they represent a true hazard to manned aircraft operating in the same airspace.

Airbus Helicopters and LAMIH-UVHC

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

Often, studies compile discussions on both path-planning and dynamically feasible motion primitives, stating for smoothed trajectories like in [58] where the system firstly computes a kinematically feasible obstacle-free path and where a local motion planner computes more accurate trajectories at higher level of detail, as shown in Fig. 2.8. But the motion primitives are often precomputed and correspond to trimmed trajectories stored on-board with defined constrains [27] [55] [59]. The dynamic generation in-flight of motion primitives in 3D with parametrisable properties, in line with the kinematic and dynamic constraints, locally testifying of the current in-flight safety, is not addressed. Trajectories generated analytically in flight cannot be stored. Actually, having series of characterized positions along the trajectory is hard to store. They are partly stored (Figs. 2.10 and 2.11). Frequently, this question is raised before with 2D, 3D or combined 2D-3D path-planning methods. Precomputed feasible trajectories or smoothed paths serve to guide the aircraft in paths already computed or shaped with target rules.


Fig. 8. Examples for the local path planner in free of obstacles: The greedy best-first search explores motion nodes toward the gate in a greedy way. The heuristic function $h_{2}$, the extended 3D Dubins metric, guides the node expansion efficiently toward the goal state. All motion expansions queued in the search tree are displayed in order to see which node has a best cost-to-go at every iteration until it reaches the goal region. The gate has different yaw angles $\phi$ in figures.

Figure 2.8. Examples of the path-planner [58]
Currently, the short term situation awareness, in manned aircraft is addressed through equipments like the TAWS (Terrain Awareness and Warning System) ${ }^{4}$ / HTAWS (its helicopter version) and the TCAS (Traffic Collision Avoidance System) ${ }^{5}$. In [52], the Situation Awareness (SA) states frame-

[^6]

Figure 11: The lateral and vertical action spaces for threat resolution. For lateral maneuvers, standard and half-standard rate turns are considered every 15 seconds resulting in heading changes of 45 and 22.5 degrees respectively. For vertical maneuvers, 500 and $1000 \mathrm{ft} / \mathrm{min}$ climb and descent are considered every 15 seconds.

Figure 2.9. Avoidance trajectories to collision threat [19]
work are illustrated in three steps as follows:

- "Perception (Level 1 SA): The first step in achieving SA is to perceive the status, attributes, and dynamics of relevant elements in the environment. Thus, Level 1 SA, the most basic level of SA, involves the processes of monitoring, cue detection, and simple recognition, which lead to an awareness of multiple situational elements (objects, events, people, systems, environmental factors) and their current states (locations, conditions, modes, actions).
- Comprehension (Level 2 SA): The next step in SA formation involves a synthesis of disjointed Level 1 SA elements through the processes of pattern recognition, interpretation, and evaluation. Level 2 SA requires integrating this information to understand how it will impact upon the individual's goals and objectives. This includes developing a comprehensive picture of the world, or of that portion of the world of concern to the individual.
- Projection (Level 3 SA): The third and highest level of SA involves the ability to project the future actions of the elements in the environment. Level 3 SA is achieved through knowledge of the status and dynamics of the elements and comprehension of the situation (Levels 1 and 2 SA), and then extrapolating this information forward in time to determine how it will affect future states of the operational environment." [52]

The TAWS and the TCAS equipments provide a Level 3 SA based on terrain elevation data, which is going to be used in this study. The sensors technologies will not be studied in this thesis.

In the design of the avionics function for piloting a helicopter in emergency situations, we introduce in this thesis the concept of Short-Term Navigation Safety Monitoring (STNSM), developed further in chapter 3, for increasing the situation awareness. The STNSM is positioned on the preven-

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

tion scheme of existing collision avoidance embedded devices like the TAWS ${ }^{6}$ and the HTAWS ${ }^{7}$, its helicopter version, and Sense and Avoid (S\&A) technologies mentioned in the previous section. The concept is different from the usual navigation safety monitoring because it focuses on a flight time of about 30 seconds ahead of the current position (in its first version as detailed further in chapters 3 to 8). Indeed, as concerns the S\&A existing works, a minimum of 30 seconds of prevention time fits the detection or reconstitution capacities of the embedded sensors used to support these technologies. They offer a knowledge of the surrounding environment in terms of collision threats with the terrain elevation, obstacles and other stakeholders. Hence, Barreiro et al. [19] present an algorithm capable of predicting medium-term conflicts in a frame time between 30 seconds and 2 minutes of flight, for UAVs with intruder aircraft. The algorithm computes the most probable trajectory of the intruder aircraft based on a conic-like discretization of the space ahead of the intruder aircraft with possibles directions. Fig 2.9 illustrates the method. The study identifies flight legs and stores possible behaviours of the intruder aircraft. The legs are deduced from the observation of trajectories. They consist of portions of trajectories, where the aircraft is in a particular mode, like climb, descent, flying straight, turn etc. A Bayasian network functional entity takes into account the current state of the intruder and computes the most likely resultant trajectory thanks to a route database. This method is not deterministic hence not suitable for embedded avionics but it provides an overview of situation awareness monitoring with manoeuvres proper to the aircraft, which is interesting for short term safety.

The prediction of conflicts in short term safety monitoring increases the situation awareness of the crew. The warning concept based on leg extraction, presented in [19], is a way of computing the resultant predicted trajectory of the intruder aircraft so the UAV could adapt its route and avoid the collision threat. However, the combination of all the possible trajectories is very costly to compute, and evaluate accurately for a prediction covering up to 2 minutes of flight.

The STNSM concept ensures situation awareness and local obstacle avoidance based on a 3D partitioning of the space ahead and around the aircraft with dynamic generations of gradually soliciting avoidance trajectories, feasible by the aircraft, to a possible threat.

In the frame of environment and time bounded helicopters missions, saturating at the same time the flight trajectory above constraints becomes an important challenge. To solve it, 3D flight path generation methods relying on motion primitives have already been performed and provided efficient results [30] [58]. The case of Yasmina Bestaoui works [26] is interesting as it addresses the problematic of transitions between two flight situations by introducing the use of transition curves with linear curvature and torsion, or quadratic torsion. This is of real interest because helicopters manoeuvres to capture an oriented 3D space position under time constraints often require the combination of a climb angle increase and a turn, in order to provide a space curve. The established motion is then a helix arc. Before reaching the established motion, flight records and helicopters heavy dynamics simulation models results show that the required 3D transition can be relevantly modelled by the kind of curve with linear curvature and torsion.

We address in this contribution a kinematics motion primitives algorithm. This algorithm relies on clothoids, straight segments, spiral arcs and 3D transitions. The main feature of the 3D transitions

[^7]
## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

generated by our algorithm is that their generation relies on an original integration method that can guaranty different forms of 3D transitions with very light parameterization. Moreover our algorithms authorize very simple laws on curvature $\kappa$ and climb angle $\theta$ parameterized by the curvilinear abscissa $s$. Therefore it generates 3D Euler spiral, 3D spiral with quadratic torsion and curves traced on cylinder surfaces. 3D transitions and other described primitives are then aggregated by the means of an algorithm inspired by Dubins curves [46] extended to 3D.

To solve the problem of path of minimal length for aerial vehicle with prescribed initial and final space positions and speed vectors, solutions relying on algorithms for Pythagorian Hodograph curves have been performed [88] [89]. Those solutions are performing to provide valid solutions but they face difficulty to simultaneously control and guaranty saturation of intrinsic trajectory dimensioning constraints like : maximal curvature $k_{\max }$, maximal torsion $\tau_{\max }$, maximal climb angle $\theta_{\text {max }}$, and their derivatives constraints $\left(\frac{d k}{d s}\right)_{\max },\left(\frac{d \tau}{d s}\right)_{\max },\left(\frac{d \theta}{d s}\right)_{\max }$. Those limits are generally determined by flights tests records and helicopter heavy dynamics simulation models.

The characterization of the STNSM with motion primitives implies an isotropic trajectory generation and evaluation in the 3D space frame around the aircraft.

The study presented in this PhD thesis aims to bring a generic proof of concept of the algorithms, in terms of prevention range that could be adapted according to the mission needs. For that reason and for ensuring a comparison bench later in the development process (see chapter 8), the study will target a time prediction frame for STNSM on the basis of existing embedded solutions for civil aircraft, i.e. about 30 seconds prevention flight time like the HTAWS.

Besides, for the purpose of this study, the elicitation of the pilots experience used in the design framework, shows that an avoidance trajectory without collision for the next 30 seconds is considered safe (see details in chapter 6). The HTAWS configurations and parametrizing varies from a manufacturer to another, but globally speaking, the device provides an information of collision, based on the extrapolation of the current helicopter state, about $30-40$ seconds before the impact. Short Term Navigation Safety Monitoring, developed in this study, is all about the extrapolation of the current state of the aircraft isotropically in the three-dimensional space frame around the aircraft.

In [58], an efficient motion planning for small fixed-wing UAVs is presented for accomplishing 3D air slalom scenarios.

Characterization of the surrounding environment as seen here implies short-term navigation over a 30 seconds flight time physically formalized with trajectories with high constraints, which also stand for emergency avoidance manoeuvres.


Figure 2.10. "Generation of motion primitives: (a) A reachability tree for a fixed-wing UAV stopped at the third depth (b) Precomputed motion primitives at different starting states" [58]


Fig. 3. Pre-computed motion primitives. The proposed method seeks to encapsulate much of the complexity of dynamics and control of microUAV's with motion primitives, off-line pre-computed controls that represent feasible motions of the system. By representing system reachability with a carefully designed set of control samples, the need to reason about system dynamics at planning time is eliminated, allowing ultra-low power CPU's (perhaps even lacking floating-point units) to compute elaborate motion plans in real-time. The figure shows a set of primitives of a quadrotor (gray circle) while it is hovering in place (a) and moving at a certain velocity along the Z-axis (b).

Figure 2.11. Pre-computed motion primitives taken from [80]

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

### 2.3.2 Dubins-like three-dimensional path-planning

In order to maintain the link with the works presented by [91] and keep a system logic with short term navigation safety monitoring and actual navigation, we address in this thesis a possibility to connect an alternative flight plan that could be computed during the mission or that is already stored in the system on-board before the mission with Dubins-like three-dimensional paths.

The motion primitives used for exploring the space dynamically, mentioned in the previous section would constitute this path in order to be compliant with the three-dimensional idea.

Works like those illustrated in Figs. 2.12 and 2.13 constitute good references for 3D Dubins-like paths however they don't integrate the 3D aspect everywhere and especially at the ends of the paths.


Figure 2.12. Example of Dubins path in 3D taken from [78]

(a)

(b)


Fig. 6. Two heuristic functions to estimate the optimal cost-to-go: (a)-(b) Examples for 2D Dubins curve which is the shortest length path between $\mathbf{x}_{I}, \mathbf{x}_{G} \in S E(2)$, (c) $h_{2}$ in $\mathcal{C}=\{x, y, z, \theta, \phi\}$, (d) $h_{1}$ in $\mathcal{C}=\{x, y, z, \phi\}$

Figure 2.13. Example of path planning [58]

### 2.4 Dynamic Decision Making and notification of alarms reflecting the operational reality of the flight

In a concern of autonomous safety management and analysis of the possible states of the aircraft in the near future, the previous sections have addressed issues around the design and evaluation of autonomous systems in avionics and partitioning of the immediate environment reachable by the aircraft ahead of the current 3D position. This section is going to address the rendering of the current flight situation to the system for the purpose of dynamic decision making in case of emergency and generation of alarms.

Operational research or operations research is a discipline that deals with the application of advanced analytical methods to help make better decisions [3]. According to ROADEF [4] operational research is a quantitative approach permitting to make better decisions. It provides tools to rationalise, simulate and optimise the architecture and functioning of industrial and economic systems. It suggests models to analyse complex situations and allow the decision-makers to achieve efficient and robust choices.

The problematic and objective of this research work, as stated in the Introduction is to bring a solution for reducing operational accident rates through a real-time autonomous decision-support avionics function for piloting a helicopter in emergency situations. More precisely the study is focused on CFIT (Controlled Flight Into Terrain) accident scenarios, as stated before, due to accident rates

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

who place them amongst the most frequent accidents. Nowadays, equipments like the TAWS [5] and HTAWS (its version for helicopters) are dedicated to the avoidance of CFIT accident scenarios. However, the use of this equipment shows that the rate of alarms is very high in hilly environments with high density of obstacles, making it not suitable for certain missions.

Various research works have been conducted to suggest new alarms, and reduce the nuisance due to the alerting rules of avionics systems. In [95], the prevention of CFIT mishaps is presented utilising an Automatic Ground Collision Avoidance System. Indeed, the study focuses on the avoidance of CFIT accidents but it also provides a positioning on the reduction of nuisance warnings. As said in this study, no criteria exist to indicate the threshold between accurate warning and those considered as nuisance by the pilots. In [95], authors provide a method for evaluating the remaining time to obstacle with the ground) as a function of the pilot's anxiety towards the danger, standing for the pilot's perception of the danger, in order to generate avoidance trajectories with gradual dynamic solicitation. The study has been conducted for fighter planes.

In most cases, CFIT accident scenarios happen because the pilot looses situation awareness. This is even more critical at low altitudes or when the navigation is taking place in difficult flight situations (degrading meteorological conditions, night flight, mono pilot mission etc.).

In the context of this PhD thesis, helicopter flight behaviours are studied for improving the decisionmaking at danger sight, taking into account different flight situations, possibly dangerous. For that reason, the notion of short term navigation introduced in the previous section and the analysis of the flight envelope in a near future is of paramount importance to provide a good quantification of the situational awareness. In this work, we are not going to involve sensors studies for the environment rendering. The research is going to focus on algorithms that could be imagined to quantify the situation awareness of the aircraft, autonomously, for a given terrain elevation and provide an optimisation of the choice in regards to the final escape manoeuvre.

The quantitative approach for determining indicators of danger sight and criteria permitting to quantify the current in-flight situation is detailed in chapter 5. Based on the experts knowledge and experience in emergency situations, chapter 5 explains the empirical approach used to identify various flight behaviours potentially dangerous and that could be assimilated to CFIT accident scenarios in order to derive significant criteria and parameters that could characterise the CFIT undesirable event.

In [24] and [22], a functional architecture for preventing aircraft loss of control accidents is presented. The architecture includes a resilient adaptive guidance loop for off nominal conditions with functionalities such as onboard mission planning and online trajectory generation, which actually comforts the importance in having a risk assessment module for evaluating the current flight situation onboard. Besides, the study insists on the importance of crew interface management with improved situation awareness and crew response under off-nominal conditions. However, the study does not present a way to measure quantitatively the feasible trajectory for recovery and safe manoeuvring, and landing.

In this study we are not going to contribute on the decision-making research field. However, we are going to suggest a parametrisation of an existing method in order to contribute on the generation of alarms for the crew and on the choice of an appropriated escape manoeuvre adapted to the progression

## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

of the aircraft towards the terrain. The study will focus on the pilots preferences for the choice of the best avoidance manoeuvre, based on a set of criteria. Hence, according to [48] a multi criteria method or more precisely a decision-making multi criteria method is based on a set of parameters, defining an elementary language to translate a desiderata modelling (of the deciders experts pilots) into an executable code capable of comparing the escape manoeuvres between themselves and eventually to a reference manoeuvre considered as the best possible (cf details in 3.6.4).

In the existing equipments for CFIT prevention, or more generally for collision avoidance, the alarms are calibrated on absolute thresholds. The idea of this research is to integrate both absolute threshold extracted from interviews conducted with Airbus Helicopters experts as indicators of danger sight and use their expertise to parametrise a method which is able to compare the escape manoeuvres in order to compute an optimised final solution matching with the preferences and the thresholds issued from the knowledge and operational expertise of Airbus Helicopters flight test pilots and experts.

The multicriteria method PROMETHEE ${ }^{8}$ (Preference ranking organisation method for enrichment evaluation) [6] belongs to the family of outranking methods initiated by Pr. Bernand Roy as stated in [48]. In this study we will focus on the parametrisation of PROMETHEE II [69] [33] [34] [68] [36] which compares the actions in pairs by addressing each criterion in turn. An action, in this study stands for an escape manoeuvre, more commonly called trajectory solution or solution thereafter.

### 2.5 Conclusion and positioning

In this chapter the research works are positioned against the current technologies in use, and in development for the avoidance of operational accidents with a focus on CFIT accident scenarios. In this chapter we have also positioned the study with respect to considerations taken from various research fields compliant with the development of functionalities necessary for the avoidance of operational accidents.

Indeed, this study is positioned on the frame of autonomous systems design in so far as the final system should be able to monitor the safety of the aircraft, diagnose the risk of collision and provide alarms and estimated safe avoidance trajectories when necessary, without considering that the pilots are in the loop. The system is designed to be self reliant in terms of data necessary for the computations and in terms of decision-making. Chapter 3 will detail the functional architecture of the system and insist on the part played by the pilots in the design of the system, its applications, and its autonomous capabilities.

The study has the ambition to answer a complex question related to the avoidance of operational accident scenarios with a focus on CFIT accidents. Today, emergency situations in-flight do not have a formal representation, and there is no complete solution in the research fields to answer this problematic. Accident models exist as well as detailed accidents reports issued from official investigation boards. they permit to understand accident loops. However, there are no adapted systems to answer this problematic and contribute on the reduction of operational accidents. The current equipments are not always efficient nor adapted to all ranges of missions. Besides, the quantification of the situation awareness and the generation of appropriate alarms, relies on sector-specific know-how.

The key factor in the reduction of CFIT accidents is a good situation awareness. As these accidents are often due to human mistakes, appropriate training is useful.

[^8]
## CHAPTER 2. STATE OF THE ART - DISCUSSION AROUND THE RELATED WORKS

We have to take into account:

- The situation awareness by computing an envelope of trajectories in the 3D space frame,
- The constraints linked to the aircraft through a kinematic model designed for the aircraft,
- The confidence of the users (pilots and experts for ground applications),
- The regulations and certification constraints.

In this study we suggest an algorithmic approach to solve the problems through a system. We suggest a generic approach issued from the study of accident reports and Airbus Helicopters experience and feedback. The next chapter will detail the functional architecture of the system and the motivations for this approach.

## Chapter 3

## RAMSES Functional Architecture

### 3.1 Introduction

Risk Assessment Model for in-flight Safety Enhancement and Strengthening (RAMSES) is the avionics function concept developed in this study. RAMSES functional architecture has been thought in a framework for the design and evaluation of autonomous systems with the goal to reduce the rate of operational accidents in the Airbus Helicopters fleet. RAMSES aims to bring a solution to the in-flight dynamic safety monitoring through permanent risk assessment based on the aircraft's dynamic and kinematic capabilities; including the Airbus Helicopters pilot's judgement for the choice of escape manoeuvres before the crash threat becomes imminent. This chapter will explain how the RAMSES functional architecture has been derived from the analysis of accident reports (3.5) and positioning towards safety monitoring in-flight (3.2). This chapter establishes the limits of the present study and details the objectives of the thesis (3.3) with the associated set of assumptions and validation of the concepts in line with the Airbus Helicopters safety concerns (3.4). Besides, this chapter will also position the RAMSES avionics function concept initiatives through a detailed bloc diagram definition in 3.6.

### 3.2 Methodology of research

The design of the RAMSES functional architecture has to address the challenge of increasing autonomy for helicopters in operational emergency situations. As stated in the introduction, the problem has to be taken gradually, separately by identifying the functional blocs necessary to the global design. The functional architecture of RAMSES is called to account for CFIT (Controlled Flight Into Terrain) accident causes prevention. For that reason, the methodology of research is based on a detailed study of CFIT accident reports of the Airbus Helicopters fleet.

### 3.2.1 Understanding the Accident Loop

The logic of an accident scenario is addressed through several accident models like the Reason model, the Domino model or the Swiss Cheese model [83]. In all these cases, the accident happens because safety barriers have been overcome. Characterizing these safety barriers is very difficult. Often they rely on characteristic parameters of the mission, be it in aviation or not; and finding the accurate parameters to monitor in order to prevent the accident form occurring might be proper to the current situation. For that reason, it is of paramount importance to identify the moment when

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

the accident scenario starts, and formalise this moment with facts, like for example the occurrence of a significant environmental constraint perturbing the mission, i.e. the incapacity of the aircraft to perform a certain number of escape manoeuvres, the surrounding obstacle becoming closer, a degrading visibility etc.

The role of RAMSES avionics function concept is to provide the crew with an escape action before the current flight situation becomes too dangerous for the aircraft and its occupants. Fig. 3.1 is a framework of the accident loop composed of separate undesirable events $E_{1}, E_{2}, E_{3}, E_{4} \ldots$, and of the final accident $A$. However, an accident scenario is not a simple chain of causes and contributing factors. It is much more complex for the family of accidents treated in this study because they are unpredictable in-flight. In CFIT accident scenarios, the pilot is not aware of the collision threat. These accidents remain difficult to prevent because the crash happens in full consent of the crew. Naturally, the accident reports published by official investigation boards ${ }^{1}$ are often detailed and permit to reconstitute exactly how things happened before the accident; which means that for each report, it is often possible to derive a chain of significant undesirable events similar to the one presented in Fig. 3.1 in order to visualize how the undesirable events are sequenced. By contrast, the way an accident happens in-flight is often unique from a case to another, and even if characteristic trends could be extracted for operational accidents, they remain unnoticeable in real-time by the crew. For that reason, identifying the right moment to act in prevision of a crash is very hard in CFIT accident scenarios. A formal representation of this accident type does not exist. The avionics equipments like the TAWS (Terrain Awareness Warning System) are used to prevent CFIT accident scenarios, however are not adapted for all the missions, especially when they require to go close to obstacles, or to navigate in hilly environments because these equipments generate a high rate of false alarms in these situations. Indeed, the alerting rules of such equipments do not take into account the whole environmental context around the aircraft nor the pilots experience of the danger.

With the RAMSES avionics function concept, the study described hereafter aims at including the pilot's knowledge in the system in order to adapt the alerting rules at danger sight and enable a decision making capability for emergency avoidance to prevent the crash. For that reason, in 3.6 the bloc diagram definition of RAMSES details different levels of alerting indicators coupled to a multicriteria method enabling an explicit optimisation of an avoidance manoeuvre choice in case of emergency.

Typically, what happens in the case of a CFIT accident is that an environmental constraint or an inappropriate manoeuvre $E^{\prime}$ (Fig. 3.1) pushes the aircraft into a danger loop leading to the accident; RAMSES avionics function concept must find the best moment (principally based on new alerting rules and optimised decision-making capabilities) to trigger actions $E^{\prime \prime}$ (Fig. 3.1) in order to get out of the danger loop and restore an acceptable safety threshold. Finding the right Decision Point requires to work on the alerting rules of the avionics function concept and establish a method for permanent in-flight autonomous and adaptive safety monitoring. Indeed, as the terrain elevation map changes during the flight, and the obstacle density evolves, the avionics function concept must be able to detect, according to the current flight situation whether there is a threat or not. If the threat is real, then the function should be able to forecast it in order to leave enough time to the crew to take a corrective action, computed by RAMSES. In Fig. 3.1, the decision point is taken at the

[^9]

Figure 3.1. Accident loop made up of undesirable events $E_{1}, E_{2}, E_{3}, E_{4}$, etc provoked by an undesirable event $E^{\prime}$
undesirable event $E_{2}$; however, it could also be $E_{3}, E_{4}$ etc. but not $E_{1}$. In case a corrective action has been suggested by RAMSES and performed by the crew to get out of the accident loop at $E^{\prime \prime}$, then the aircraft should be able to reach its target position (final position of the mission or in-flight safe position).

The safety monitoring must rely on an accurate discretization or partitioning of the surrounding environment, so the function concept can judge independently of the crew whether a situation is threatening; to make sure that the avoidance trajectories and the warnings given to the crew, reflect the progression of the danger.

The RAMSES functional architecture reflects these considerations. The system must be highly adaptive in-flight, autonomously resuming control in case of emergency and ensure a permanent safety monitoring based on data computed on-board. Given the previous considerations, the functional blocs necessary to the avionics function design are:

- Discretization of the surrounding environment,
- Evaluation of the environment,
- Real-Time Risk assessment for safety monitoring,
- Dynamic Decision-Making adapted to the operational situation and suggestion of an avoidance manoeuvre as a prevention to a possible crash.

Three degrees of safety are addressed through the study: primary, secondary and tertiary safety as follows:

- Primary safety: set of active security actions that could be triggered before the accident occurs, which aim at avoiding the accident, i.e. avoidance manoeuvres and alarms,


## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

- Secondary safety: set of preventive passive actions which intend to minimize the direct consequences of the crash, i.e. the application can predict when the accident is unavoidable in order to trigger protective actions,
- Tertiary safety: When the accident is unavoidable the application can send the vehicle's relevant flight data to rescue teams.


### 3.2.2 Positioning within Airbus Helicopters

The study presented in this thesis has been conducted upon review of global helicopter accident statistics published by the IHST [96]. It could be noticed that the pilot judgement and/or a failure to apply the safety procedures stand among the main operational accident causes; where operational accidents happen the most frequently in helicopter operations.

In order to guide the thesis and confirm the tendencies in accident rates revealed by the IHST report, a survey has been conducted exclusively on the Airbus Helicopters fleet, over a period of 10 years. For a discretion concern the survey will not be revealed in this document, however it allows to confirm that operational accident scenarios require attention and represent a challenge for innovative avionics solutions to assist the crew in CFIT accident causes.

Airbus Helicopter (former Eurocopter) suggests a method for the identification of dangers and risk management in the information notice dated from 25/04/2013 [1]. The approach developed in this document is intended to improve the global flight safety, which remains a major priority for Airbus Helicopters. The method relies on:

- the establishment of generic and specific dangers that could be encountered,
- the identification and qualification of the consequences of the dangers on the activities,
- the definition of adapted corrective and preventive measures regarding the dangers in order to decrease their impact of the safety.


### 3.2.3 Definitions - Glossary

Undesirable Event or Emergency Situation: In-flight environmental constraint or situation leading to the decrease in on-board safety. An undesirable event or emergency situation is penalizing for the progress of the mission and could lead to an accident.

Accident: An accident is composed of many undesirable events decreasing the in-flight safety.
Trajectory Solution: It is an avoidance manoeuvre computed with the kinematic model of the aircraft, respecting the aircraft's flight envelope. A Trajectory Solution is computed for 30 seconds of flight ahead of the current flight state, by sections of 10 seconds of flight put together; computed isotropically in the three-dimensional space frame. A Trajectory Solution has been evaluated and is considered safe for the next 30 seconds of flight. It can be used as an alternative direction to the current path.

Dynamics Model: It is the model of the aircraft's behaviour over time. The dynamics model of an aircraft is a "set of mathematical equations used to calculate the physical forces acting on a simulated aircraft, such as thrust, lift, and drag" [7].

Airbus Helicopters and LAMIH-UVHC

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

Kinematics Model: It is the model deduced from the dynamic model of the aircraft, describing the aircraft's motion, in accordance with the flight envelope. The kinematic model refers to the "geometry of motion" [60], [87].

Set of avoidance Trajectory Solutions: All the avoidance Trajectory Solutions computed ahead of the current flight state and considered safe for the next 30 seconds of flight. The set of avoidance Trajectory Solutions is computed identically in the 3D space framework.

Decision Point: Moment when RAMSES estimates that the safety is too low and suggests to trigger an avoidance Trajectory Solution. State of the helicopter: Set of parameters describing the state vector of the helicopter at the current flight position. The state of the helicopter includes:

- The 3D position of the helicopter,
- The speed of the helicopter,
- The heading of the helicopter,
- The direction of the helicopter.

Flight point: equivalent to the flight state, i.e. state of the helicopter.
Criterion: Four criteria have been identified from the operational use cases treated in this study to support decision-making and risk assessment in prevision of a crash.

Safety Monitoring: It refers to the permanent risk assessment on-board. The Safety Monitoring plays a key role in finding the Decision Point when an emergency action is needed to avoid the crash.

Automatic Flight Control System: The computer that automatically maintains a navigation instruction like for example a heading, a direction, a preset route.

Interface: In the RAMSES functional architecture, an interface is used to make the link between a functional bloc, composing the functional architecture, and what lies beyond, like the automatic pilot, the instructions given by the crew etc.

Functional bloc: It is a separate part composing the functional architecture, and having a specific role in the system, like computing avoidance trajectories for example.

Functional architecture: It is the architectural model that identifies the principal functions corresponding to the system needs.

Avionics Function: part of the avionics suite, the electronic systems used on the aircraft.
Safety threshold: value testifying that the current flight situation has an acceptable perimeter of action in the near future (approximatively 40 seconds of flight).

A False Alarm is defined in this study as the gap between the danger perception by the pilot (operational reality) and the reported information from the HMI or the electronic device/equipment used to support the avionics function/capability.

### 3.3 Limits of the present study - Hypothesis

### 3.3.1 Set of assumptions

The proof of concept has been conducted for an "ideal" helicopter, at constant speed. Indeed, in order to test and validate the RAMSES avionics function concept, the study does not need to impose a specific helicopter of the Airbus Helicopters fleet. Hence, the simulated flight loop used for the tests was basic with three input commands:

- The True Air Speed (TAS),
- The roll command,
- The vertical speed command.

The characteristics of the flight loop are more detailed in chapter 4.

### 3.3.2 Objectives of the thesis

The objectives of the study detailed in this document is to design, develop, test and validate an approach to prevent the CFIT accident causes with prevention steps in the form of warnings and emergency manoeuvres feasible by the aircraft.

The approach has to be deterministic, fulfil the safety constraints imposed by the air traffic regulations and the Airbus Helicopters flight safety department along with dynamic constraints imposed by the capabilities of the aircraft.

Besides the approach has to take into account the Airbus Helicopters experts and pilots knowledge collected through interviews when they are put in operational emergency situations. The RAMSES avionics function concept should be able to restore a notion of danger close to the a pilot's perception of the danger. Therefore, the study on warning rules and actions taken to prevent the danger sight would be of paramount importance in the study. The undesirable events happening during the mission are assimilated to loss of control points on the flight situation as stated in [1]. The role of RAMSES is to restore an acceptable safety level and monitor the flight continuously.

### 3.4 Validation of the concepts

The concepts developed in the study are based on existing concerns and observations pointed by the safety teams. The CFIT accident scenario treated in this study has been formalised in [1] as shown in Fig. 3.2. It appears that the CFIT accident scenario mainly occurs because of an incorrect trajectory of the crew or a deviation of the planned route.

In order to answer these main reasons, the RAMSES avionics function architecture addresses two degrees of navigation: the short term navigation concept ensured by RAMSES through a permanent safety monitoring and situation monitoring (chapter 5) as well as computation of optimised avoidance trajectories as a prevention to a possible collision threat (more widely developed in chapter 6). The function ensures the link with regular navigation or what is going to be called the long term navigation in this thesis (path-planning) with data issued from a dedicated function detailed in [91]. The study aims to connect two different PhD thesis works within a common system logic. The connection

Airbus Helicopters and LAMIH-UVHC
between the two works are addressed in the trajectory generation functional bloc (chapter 4). They consist in providing a path-planning method, meeting constraints of both the current flight situation and the alternative route flight points.

The main concern is to secure the current flight situation by securing the current trajectory of the aircraft.


## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

### 3.5 The RAMSES Functional Architecture

RAMSES Functional Architecture (FA) is composed of five principal Functional Blocs as shown in Fig. 3.3. Each functional bloc has a specific technical contribution meeting a formal requirement to prevent the CFIT (Controlled Flight Into Terrain) accident threat. In this thesis, the research works will focus on CFIT accidents as stated before. However, the RAMSES functional architecture has been thought in order to meet preventive requirements of operational accidents, more generally speaking. For that purpose, the discussion that follows will bring elements to support this logic.

As explained above, the idea of the RAMSES avionics function concept is to monitor the danger proximity, prevent the danger sight and continually provide the crew a set of feasible trajectories, called trajectory solutions, safe up to 30 seconds of flight, to fall back on in case of emergency, for every flight point under the aircraft's dynamic capacities constraints, equally in the three-dimensional space frame. The monitoring of the danger is relative to the undesirable event and has to be adapted according to the flight situation, which means that input parameters given to the system should be characteristic of the undesirable event to avoid.

In the case of a CFIT accident scenario, the understanding of the immediate environment ahead and around of the aircraft is of paramount importance. The system must be able to evaluate possible future states of the aircraft and determine whether they are dangerous or not.

The dynamic properties of the helicopter are taken into consideration for each flight point. The RAMSES avionics function concept incorporates the kinematics properties deduced from the dynamic model of the aircraft in order to compute accurate motion primitives imitating the aircraft's behaviour.

Besides, the functional architecture displayed in Fig. 3.3 highlights possible interfaces with the autopilot (AFCS) and a potential human machine interface in order to guarantee that the RAMSES function concept could be tested in simulation environments at the Airbus Helicopters design office and on the simulation tools of the University of Valenciennes.

The main functional blocs composing the RAMSES architecture and playing a formal role in the prevention of CFIT accidents are:

- The trajectory generation functional bloc
- The trajectory evaluation functional bloc
- The risk assessment functional bloc
- The classifier functional bloc
- The decision-making functional bloc


Figure 3.3. RAMSES functional architecture

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

### 3.6 Bloc Diagram Definition

### 3.6.1 Trajectory Generation Functional Bloc

The trajectory generation functional bloc computes three-dimensional avoidance trajectories compliant with the flight envelope of the aircraft. Each trajectory stands for 30 seconds of flight, at a known speed kept constant, and is composed of three sections (possibly all different) in order to guarantee the agility of the aircraft in the manoeuvres and its capacity to reach a direction different from the current route. Indeed, the idea of the trajectory generation functional bloc is to characterise the surrounding environment of the aircraft with all the possible trajectories with gradual solicitation of the aircraft's dynamic capabilities in order to have a good "view" of the reachable space to 30 sec onds of flight. The trajectory generation functional bloc permits to discretize the space ahead and around the aircraft with trajectories in order to cover the immediate environment with potential future positions that could be evaluated with respect to the terrain elevation data and/or obstacles.

The details of the trajectories design are explained in chapter 4 and the choice for computing trajectories valid for 30 seconds of flight is explained in chapter 4.

Besides, the trajectory generation functional bloc ensures that the best avoidance trajectory, chosen by the crew or by the decision making functional bloc (subsection 3.6.5), could be computed at any time in order to be evaluated (subsection 3.6.2) and transmitted to the crew for approval; or directly given to the autopilot (subsection 3.6.6) for the application of an emergency manoeuvre.

The trajectory generation functional bloc is at the beginning of the RAMSES avionics function concept chain. It can receive requests directly form the decision-making functional bloc (Fig. 3.3). It could be envisaged that the trajectories computations are done in parallel units to make the system go faster. However, in this study and in order to test the first version of the avionics function concept in a first demonstrator, the computations will be done sequentially.

### 3.6.2 Trajectory Evaluation functional Bloc

The trajectory evaluation functional bloc receives all the trajectories computed by the trajectory generation functional bloc and evaluates their position with the terrain elevation data base or with the danger zones, precomputed using a method inspired from the distance fields [95], in order to stick the terrain elevation as much as possible. The computation of the danger zones, which ensure the partitioning of the space vertically is going to be detailed in chapter 5 .

The evaluation of the trajectories with respect to the terrain data base and the danger zones is also detailed in chapter 5. The idea is to evaluate the collision of the envelope of trajectories computed by the trajectory generation functional bloc with different layers above the ground in order to make the progression towards the ground more easily detectable by the system.

More precisely, the three sections composing the trajectories are estimated separately with respect to the terrain or with the danger zones.

In addition, a fourth section, standing for the extrapolation of the third section composing a trajectory, is computed and estimated in order to take into account an additional security margin on the model of the current equipment in use on-board like the TAWS (Terrain Awareness Warning System). Evaluating the trajectories in this way ensures that the decision making functional bloc, the classifier functional bloc and the risk evaluation functional bloc have enough information on the surrounding
environment to help in the choice of an optimal solution, considered the best avoidance trajectory solution for the crew.

### 3.6.3 Risk Evaluation Functional Bloc

The risk evaluation functional bloc monitors the safety of the current situation with respect to the remaining available trajectory solutions evaluated by the trajectory evaluation functional bloc. The risk evaluation functional bloc ensures that the global safety thresholds are respected by the current in-flight situation and otherwise it triggers warnings reported to the decision-making functional bloc to warn the crew, if necessary, of the incoming danger. The risk evaluation functional bloc monitors the collision of the envelope of trajectory solutions, based on deterministic rules extracted from the interviews with AH pilots and experts. Section 5.6 details the risk evaluation process.

This is different from the classifier functional bloc detailed in 3.6.4, in the sense that the risk functional bloc monitors the evolution of all the trajectory solutions as a global system. It does not take into consideration each trajectory separately, it will generate warnings based on more general rules, together with the classifier functional bloc, as a complementary entity looking the surrounding environment as a single system evolving dynamically.

The risk evaluation functional bloc estimates permanently the capacity of the system to recover from a degraded safety by evaluating the state of the discretized environment ahead of the current flight position. Hence it estimates if the collision is likely to happen.

Practically, it could be said that the risk evaluation functional bloc evaluates the capacity of the system to be resilient towards the danger threat. In this study, the notion of resilience is not developed/formalised further. However, the concept of resilience could be mentioned here like in the works [22] [24], even if it is not going to be thoroughly studied, in the sense that a similar way for preventing the undesirable events is used: the RAMSES avionics function concept analyses the future state of the aircraft in order to adjust the current state and predict whether the current situation could recover from the corresponding degraded safety, which is going to be detailed further in chapter 6 .

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

### 3.6.4 Classifier functional Bloc

The Classifier functional bloc is part of the RAMSES functional architecture. A detailed view of the Classifier is displayed in Fig. 3.4. The Classifier is based on a known multicriteria method: PROMETHEE II (Preference ranking organization method for enrichment evaluation) [69] [33] [34] [68] [36] used two times in succession at each iteration of the system. There are no contributions on the method in this study. It has been used in a simplified version and the code has been provided for the purpose of this study by Dr. D. Duvivier [48] as an embedded tool. The parametrisation of the method has been done in collaboration with Airbus Helicopters based on interviews with Airbus Helicopters flight test pilots and experts in order to render an operational reality in the generation of alarms and in the choice of relevant avoidance manoeuvres towards the collision threat. This part is going to be explained in chapter 6.

All the data treated by PROMETHEE II come from the Central Data Structure (CDS) where the Classifier performs read and write accesses. More precisely, the Classifier acts as trajectories comparator, dynamically and permanently during the flight. The trajectories generated by the Trajectory Generation functional bloc are evaluated, rated and stored in the CDS. The PROMETHEE II method compares all the trajectories relative to each other and relative to a trajectory considered a reference, i.e. the best possible trajectory for the system in order to compute the preferred avoidance trajectory solution. The current trajectory stands for the extrapolated current state of the aircraft to 30 seconds of flight. It has not to be the safest trajectory. However it is natural that this trajectory constitutes the reference for the comparisons within PROMETHEE II because it constitutes the whole purpose of the evaluations. The immediate environment and the danger sight is rated according to the current position, the current flexibility of manoeuvres and according to the future state of the aircraft and the future flexibility of manoeuvres.

All the trajectory solutions are then ranked by PROMETHEE II a first time as shown in Fig. 3.4. They are compared to the current trajectory corresponding to the extrapolated trajectory of the current state, which is considered as the reference for the comparison process. Indeed, the Classifier is part of a system, which purpose is to monitor the in-flight safety. Therefore, the system determines whether the current flight trajectory is safe or not. This is done with safety indicators at different levels. As for the Classifier, especially in the second step (PROMETHEE II BEST) the current trajectory flown by the aircraft is compared to the best ranked trajectory solutions taken from the global envelope of trajectories. If the current trajectory is too far from the best trajectory solution computed by the method, then it is assumed that an alarm should be raised and sent to the Decision Making functional bloc in order to warn the crew or perform an avoidance manoeuvre.

The threshold detecting the gap between the best ranked trajectory solution and the current trajectory (extrapolation of the current state of the aircraft) will be determined experimentally in simulation to provide a first version of the method and allow to validate the concepts in a first demonstrator. This threshold constitutes one of the main factors determining the final alarm permitting to warn the crew of the incoming danger. This step counts in setting up new alarm rules completing the safety indicators provided by the lower functional blocs of the RAMSES architecture.

It could be envisaged that the multicriteria method used in the Classifier functional bloc requires different parametrisations according to the flight situation, the mission performed by the crew or

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

regarding the pilots preferences in terms of safety monitoring. For that reason, a selection of operating modes has been provided in the first version of the Classifier functional bloc.

The tests detailed in the next chapters will demonstrate the predominance of some parameters rather than others. It could easily be envisaged to use a different set of parameters (and/or additional criteria) in the second instantiation of PROMETHEE II to refine or strengthen the decisions. Indeed, the role of the Classifier is twofold; it has to rank all the trajectory solutions in order to compute one best trajectory among the global envelope computed by the Trajectory Generation functional bloc, and it has to assess of the utility to deviate the current flight. For that reason the parametrisation of PROMETHEE II is of paramount importance.


Figure 3.4. Classifier functional bloc - detailed view

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

### 3.6.5 Decision Making Functional Bloc

This functional bloc acts as the final decision-maker of the chain. It is in charge of managing the information between the pilots and the system via an interface like a HMI (Human Machine Interface); and it acts as the link between the autopilot (AFCS), potentially, and the rest of the RAMSES functional blocs.

The decision making functional bloc monitors the final actions taken to avoid the collision, like an emergency avoidance manoeuvre. In order to test and validate the RAMSES avionics function concept an accident of the Airbus Helicopters fleet has been considered and it is detailed in section 7.2. However, CFIT (Controlled flight Into Terrain) accident scenarios may occur in different operations and missions. For that reason it is essential to take into account the current operational situation of the flight, which could be different from a mission to another. As explained above, the functional architecture of RAMSES has been designed on observations and analysis of CFIT accident scenarios. Therefore, the RAMSES functional architecture presented in 3.3 is generic enough to be adapted to the mission and the changing environment. However it is required that the input parameters, permitting to make a difference between two different operational situations, are known in advance. For that reason, the decision making functional bloc is closely linked to the pilot's state of mind and its perception of the operational reality of the flight.

In order to convey the operational reality of the current in-flight situation, the decision making functional bloc relies on the elicitation of the pilot's knowledge put in emergency situations.

For the purpose of the study, only one example of CFIT operational scenario is going to be tested with a reconstituted accident of the fleet. Indeed, the limitations implied by the study on the speed and acceleration variations and more generally speaking the set of assumptions are limiting the compatible cases of the AH accident data base for the concept validation. However, various tests will be performed in order to identify the concept profits in safety monitoring and provide a study on innovative warning rules translating the operational constraints associated to the progress of the mission.

The decision making functional bloc adapts the choice of the optimal trajectory solution with respect to the flight situation. In the first version of the RAMSES demonstrator, only the DVE CFIT scenario will be analysed. However, the decision making functional bloc is meant to evolve towards a state machine composed of all the possible operational situation leading to a CFIT accident scenario. For each flight situation, a separate state would be associated with possibly different parameters derived from the AH pilot's and experts knowledge.

In chapters 6 and 7, two CFIT configurations are going to be defined and analysed:

- A regular CFIT configuration,
- A special CFIT configuration adapted to the reconstituted accident treated in 7.2.

The main difference between the two configurations is the parametrisation of the Classifier functional bloc reporting the ranking of the trajectory solutions and the best fitted trajectory solution for the current flight situation; translating by this way the capabilities of the RAMSES avionics function concept to adapt dynamically to a degrading flight situation, which is the strength of this system and the logic of an autonomous avionics function concept.

## CHAPTER 3. RAMSES FUNCTIONAL ARCHITECTURE

### 3.6.6 Interfaces

The interfaces between the functional blocs of the RAMSES architecture and the external systems or devices like the HMI (Human Machine Interface) and the autopilot (AFCS) are not treated in this study. However, in a concern of compliance with the Airbus Helicopters simulation tools, and considering the fact that the RAMSES concept should be able to interact in a test environment (on AH simulation tools for example), the interfaces are included in the functional architecture presented in Fig. 3.3.

## Terrain Interface

The terrain interface aims at transforming the terrain data input of the mission area, coming from a sensor, from a data base or both, into a digital elevation matrix comprehensible by the trajectory evaluation functional bloc. The terrain elevation data are then pre-processed into danger zones and stored for the trajectories evaluation and the collision risk assessment by the other functional blocs of the RAMSES architecture.

The terrain interface development has been done in this study to provide a first test. If the terrain data evolves the interface will be adapted.

## Human Machine Interface (HMI)

The Human Machine Interface (HMI) development is not part of this study. However, given the amount of information that could be computed by RAMSES, the HMI was an issue from the beginning of the study. Indeed, the function acts as a permanent safety monitor in-flight and suggests avoidance trajectory solutions in case of undesirable event. However, if the crew is not receptive to the emergency manoeuvres then it could be imagined that the function takes over the control of the aircraft and sends an avoidance trajectory to follow to the AFCS.

## Automatic Flight Control System (AFCS) Interface

The Automatic Flight Control System (AFCS) Interface won't be detailed in this document because it is not a part of the study. We assume, for the purpose of the study, that the data given as input to the AFCS Interface could be an entire trajectory computed by the trajectory generation functional bloc, composed of 3D positions and their orientation. In order to test the RAMSES function concept there is no need for more details. Moreover, the AFCS Interface and the AFCS are considered as "black boxes" here. The study will focus on what is happening before the AFCS is solicited, i.e. how to determine the decision point when an emergency manoeuvre is crucial for avoiding the accident.

## Alternative Flight Plan Interface

The Flight Plan Interface is a way to connect the short-time navigation concept, enhanced by the RAMSES avionics function, to the actual navigation phase performed during the mission, by injecting a new flight plan. The purpose of having a possible alternative flight plan to the current one is to ensure that if an emergency occurs, and the helicopter moves away from the current route, there is a way to guide the aircraft towards a safe route computed during the mission by an external function to RAMSES. The research works around this topic have constituted the subject of a PhD thesis [91]
conducted by the University of Valenciennes in partnership with Airbus Helicopters, and they are integrated here in order to follow a logic of a complete system.

### 3.7 Conclusion

The RAMSES avionics function concept has been thought and developed with the idea of delegating further autonomy to the aircraft during the flight especially in operational emergency situation.

In this chapter we have introduced the functional architecture of the RAMSES avionics function concept (Fig. 3.3) by reasoning over the technical contributions necessary to the meet the requirements for the avoidance of operational accidents and more specifically the CFIT (Controlled Flight Into Terrain) accident.

For that purpose, the following main functional blocs composing the RAMSES architecture have been explained:

- The trajectory generation functional bloc
- The trajectory evaluation functional bloc
- The risk assessment functional bloc
- The Classifier functional bloc
- The decision-making functional bloc

Additionally, the system's interfaces with possible environmental inputs and external systems have been situated in the framework of the RAMSES design.

In order to fulfil the safety concerns upon which the research works are based, the functional blocs composing RAMSES have been derived on observation, surveys and analysis of operational accidents of the Airbus helicopters fleet. The main goal was to understand the accident loop composing all these accidents and find common trends to structure the system, make it flexible and adaptable dynamically to the crew's needs.

Indeed, the system has been thought to monitor the danger sight associated to undesirable events and provide an unnoticed safety monitoring of the flight on-board the aircraft to provide consistent warnings, alarms and possibly escape manoeuvres before the crash would occur.

## Chapter 4

## RAMSES: Trajectory Generation Functional Bloc

### 4.1 Introduction

The Trajectory Generation functional bloc is part of the RAMSES architecture (Fig. 4.1). It relies on an analytical model capable of computing accurate three-dimensional trajectories representative of a helicopter's flight, as described in section 4.3. This chapter is going deeper in the explanation of algorithms running in the Trajectory Generation functional bloc. More precisely, this chapter will detail the construction of the analytical model, upon which the trajectories are computed, derived from the observation of a simulated helicopter flight loop (4.2). Moreover, this chapter will present the method for extracting the primary motion primitives necessary to the design of the three-dimensional paths feasible by the aircraft. This way the chapter will also cover a path-planning method for connecting two randomly oriented positions in the three-dimensional space frame, under complex constraints at the same time along the path and at its ends (4.4).

The path-planning methods presented in this chapter aim at making the link between the concepts of short term navigation (covered by the RAMSES avionics function concept) and long term navigation introduced in chapters 2 and 3; one the same occasion ensuring the logic of continuity between the research works presented in this thesis and the study on path-planning covered by [91]. Indeed, in the functional architecture of the RAMSES avionics function presented in Fig. 4.1, the long term navigation is addressed through an external bloc interacting with RAMSES: The Alternative Flight Plan bloc, that could be solicited any time by RAMSES to get a new flight plan if needed.


Figure 4.1. RAMSES functional architecture - focus on the Trajectory Generation functional bloc

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

### 4.2 From the dynamic model of the aircraft to the mathematical characterization of the flight

### 4.2.1 Process mapping - Using a Helicopter Flight Loop in a Simulated Environment

For the purpose of this study, as explained before in chapter 3, an efficient way to obtain a projection of the possible positions of the aircraft equally in the three-dimensional space is needed. The projection represents a realistic image of all the successive potential future states of the aircraft ahead of the current position for a given period of time, taking into account both the current state and the dynamic limits of the aircraft.

Having an analytical motion primitives based model capable of computing accurate flight trajectories with a reduced number of characteristic parameters is of major interest for embedded systems because it is much lighter to process than a complex dynamics model. Indeed, helicopter's successive positions can easily be derived from the flight mechanics equations ruling the dynamics model of the helicopter. However, three dimensional path planning with varying constraints in torsion, curvature, angle of climb and their derivatives along the path is difficult to fulfil using only flight control input commands. For that reason, one efficient solution is to characterize the flight behaviour of the aircraft mathematically by observing its original dynamic flight loop in simulation. Otherwise, the system would have to take into account the original flight loop for the computations, and solve, for each new flight state, systems of differential equations ruling the dynamic model, taking into account successive integrations of acceleration and speed to obtain the positions composing the movement.

For the purpose of this study, a simplified flight loop of an "ideal helicopter" has been used to produce the data in a simulation environment. The flight loop used hereafter is not representative of a particular helicopter. It has only been used as a tool in order to design and implement the analytical model and eventually provide a test device. The flight loop of the "ideal helicopter" relies on the following assumptions:

- The wind model is not considered,
- A standard ICAO atmosphere is considered,
- A constant weight (helicopter+fuel+passengers) is assumed during the mission,
- The avoidance manoeuvres forming the trajectories are generated with gradual solicitation not exceeding $\pm 20$ degrees of roll angle and $1500 \mathrm{ft} / \mathrm{min}$ for the vertical speed,
- The TAS (True Air Speed), which is also the cruise speed, is kept constant during the flight and set to 70 kt ,

However, the method developed for the extraction of intrinsic parameters characterizing the helicopter's dynamic behaviour remains valid for any other helicopter flight loop ${ }^{1}$.

Only the values of the extracted parameters would change as they would characterize another helicopter's dynamic behaviour and limits. This method consists of studying the flight loop recordings of the aircraft's successive positions for a given control law in order to identify whether one or several

[^10]
## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

mathematical curves put together could fit the trajectory generated by the flight loop (Fig. 4.2). More precisely, the flight recordings have been produced by acting exclusively on three input commands which permitted to create all the possible combinations of trajectories with graduate solicitation of the aircraft. These three input commands, as shown in Fig. 4.2 are :

- The True Air Speed in knots (TAS)
- The Vertical Speed in feet/min (VS)
- The Roll Angle in degrees


Figure 4.2. From the Helicopter's Simulated Flight Loop to the Mathematically Computed Trajectories

Hence, three types of computed trajectories where identified from the simulation data. We call them :

- Climb trajectory obtained by increasing or decreasing the vertical speed and maintaining the true air speed constant with no roll angle,
- Lateral trajectory obtained by increasing or decreasing the roll angle and maintaining the vertical speed and the true air speed constant,
- Oblique trajectory obtained by combining both variations of vertical speed and roll angle for a constant true air speed.


## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

The Lateral and Climb trajectories are two-dimensional curves, as they are contained respectively in the horizontal and the vertical planes. The Climb trajectory naming covers both climb and descent trajectories. They are of same type and composition in term of motion primitives association. The only difference is that the angle of climb is negative for the descent trajectory. The Oblique trajectory is a space curve.

Fig. 4.2 maps the extraction process of the parameters needed for establishing the analytical model on which relies the RAMSES Trajectory Generation functional bloc. All the parameters are identified and computed from the flight recordings produced by the simulated flight loop. In the end, the analytical model is expected to have a data base of parametrized primary motion primitives, i.e. mathematical equations, as well as transition curves between them in order to ensure a compliance with the simulated helicopter flight. In this study, given the flight loop inputs, we only had to deal with three degrees of freedom as shown in Fig. 4.3. The True Air Speed expressed in knots stands for the horizontal speed of the aircraft, it was kept constant during the simulations. Vertical Speed expressed in feet per minute permits to assess the rate of climb of the aircraft. Eventually, the roll angle specifies whether the aircraft was performing a turn, i.e. if the trajectory was straight or if it had a rounded shape with non-zero curvature.


Figure 4.3. The three degrees of freedom actioned by the Basic Flight Loop
Accordingly, the data positions of the aircraft, collected in simulation, are translating the variations of the three input commands of the flight loop. Therefore, the observed trajectory profiles should enhance variations on parameters such as the curvature $\kappa$, the angle of climb $\theta$, the torsion $\tau$ and their derivatives $d \kappa, d \theta, d \tau$ translating the limits of performance of the dynamics model respectively for each parameter. As a result, the maximum curvature $\kappa_{\max }$ identified in the recordings would give the maximum radius of curvature feasible by the aircraft; indeed, the dimensional analysis shows that for a kinematics problem it is common to compute the radius of curvature $R$ as the inverse of the curvature :

$$
R=\frac{1}{\kappa}
$$

For a plane curve, $R$ is the absolute value of

$$
\frac{d s}{d \phi}=\frac{1}{\kappa},
$$

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

where $s$ is the arc length of the curve from a fixed point $\phi$ is the tangential angle formed by the curve and $\kappa$ is the curvature.

Equally, the analysis of the climb rate along the recorded trajectories should give the distribution of the climb angle $\theta$ for each trajectory, where $\theta$ is given by the vertical difference $d z$ between two consecutive points of the curve, respectively to the arc length between these two points :

$$
\theta=\arcsin \left(\frac{d z}{d s}\right) .
$$

Obviously, the trajectories contained in the horizontal plane, i.e. essentially lateral trajectories have zero torsion and zero angle of climb.

### 4.2.2 Smoothing of the Flight Data Collected in Simulation

In order to derive the distributions of the curvature $\kappa$, the angle of climb $\theta$, the torsion $\tau$ and their derivatives the flight recordings had to be treated first. Accordingly, the data collected in simulation have been smoothed using the Bezier curves [28] to get the characteristic parameters needed for computing the motion primitives. Other numerical methods could have been used here to compute the discrete curvature distribution but the results were not as good as with the Bezier curves smoothing. Besides, the Bezier curves are a convenient choice for this study because a few control points are needed to characterize the simulation recordings. More precisely, the main challenge was to obtain a formal representation of what is happening during the transitions and changes along the path. Indeed, the observations of the flight data are expected to reveal specific mathematical primary motion primitives like circle arcs for a horizontal turn or helix spires when we combine both variations in the vertical speed command and the roll command. These primitives are very well known, and easily computed. However, what happens between them is less obvious and requires a specific characterisation. The transition's properties between the primary motion primitives remain unknown: like for example what type of curve could fit the flight data between an initial state with zero curvature, torsion and climb angle to a final state where these parameters are saturated? As the resulting curves produced with the Bezier curves smoothing fit very well the simulation data, the distributions of curvature $\kappa$, climb angle $\theta$ and torsion $\tau$ were derived from there.

Indeed, flight data produced in simulation or taken from real flights are a succession of space states with information on positions, speed etc. The curves generated with this data are not smooth and require a pre-processing, otherwise the discrete approaches in curvature and torsion are not representative of the motion behaviours (see Appendix A). For that reason, smoothing the flight data with Bezier curves ensures that the resultant curve is $\mathcal{C}^{\infty}$ and hence $\mathcal{C}^{3}$, making the curvature and torsion computations possible.

The radius of curvature $R$, for a curve defined parametrically by functions $x(t)$ and $y(t)$ is given by:

$$
R=\left|\frac{d s}{d \phi}\right|=\left|\frac{\left(\dot{x}^{2}+\dot{y}^{2}\right)^{\frac{3}{2}}}{\dot{x} \ddot{y}-\dot{y} \ddot{x}}\right|,
$$

where

$$
\left(\dot{x}=\frac{d x}{d t}, \dot{y}=\frac{d y}{d t}\right)
$$

and

$$
\left(\ddot{x}=\frac{d \dot{x}}{d t}, \ddot{y}=\frac{d \dot{y}}{d t}\right) .
$$

As the flight data contains the successive positions of the helicopter during the flight, knowing the period between two successive points, we have the information about the speed and the acceleration along the path.

If we take the first three derivatives of the curve $f^{\prime}, f^{\prime \prime}, f^{\prime \prime \prime}$, we can obtain the expressions of the curvature and the torsion using the orthonormal basis TNB (Tangent, Normal, Binormal) frame (Fig. $4.4^{2}$ ) as shown below :

$$
\begin{gather*}
\kappa=\frac{\| f^{\prime} \wedge f^{\prime \prime}{ }^{\prime}}{\| f^{\prime}{ }^{3}{ }^{3}}  \tag{4.1}\\
\tau=\frac{\operatorname{det}\left(f^{\prime}, f^{\prime \prime}, f^{\prime \prime \prime}\right)}{{ }^{\prime} f^{\prime} \wedge f^{\prime \prime} \|^{2}} \tag{4.2}
\end{gather*}
$$



Figure 4.4. A space curve; the vectors $\mathbf{T}, \mathbf{N}$, and $\mathbf{B}$; and the osculating plane spanned by $\mathbf{T}$ and $\mathbf{N}$

The Trajectory Generation functional bloc provides the system with accurate trajectories, simulated ahead of the current flight state. This way, for each flight point the system disposes of a relevant physical representation, equally in the three-dimensional space frame, of potential successive positions of the aircraft during a given period of time. A flight point is a spatial representation of the helicopter's state, including its position, speed, orientation and heading ${ }^{3}$ Hence, for each flight point the information listed before are known by the system. The flight points are spaced by fixed periods of time

[^11]
## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

all equal along the flown path. The period between two consecutive flight points is given in the study and will be specified for each use case developed hereafter ${ }^{4}$. In addition, this representation of the aircraft's state, with extrapolated trajectories takes into account the current aircraft's constraints.

### 4.2.3 Construction of the Trajectories Composing the Physical Environment, Image of the Helicopter's positions extrapolated to 30 seconds of Flight

The trajectories computed by the Trajectory Generation functional bloc are composed of successive extrapolations of the usual flight control commands, put together. The trajectories are computed for 30 seconds of flight ahead of the current aircraft's position in order to be compliant with the safety constraints imposed by the pilots regarding the validity of escape trajectories (cf chapter 6). As stated before, the challenge of the Trajectory Generation functional bloc is to translate the most accurately the dynamics behaviour of a helicopter through an analytical model relying on few parameters, more flexible regarding the kinematics constraints imposed along the computed trajectories, and lighter to process if it had to be embedded. Regarding the previous assumptions, the parameters coming into play for the analytical model are listed in Table 4.1.

| Parameters | Symbol |
| :--- | :---: |
| Curvature | $\kappa$ |
| Angle of climb | $\theta$ |
| Torsion | $\tau$ |
| Derivative of curvature | $d \kappa$ |
| Derivative of angle of climb | $d \theta$ |
| Derivative of torsion | $d \tau$ |

Table 4.1. List of parameters extracted from the Flight Data produced in the simulation environment and necessary to the construction of the analytical model

Each trajectory is made of three primary sections, where every section is linked to the next one by an adapted transition.

It is of major interest for embedded systems in the sense that it is light to process as it depends on few parameters, most notably the curvature $\kappa$, the angle of $\operatorname{climb} \theta$, the torsion $\tau$ and their derivatives listed in table 4.1.

The model computes sequences of dynamic manoeuvres standing for avoidance trajectories feasible by the aircraft, in the three-dimensional space frame as shown in Fig. 4.6, with high constraints on time, in unprepared terrain. This is repeated three times, i.e. for each current flight point a set of manoeuvres is computed, and for every manoeuvre this is repeated and so on, until we form a set of trajectories formed of three different manoeuvres of $10 s$ of flight as shown in Fig. 4.5 and Fig. 4.7. This reachable envelope of trajectories, as illustrated in Fig. 4.8, guarantees an isotropic discretization of the three-dimensional space within a given period of time, which represents 30 s of flight. The trajectory generation functional bloc ensures the continuity of the curvature and the torsion along every sequence manoeuvre and every trajectory [72].

[^12]Airbus Helicopters and LAMIH-UVHC


Figure 4.5. An avoidance trajectory is composed of three sequence manoeuvres to guarantee an isotropic discretization of the three-dimensional space frame reachable for a given flight time


Figure 4.6. Sets of alternative avoidance manoeuvres to the current path, low and strong solicitation, equally oriented in the three-dimensional space frame.

The files have been recorded by acting exclusively on three degrees of freedom (Fig. 4.3) horizontal and vertical axis through the True Air Speed (TAS) and the Vertical Speed (VS) and an additional degree of freedom with the roll angle command with reference to the horizontal axis as shown in Fig. 4.3.

This method for parameter extraction remains valid if the flight loop changes, the model remains valid but the output values of the parameters change. In order to partition the immediate environment around the helicopter exclusively with trajectories we performed three type of input commands with different solicitations combining variations on the vertical speed and the roll angle (Fig. 4.5). The data collected from the simulation tools is smoothed using Bezier curves [72] [28] in order to derive the characteristics parameters. It appears that every sequence manoeuvre can be decomposed in primary motion primitives as : clothoid arcs, circle arcs, straight lines, helix spires and three-dimensional transition spires [72]. The three-dimensional transition spires are used to connect two-dimensional flight positions to a three-dimensional path and they have been described in a previous paper [72]. The 3D transition can take different shapes and they can have different properties by only acting on its initial and final constraints, which are mainly the curvature $\kappa$ and the angle of climb $\theta$ (developed

Airbus Helicopters and LAMIH-UVHC


Figure 4.7. One typical trajectory of the immediate environment reachable by the aircraft in 30 seconds of flight. The trajectory is formed of three different sequences of avoidance manoeuvres.


Figure 4.8. Envelope of avoidance trajectories with three different sections composed of motion primitives

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

in section 4.3.3).

### 4.3 Trajectories Extracted from the simulation model

### 4.3.1 Design of Lateral Trajectories

The choice of the motion primitives cited in Table 4.1 is not neutral. It is not easy to have a good representation of the travelled path of a helicopter during a given mission. Besides, it is even harder to get a good approximate of the transition phases between two flight levels for example of two different headings.

A helicopter travelling a circular path experiences a centripetal acceleration. When the vehicle flying on a level flight experiences a sudden transition to a tangential circular path, it experiences the centripetal acceleration starting at the very tangent point and causing discomfort. The centripetal acceleration is given by $\frac{V^{2}}{R}$. Hence, in order to have a linear evolution of the centripetal acceleration, for a constant speed it is necessary to have a linear evolution of $\frac{1}{R}$, thus a linear evolution of the curvature $k$, which gives a clothoid curve for the transition phases.

An alternative to approaching the trajectory of a helicopter by mathematical motion primitives would be to integrate twice the impulse of an acceleration command, as it is given to the automatic pilot computer. This impulse has a trapezoidal shape (similar to Fig. 4.10). However, instead of having a clothoid for the transition phases it would be a cubic curve (polynomial curve of degree 3 ), which is an approximation of the clothoid curve for small angular changes. In the same way, instead of using a circle as one of the motion primitives it would have been a parabola, which is an approximation of the circular curve for small angle changes.

We define the lateral trajectory as a two-dimensional horizontal path obtained by applying a turn, or a roll angle, to the helicopter. The experiment has been done for different roll angles as shown in Figure 4.3.1.


Figure 4.9. Curvature profiles obtained from simulation data, with Bezier curves smoothing - results computed for different roll angles

From the simulation recordings, parameters have been extracted such as the maximum curvature $\kappa_{\max }$ and the maximum derivative of the curvature $d \kappa_{\max }$. Indeed, the simulation data for such trajectories have permitted to establish a common profile for the curvature distributions. It is noted in

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

Figure 4.3.1, that the curvature changes linearly with the arc length of the curve before reaching a maximum value and remaining constant. Besides, we do not take the maximum values observed in simulation for those parameters. A security margin is kept in order to avoid exceeding the flight envelope and therefore the actual capabilities of the helicopter. Hence the first portion of the lateral trajectory, until $S_{1}$ is reached, is a clothoid followed by a circle arc with constant curvature $\kappa_{\max }$ and radius $R=\frac{1}{\kappa_{\text {max }}}$; where

$$
S_{1}=\frac{\kappa_{\max }-\kappa_{0}}{d \kappa_{\max }}
$$

and $S_{\text {tot }}$ depends on the speed and flight time of the aircraft.


Figure 4.10. Framework of the curvature distribution for a lateral trajectory as a function of the curvilinear abscissa

Figure 4.11 displays a result comparing the trajectory obtained in simulation with the computed trajectory for 30 seconds of flight at a speed of 70 knots. The computed path is very close to the simulation data.


Figure 4.11. Results for a lateral trajectory during 30s of flight - simulation (red) and computed trajectory (blue)

### 4.3.2 Design of Climb trajectories

We define a climb trajectory as a two-dimensional vertical path obtained by applying a vertical speed to the helicopter. In the same way as for lateral trajectories, the experiment has been done for different vertical speeds. An example is displayed in Figure 4.12.


Figure 4.12. Curvature profiles obtained from simulation data, with Bezier curves smoothing for climb trajectories at different vertical speeds

Four distinct parts have been identified in the climb trajectories, suggesting four different motion primitives, which are two clothoids (for the linear evolution of the curvature), a circle arc between the clothoids and a straight line with zero curvature at the end (Figure 4.13). Here again we do not take the very maximum values for $\kappa_{\max }$ and the $d \kappa$ slopes. $S_{1}$ and $S_{t} o t$ are found the same way than for the lateral trajectory. In simulation we have $S_{3}$ as it corresponds to the final climb angle of the climb trajectory, which permits to deduce $S_{2}$.


Figure 4.13. Diagram of the curvature distribution for a climb trajectory
Results for a climb trajectory are displayed in Figure 4.14.
When the straight line is captured the final angle of climb is reached. The computed trajectory is compliant with the capabilities of the helicopter. It does not exceed the actual climb performances but remains very close to the simulation for a given vertical speed.

### 4.3.3 Design of Oblique trajectories - focus on the three-dimensional spiral transition

The oblique trajectory is obtained in simulation by both increasing the vertical speed and applying a turn, i.e. a roll angle, to the helicopter. The simulation results were performed with different vertical speeds and roll angles. In order to extract the characteristic parameters of this trajectory and capture its different states and stages with the intention of reproducing it mathematically, only initial


Figure 4.14. Results for a climb trajectory on 12 seconds
conditions have been imposed with zero torsion and zero curvature. From there on, we have an open loop trajectory generation system allowing all possible observations.

According to the fundamental theorem of (the local theory of) space curves [1], "in differential geometry, every regular curve in three-dimensional space, with non-zero curvature, has its shape (and size) completely determined by its curvature and torsion. A curve can be described, and thereby defined, by a pair of scalar fields: curvature $\kappa$ and torsion $\tau$, both of which depend on some parameter which parametrizes the curve but which can ideally be the arc length of the curve. From just the curvature and torsion, the vector fields for the tangent, normal, and binormal vectors can be derived using the Frenet-Serret formulas. The integration of the tangent field (done numerically or analytically) yields the curve".

Since the curves we are dealing with are regular and $C^{\infty}$, knowing their torsion and curvature for all points ensures their unicity. However, even if the Bezier curves smoothing works perfectly fine for finding the curvature distribution along the oblique trajectory taken from the simulation recordings, this method reveals some oscillations with the torsion which makes it difficult to identify formally the maximum value of the derivative of the torsion $d \tau_{\max }$. Despite these considerations the method enables to find the maximum value of the torsion $\tau_{\max }$ because the distribution stabilizes after the oscillations. The discrete derivation directly from the simulation recordings has also been tested but this method does not give satisfying results either. This is why a specific method for the design of the oblique trajectory is required here.

We note that the Bezier curves smoothing method gives a linear evolution of the curvature when both the vertical speed is increased and a turn is applied to the aircraft. An example is displayed in Figure 4.15.

Actually, it has been observed in simulation at some point that the helicopter captures a helicoidal climb. At this stage, the curvature is maximal and the torsion of the trajectory measured in simulation is also saturated, therefore we have $\kappa_{\max }, \tau_{\max }$ and $\theta_{\max }$. Moreover, we are able to objectivize the derivative of the curvature $d \kappa_{\text {max }}$. Regarding these considerations we are able to suggest a relevant helicoidal trajectory given the capabilities of the helicopter with $\tau_{\max }$ and $\kappa_{\max }$. The parametric equations of a circular helix are:

$$
\left\{\begin{array}{l}
x(t)=a \cos (t) \\
y(t)=\epsilon a \sin (t) \quad \text { with } \quad \epsilon= \pm 1 \\
z(t)=b t
\end{array}\right.
$$



Figure 4.15. Distribution of the curvature $\kappa$ for oblique trajectory with $1000 \mathrm{ft} / \mathrm{min}$ vertical speed and 20 degrees roll angle

Parameters $a$ and $b$ are derived from the radius of curvature $R_{c}=\frac{1}{\kappa}=\frac{c^{2}}{a}$ and the radius of torsion $R_{t}=\frac{1}{\tau}=\epsilon \frac{c^{2}}{b}$.

However, what happens before the helix has to be computed differently. At this stage we can compute the final torsion as follows:

$$
\tau_{\max }=\tan \left(\theta_{\max }\right) \kappa_{\max }
$$

where $\kappa_{\max }$ is the maximum curvature and $\theta_{\max }$ is the final angle of climb:

$$
\theta_{\max }=\arctan \left(\frac{P_{z}}{R}\right)=\arctan \left(P_{z} \kappa_{\max }\right)
$$

where $P$ is the first point of the helix spiral as shown in Figure 4.18 and $R=\frac{1}{\kappa_{\max }}$ is the radius of the cylinder $(\mathscr{C})$.

Therefore, observations show that the oblique trajectory is composed of a helicoidal path preceded by a three-dimensional spiral transition, which has to be computed taking into account the curvature and climb angle at ( $\mathscr{P}$ ). Moreover, the curvature and remaining climb angle distributions, during the 3D spiral transition, respectively increase and decrease linearly as shown in Figure 4.16.

We suggest a simple integration method for the 3D spiral transition based on elementary helix spirals in the sense that each elementary spirals would have :

- a constant elementary curvature $\kappa_{i}$
- a constant elementary climb angle $\theta_{i}$
- a constant elementary torsion $\tau_{i}$
as shown in Figures 4.18 and 4.17. Moreover using a helix spiral is the easiest way to approximate a skew curve. Besides, the elements are computed with the maximum derivative of the curvature


Figure 4.16. Diagram of curvature $k$ and remaining climb angle $\theta$ distributions for the threedimensional spiral transition
$d \kappa_{\text {max }}$, hence sustaining the optimality of the length $s$ of the 3D spiral transition towards the helix. At the end of every infinitesimal helix spiral, a new center of the helix is computed as well as updated helix parameters $a_{i}$ and $b_{i}$ in order to process the next spiral portion as shown in Figure 4.17. This process is repeated until the final curvature $\kappa_{\max }$, the final climb angle $\theta_{\max }$ and therefore the final torsion $\tau_{\text {max }}$ are reached.


Figure 4.17. Framework of the design of the 3D spiral transition as a series of infinitesimal spirals (blue), top view

Besides, by acting only on the distributions of the curvature and climb angle along this spiral transition we have:

$$
\left\{\begin{array}{l}
\kappa(s)=\alpha s  \tag{4.3}\\
\theta(s)=\beta s
\end{array}\right.
$$

where $\kappa$ is the curvature and $\theta$ is the remaining climb angle. They are both expressed as a function of $s$, the curvi linear abscissa.

The torsion is defined as $\tau=\kappa \tan (\theta)$, using (4.3) we have:

$$
\begin{gathered}
\Leftrightarrow \tau=\alpha s \tan (\beta s) \\
\Rightarrow \frac{d \tau}{d s}=\alpha \tan (\beta s)+\frac{\alpha \beta s}{\cos (\beta s)^{2}} \\
\approx \alpha \beta s+\alpha \beta s \frac{1}{\left(1-\frac{(\beta s)^{2}}{2!}\right)^{2}}
\end{gathered}
$$



Figure 4.18. Framework of the oblique trajectory with the three-dimensional spiral transition (blue) connected to the helicoidal path (red) at point $P$

$$
\begin{aligned}
& \approx \alpha \beta s+\alpha \beta s \frac{1}{1+2 \frac{-(\beta s)^{2}}{2!}} \\
& \approx \alpha \beta s+\alpha \beta s\left(1+(\beta s)^{2}\right)
\end{aligned}
$$

Neglecting the higher terms,

$$
\begin{equation*}
\frac{d \tau}{d s}=2 \alpha \beta s \Rightarrow \tau(s)=\alpha \beta s^{2} \tag{4.4}
\end{equation*}
$$

The torsion is parabolic along the 3D spiral transition with $\kappa$ and $\theta$ evolving linearly from initial conditions $\kappa=0$ and $\theta=0$ to $\kappa_{\max }$ and $\theta_{\max }$.

In the case when the 3 D spiral transition is maintained at maximum curvature $\kappa_{\max }$, i.e. the curve is evolving on a cylinder with radius $R=\frac{1}{\kappa_{\text {max }}}$, the previous discussion becomes slightly different.

$$
\left.\begin{array}{c}
\left\{\begin{array}{l}
\kappa=\alpha \\
\theta(s)=\beta s
\end{array}\right.  \tag{4.5}\\
\tau(s)=\kappa \frac{b}{a}
\end{array}\right\}
$$

The torsion is linear.
Finally, there is a third case to be considered, when the 3D spiral transition is maintained at contant climb angle and varying curvature. Typically to make a transition from a helix spiral at maximum curvature $\kappa_{\text {max }}$ to a straight line with zero curvature $\kappa=0$.

$$
\begin{align*}
& \left\{\begin{array}{l}
\kappa=\alpha s \\
\theta(s)=\beta
\end{array}\right.  \tag{4.6}\\
& \tau(s)=\kappa \frac{b}{a}
\end{align*}
$$



Figure 4.19. Change of torsion on a cylinder for the 3D spiral transition (red curve) with curvature constant along the transition and equal to $k_{\max }$

$$
\tau(s)=\kappa s \tan (\beta) \approx k \beta s
$$

The torsion is linear .
As a conclusion, the three-dimensional spiral transition described in this section can take different shapes by only acting on its initial and final inputs which are mainly the curvature $\kappa$ and the angle of climb $\theta$.

- If $\theta=$ constant, then we obtain a three-dimensional Euler spiral
- If $\left(\theta_{0}, \kappa_{0}\right)=(0,0)$ and $\left(\theta_{\text {final }}, \kappa_{\text {final }}\right)=\left(\theta_{\max }, \kappa_{\max }\right)$, then we obtain the 3D spiral transition with a quadratic torsion (4.4).
- If $\kappa=$ constant and $\theta$ is linear as derived from (4.6) then we can obtain a curve plotted on a cylinder surface, which is very convenient for decreasing the torsion of a path when the curvature must remain constant (Figure 4.19).

The 3D spiral transition is convenient for getting rid of 3D constraints in path generation, for example when connecting two randomly oriented position of the 3D space frame with mathematical motion primitives, typically for avoiding to put together 2D motion primitives in different planes [72].



Figure 4.20. Three-dimensional spiral transition plotted for a total curvi-linear abscissa of 400 meters with initial and maximum curvatures $\left(\kappa_{\text {init }}, \kappa_{\max }\right)=(0,0.0015)$, initial and maximum angles of climb $\left(\theta_{\text {init }}, \theta_{\text {max }}\right)=(0,0.1)$; the blue, red and magenta curves are respectively the 3D spiral transition with quadratic torsion, the 3D Euler spiral and the 3D spiral transition with constant curvature and linear angle of climb.

### 4.3.4 Extrapolated trajectory to 30 seconds of flight

Further in the study, the trajectories described in this chapter will be used for the upper system RAMSES to model and characterize possible emergency trajectory solutions to the current flight. However, as mentioned in the decision making functional bloc (chapter 6), the set of emergency situations is continuously compared to a reference trajectory which attests the state of the current flight. Moreover, the reference trajectory constitutes the projection of the current state to 30 seconds of flight if the state remains unchanged. The reference trajectory, and the set of alternative trajectory solutions, are computed for each flight point.

In order to give a clear picture of the state of the current flight situation, and provide a representative projection of this state to the next 30 seconds of flight, the circular helix spiral is used. Indeed, the circular helix spiral takes into account the current torsion $\tau$ and curvature $\kappa$. It is assumed that the variation of torsion and curvature are not significant locally. For that reason, we consider that the circular helix spiral is suited for certifying a reliable projection of what the flight will look like in the next 30 seconds if the parameters remain unchanged.

To speak more about considering changes in torsion and curvature locally, the variations for these parameters, for each flight point have been computed according to the observation of the previous positions up to 10 seconds back along the flight. Choosing to compute the forecast trajectory based on a feedback of 10 seconds represents in this study approximately 100 flight points.

The side variations due to the smoothing procedures are neglected. An example of the extrapolated trajectory to 30 seconds of flight is given in appendix B in Figs. B. 1 and B.2.

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

### 4.4 Computing an efficient three-dimensional trajectory between two positions for a helicopter flight

Connecting two positions, with different orientations, in the three-dimensional space is not an easy matter. Actually finding an optimal path is quite challenging in the sense that the classical threedimensional (3D) mathematical curves do not always fit the performances of the aircraft.

In the two-dimensional space, the optimal path between two vectors is the C-L-C Dubins path. In 3D, this solution is not valid anymore but the idea of an optimal path based on the same concept is not absurd provided that the straight line between the connection points on the initial and final circles has an additional varying vertical component. However, the continuity of the curvature along this path (in a 3D or 2D configuration) is not sustained and if the path had to be flown by a helicopter with passengers on board, it would be very difficult to follow it properly. This is why making smooth transitions based on the helicopter's actual performances between the motion primitives composing the path is of major importance.

This section is addressing the design of a feasible 3D trajectory between two possible flight headings, fitting the helicopter's flight model without exceeding the flight envelope. Besides the design is based on a framework composed of a series of 2D and 3D mathematical motion primitives developed in the previous section.

First of all, the trajectory is computed for random directions contained in non parallel horizontal planes. In a second step, the trajectory is adapted to form a transition between two way points with their respective headings between two different flight levels. Eventually, the 3D trajectory is compared to what we call a 3D Dubins-like path for comparison.

### 4.4.1 Positionning of the problem

There are two possible configurations when connecting two vectors $\overrightarrow{A A^{\prime}}$ and $\overrightarrow{B B^{\prime}}$ in the threedimensional space. Either these two vectors are both contained in two parallel plane surfaces, i.e. their vertical component is constant $z_{A}=z_{A^{\prime}}, z_{B}=z_{B^{\prime}}$ and $z_{A}=\alpha z_{B}$, where $\alpha$ is constant, but not necessary $z_{A}=z_{A^{\prime}}=z_{B}=z_{B^{\prime}}$ because we want to join two different heights in this study; or, they are randomly oriented, i.e. $z_{A} \neq z_{A^{\prime}}$ and $z_{B} \neq z_{B^{\prime}}$. In order to take the most general case, we choose to mix these two configurations as shown in Figure 4.21 for the definition of the initial and final conditions of the problem in Figure 4.22. Thus $z_{A} \neq z_{A^{\prime}}$ and $z_{B}=z_{B^{\prime}}$.


Figure 4.21. Three-dimensional view of the problem
The initial conditions (I.C.) are reported in A and the final conditions (F.C.) are reported in B (Figure 4.22). $C_{1}$ and $C_{2}$ are the centres of cylinders $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$. The design of the 3D tra-

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

jectory is based on the idea of the two-dimensional Dubins path. However, we are reasoning on three-dimensional geometric objects instead. We note that the 3D trajectory, will include a change of direction (curvature going from $k(t=0)=k_{\max }$ to $k\left(t=t_{f}\right)=-k_{\max }$ ) in order to fit the final condition requirements.

Hence, two concerns are addressed here:

- The first concern is finding a way to connect cylinder $\left(\mathscr{C}_{1}\right)$ to cylinder $\left(\mathscr{C}_{2}\right)$ taking into account the curvature constraints.
- The second concern is making the path between the cylinders coincide vertically.

In Figure 4.22, $\overrightarrow{P_{1} P_{2}}$ is the vector between points $P_{1}$ on $\left(\mathscr{C}_{1}\right)$ and $P_{2}$ on $\left(\mathscr{C}_{2}\right) . \overrightarrow{P_{1} P_{2}}$ is tangent to both cylinders. In a two-dimensional Dubins path planning, the line directed by vector $\overrightarrow{P_{1} P_{2}}$ would be one way of connecting circle arcs between $A$ and $P_{1}$ and between $P_{2}$ and $B$. Since we are in 3D, and in a concern of designing the shortest 3D trajectory between $A$ and $B$ we have helix spirals, combining both a climb and a turn, instead of circle arcs between points $A$ and $P_{1}$ and between $P_{2}$ and $B$.


Figure 4.22. Two dimensional top view of the problem
However, as the 3D trajectory would obviously need a change of direction at some point because the curvature at I.C. is the opposite of the curvature at F.C., the three-dimensional spiral transitions developed in section 4.3 .3 will be used to ensure the sustainability of the curvature along the 3D path. It is assumed that the transitions have a fixed length every time they are used so the design of the final trajectory can be focused on finding the shortest length for the other 3D motion primitives. The 3D

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

spiral transition is used with the purpose of making the link between the motion primitives, without exceeding its own capacities (derivative of the curvature $d k$ and maximum climb angle $\theta$ ).

### 4.4.2 Finding the plane containing the straight line between $S_{2}$ and $S_{3}$ with the Dubins gliding symmetry conjecture

The Dubins gliding symmetry conjecture is applicable for a Dubins CLC path type when the initial and final positions have opposite curvature values. The conjecture relies on computing a point $M$, which stands for the middle of the $\left[P_{1}, P_{2}\right]$ segment, where $P_{1}$ and $P_{2}$ are respectively the tangent points of line $\left(P_{1} P_{2}\right)$ to circles $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ as shown in Figure 4.23 . For the purpose of this study and in a concern of symmetry compliance, it is assumed that the 3D spiral transition size is constant along the 3D trajectory and computed with saturated constraints in curvature and torsion until $\left(\mathscr{C}_{2}\right)$ is reached.

The Dubins gliding symmetry conjecture is used in Figure 4.22 to find a matching direction between the cylinders. The plane containing the vector $\overrightarrow{P_{1} P_{2}}$ is tangent to $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ and could contain a straight line going from the initial cylinder to the final one. However, instead of having a plane making a direct link between $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ we need to find here a plane containing the final direction of Transtion 1 and the initial direction of Transition2 (Figure 4.25). To put in a nutshell, we have two 3D spiral transitions, one going up from $\left(\mathscr{C}_{1}\right)$ and another going down from $\left(\mathscr{C}_{2}\right)$, and they need to be aligned so their final points could be connected by a straight line in order to establish a link between $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$.

Since the spiral transitions have the same lengths, this problem is reduced to finding the size of the initial helix spiral on $\left(\mathscr{C}_{1}\right)$, which is equivalent to finding $S_{1}$ (Figure 4.25) when the final direction vector of Transition1, $\overrightarrow{d_{T_{1}}}$ and the final transition vector of Transition2, $\overrightarrow{d_{T_{2}}}$ are collinear (Figure 4.23):

Let $\overrightarrow{d_{T_{1}}}$ be defined as $\overrightarrow{d_{T_{1}}}\left\{\begin{array}{l}d_{T_{1, i}} \\ d_{T_{1, j}}\end{array}\right.$, and $\overrightarrow{d_{T_{1}}}$ be defined as $\overrightarrow{d_{T_{2}}}\left\{\begin{array}{l}d_{T_{2, i}} \\ d_{T_{2, j}}\end{array}, \overrightarrow{d_{T_{1}}}\right.$ and $\overrightarrow{d_{T_{2}}}$ colinear $\Leftrightarrow$ $d_{T_{1, j}} d_{T_{2, i}}=d_{T_{2, i}} d_{T_{1, j}}$.

Since the climb angle is already given by the climb rate of the spiral transition from $\left(\mathscr{C}_{1}\right)$, there is no need to take into account the vertical component of $\overrightarrow{d_{T_{1}}}$ and $\overrightarrow{d_{T_{2}}}$.

However, we don't know from what point the 3D spiral is computed on ( $\mathscr{C}_{2}$ ). The Dubins gliding symmetry conjecture solves this problem by taking into consideration a symmetrical construction of the path between the cylinders by giving a special importance to the middle point $M$ (Figure 4.23).

Therefore the algorithm for finding a common direction to $\overrightarrow{d_{T_{1}}}$ and $\overrightarrow{d_{T_{2}}}$ is simple. The principle is finding a final vector $\overrightarrow{d_{1}}$ collinear to $\overrightarrow{P^{\prime} M}$ and increase $S_{1}$ until this condition. A result is presented in Figure 4.24.

$$
\Leftrightarrow d_{T_{1, i}} y \underset{\vec{P}^{\prime} M}{ }-d_{T_{1, j}, j} x_{\overrightarrow{P^{\prime} M}}=0
$$

The second concern is to make both direction vectors $\overrightarrow{d_{T_{1}}}$ and $\overrightarrow{d_{T_{2}}}$ coincide vertically. This is ensured by the climb rate at the end of Transition1. By point reflection through M and keeping the same climb coefficient we have the altitude of $A^{\prime \prime}$ on $\left(\mathscr{C}_{2}\right)$.

The final distribution of the curvature along the 3D trajectory designed with the Dubins gliding symmetry conjecture is given by Figure $4.25 . S_{1}$ is obtained by a scan between $A$ and $P_{1}$ on $\left(\mathscr{C}_{1}\right)$. When $S_{1}$ is reached (Figure 4.24) the curvature decreases to zero until $S_{2}$ in order to meet the common


Figure 4.23. Finding plane $(\mathscr{P})$, the link between $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ with $A P_{1}<B P_{2}$ - top view


Figure 4.24. Cylinder $\left(\mathscr{C}_{1}\right)$ with the helix spiral and the 3D transition spiral connecting $M$
plane going through $M$ (Figure 4.23). By symmetry, the path from $M$ to $A^{\prime \prime}$ on $\left(\mathscr{C}_{2}\right)$ is completed until $S_{4}$ and the final condition on the curvature as specified initially (Figure 4.22) is achieved.


Figure 4.25. Framework of the curvature along the three-dimensional trajectory between $A$ and $B$ given by the thick black polygonal chain

Once $\left(\mathscr{C}_{2}\right)$ is reached with a given climb angle, it may happen that this climb angle is too big to achieve the F.C. at $B$, and exceeds the final altitude. Thus, the torsion of the 3D helix spiral on ( $\mathscr{C}_{2}$ ) must be reduced and the remaining series of motion primitives contained between $S_{4}$ and $S_{t o t}$ should have their torsion and hence their length adapted to satisfy the final requirements.

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

### 4.4.3 Finding the final torsion distribution on $\left(\mathscr{C}_{2}\right)$

Now that the cylinders are connected by a feasible path, the last concern consists into finding the final torsion distribution on $\left(\mathscr{C}_{2}\right)$. Indeed, from the beginning we are looking for the most efficient path between the initial point $A$ and final point $B$. This conveys the idea of a maximum climb rate feasible by the aircraft from the initial state. However, if this climb rate is maintaned, the trajectory might go too far and never reach B. This is why finding an adapted torsion distribution on $\left(\mathscr{C}_{2}\right)$ ensures a smooth path from $A^{\prime \prime}$ to $B$ (cf Figure 4.23). The path arrives with maximum torsion at $A^{\prime \prime}$ and needs to reach $B$ with zero torsion according to I.C. and F.C. in Figure 4.22. Thus, we need at least two 3D spiral transitions and one helix spiral to reach the point B. The first 3D spiral transition would make the path go from $\tau_{\max }$ to $\tau_{\operatorname{new}\left(\mathscr{C}_{2}\right)}$ (the new torsion), keeping the curvature $\kappa_{\max }$. The last one would connect the end of the helix spiral at $\tau_{\text {new }\left(\mathscr{C}_{2}\right)}$ to point B making the torsion decrease to zero and still with $\kappa_{\max }$ everywhere. Hence the remaining angle to reach from $A^{\prime \prime}$ to $B$ is defined as:

$$
\theta_{\text {remaining }}=\Delta \theta_{1}+\Delta \theta_{2}+\Delta \theta_{3}
$$

where $\Delta \theta_{1}=\theta_{r}-\theta_{\max }$ is the angle difference for the first spiral transition on $\left(\mathscr{C}_{2}\right) ; \Delta \theta_{2}=0-\theta_{r}$ is the angle difference for the second spiral transition (final transition to arrive at point B with zero torsion) and $\Delta \theta_{3}$ is the angle difference for the helix spiral between Transition 2 and Transition 3.

Finding the final torsion to get a smooth path from $A^{\prime \prime}$ to $B$ results into finding $\theta_{r}$, which stands for the optimal climb angle given that the torsion should remain lower than the maximum torsion on $\left(\mathscr{C}_{2}\right)$. Hence $\tau_{\text {new }\left(\mathscr{C}_{2}\right)}=k_{\text {max }} \tan \left(\theta_{r}\right)$ (Algorithm 1).

### 4.4.4 Connecting two different flight levels with a three-dimensional trajectory

The previous discussion has adressed the design of a three-dimensional trajectory based on a series of motion primitives. The purpose was to connect two vectors whose directions were chosen randomly in order to have the most general configuration to deal with. However, in most cases, the helicopter would have to fly from a flight level to another, i.e. from a horizontal plane with a given altitude to another horizontal plane with higher or lower altitude. This means that the helicopter would need a three-dimensional trajectory connecting two vectors contained in parallel planes.The only difference with the previous problem described in 4.4.1 is that the initial vector $\overrightarrow{A A^{\prime}}$ (Figure 4.22) is contained in a plane surface and therefore the three-dimensional trajectory is composed of an additional 3D spiral transition going from zero curvature $\kappa_{0}=0$ and zero torsion $\tau_{0}=0$ to point $A$ with $\kappa_{\max }$ and $\tau_{\max }$ as shown in Fig. 4.26. Therefore, the method to compute the 3D trajectory is identical and the Dubins gliding symmetry conjecture starts at point $A$, where the curvature is $\kappa_{\max }$ and the torsion is $\tau_{\max }$.

The algorithm 1 sums up the method used to compute the three-dimensional trajectory between A and B. $L_{h_{1}}$ and $L_{h_{2}}$ are respectively the lengths of the first helix spiral on the cylinder $\left(\mathscr{C}_{1}\right)$ and the second helix spiral on the cylinder $\left(\mathscr{C}_{2}\right) . \theta_{\text {remaining }}$ is the angle bewteen points $A^{\prime \prime}$ and $B$.

There are two problems to take into account: a two-dimensional problem where it is important to find the right direction to connect points $A$ and $B$ as a top view; and a three-dimensional problem where the vertical directions have to match too. Computing the Dubins circles permits to find the shortest path to connect two oriented points in the two-dimensional space. Therefore, it gives a frame for the design of the 3D trajectory between $A$ and $B$ using the Dubins gliding symmetry conjecture. Eventually, the 3D trajectory is connected to the final point B by adapting the torsion distribution on cylinder $\left(\mathscr{C}_{2}\right)$. Indeed, in an attempt of having an efficient 3D trajectory we keep the constraints of

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

curvature, torsion and climb angle saturated until $\left(\mathscr{C}_{2}\right)$ is reached. In this thesis, it is assumed that the altitude of point $B$ is not exceeded when $\left(\mathscr{C}_{2}\right)$ is reached. However, the climb rate should be adapted thereafter by computing a new climb rate $\theta_{r}$ which takes into account both, the final condition in $B$ where $\theta=0$, and the variation of $\theta$ due to the transitions and the helix spiral used to make the link. This last problem is decomposed in three parts:

- go from $\theta_{\max }$ to $\theta_{r}$
- keep the climb rate $\theta_{r}$ constant on the helix spiral
- go from $\theta_{r}$ to $\theta=0$ in order to satisfy the final condition and therefore reach a horizontal plane in B

```
Algorithm 1 3D trajectory from A to B
    1) COMPUTE Dubins circles and cylinders
    2) FIND Tangent plane ( \(\mathscr{P}\) ) with the Dubins gliding symmetry conjecture
    Compute \(\mathrm{M}=\) middle of \(\left[P_{1}, P_{2}\right.\) ]
    INITIALIZE \(L_{h_{1}}=0\)
    if \(\overrightarrow{P^{\prime} M}\) and \(\overrightarrow{d_{T_{1}}}\) not collinear then
        Increment \(L_{h_{1}}\)
    end if
    return Tangent plane \((\mathscr{P})\) and Trajectory \(\operatorname{Trj}\) to M
    3) Point reflection / M of \(\operatorname{Tr} j\) taking into account the climb angle in order to get to \(\left(\mathscr{C}_{2}\right)\)
    4) Adapt torsion on \(\left(\mathscr{C}_{2}\right)\) in order to reach B
    COMPUTE \(\theta_{\text {remaining }}\)
    COMPUTE \(\theta_{\text {max }}\)
    for \(\theta_{r}=\theta_{\text {remaining }} / 3, \ldots, \theta_{\text {max }}\) do
        COMPUTE 3D spiral transition from \(\tau_{\max }\) to \(\tau_{r}\)
        Compute \(L_{h_{2}}\)
        Compute helix spiral for \(L_{h_{2}}\)
        COMPUTE 3D spiral transition \(T_{\tau_{r} \rightarrow \tau_{\text {final }}}\) from \(\tau_{r}\) to \(\tau_{\text {final }}=0\)
        if final point of \(T_{\tau_{r} \rightarrow \tau_{\text {final }}}=\mathrm{B}\) then
            Break
        end if
    end for
    return \(\theta_{r}\)
```



Figure 4.26. Connecting two different flight levels with a three-dimensional trajectory. An initial transition is needed to get from zero torsion and zero curvature to non-zero torsion and non-zero curvature and start Algorithm 1

### 4.4.5 Comparison with the "3D Dubins-like path"

In an attempt of trying to compute an efficient 3D trajectory the results have been compared to a 3D Dubins-like path computed for a constant climb rate from A to B. Just as the path computed using the Dubins gliding symmetry conjecture, it is composed of two helix spirals connected by a straight line between the points $P_{1}$ and $P_{2}$ (Figure 4.23). This path is not constant in curvature and absolutely not feasible by a helicopter. However, it is the shortest Dubins-like 3D path we could obtain for comparison with the Dubins gliding symmetry conjecture results. Using the Dubins gliding symmetry conjecture we have the length d . We decide to withdraw the length of the straight line SL for comparison which gives the following ratio

$$
\frac{D-S L}{d-S L}=0.9955
$$

which makes the actual 3D path very close in terms of length to the shortest 3D path we could obtain here.

A result is displayed in Figure 4.4.5.


Figure 4.27. 3D Trajectory computed in red with the Dubins gliding symmetry conjecture compliant in curvature and torsion and the "Dubins-like 3D trajectory" in blue, not feasible by a helicopter

### 4.4.6 Finding a three-dimensional trajectory with no turn

There is a similar way to the Dubins Gliding Symmetry Conjecture for finding a suitable trajectory, with no turn, between two different 3D positions with imposed constraints. The idea of computing a middle point $M$ doesn't change except that the point is not determined the same way as for a pathplanning trajectory with a turn.

Parametric equation of the space line $\left(\mathscr{D}_{1}\right)$ described by the direction vector $\overrightarrow{P_{1} P_{2}}$ :

$$
\left(\mathscr{D}_{1}\right):\left\{\begin{array}{l}
x=x_{0}+t a  \tag{4.7}\\
y=y_{0}+t b \\
z=z_{0}+t c \\
t \in \mathbb{R}
\end{array}\right.
$$

with $\overrightarrow{P_{1} P_{2}}$ and $(a, b, c)$ defined as:

$$
\overrightarrow{P_{1} P_{2}}:\left\{\begin{array}{l}
x \overrightarrow{\overrightarrow{P_{1} P_{2}}}=x_{P_{2}}-x_{P_{1}}=a  \tag{4.8}\\
y \overrightarrow{\overrightarrow{P_{1} P_{2}}}=y_{P_{2}}-y_{P_{1}}=b \\
z_{\overrightarrow{P_{1} P_{2}}}=z_{P_{2}}-z_{P_{1}}=c
\end{array}\right.
$$

Parametric equation of the space line $\left(\mathscr{D}_{2}\right)$ described by the direction vector perpendicular to $\overrightarrow{P_{1} P_{2}}$ :

$$
\left(\mathscr{D}_{2}\right):\left\{\begin{array}{l}
x=M_{x}+t u  \tag{4.9}\\
y=M_{y}+t v \\
z=M_{z}+t w \\
t \in \mathbb{R}
\end{array}\right.
$$

As shown in Fig. 4.4.6, the new middle point $M^{\prime}$ is situated at the intersection between $\left(\mathscr{D}_{1}\right)$ and $\left(\mathscr{D}_{2}\right) . M^{\prime}$ can be derived from the equations 4.8 and 4.9.

## CHAPTER 4. RAMSES: TRAJECTORY GENERATION FUNCTIONAL BLOC

The problem can be solved in 2D first in order to compute $M^{\prime}(x, y)$ coordinates. The vertical coordinate $z$ can then be computed according to the climb angle, with the same method than for the trajectory with a turn.


Figure 4.28. Finding plane $(\mathscr{P})$, the link between $\left(\mathscr{C}_{1}\right)$ and $\left(\mathscr{C}_{2}\right)$ with $A P_{1}<B P_{2}$ - top view
The result can be seen in Fig. 4.29. It could be noticed that the trajectory is composed of 5 motion primitives put together:

- A 3D spiral transition (magenta) at the beginning to make the transition between an initial state with zero curvature and torsion to a state with maximum curvature and torsion,
- A circular helix (red),
- A 3D spiral transition (magenta) at the end of the circular helix to make the transition between an initial state with maximum curvature and torsion to a state with zero curvature and torsion (straight line),
- A straight line (black),
- A 3D spiral transition (magenta) at the beginning to make the transition between an initial state with zero curvature and torsion to a state with maximum curvature and torsion,
- a circular helix to reach the final position (green).

Eventually, the two types of trajectories with and without turn are displayed in Fig. 4.30 for an aircraft flying at 100 knots. These trajectories have been computed after analysis of simulated flight trajectories. the comparisons between the total lengths of trajectories not feasible by the aircraft but corresponding to shortest 3D Dubins-like trajectories and the computed trajectories are displayed in table 4.2.

## 3D TRAJECTORY WITHOUT PIVOTING



Figure 4.29. 3D Trajectory computed without pivot

It could be noticed that the lengths of the computed trajectories are very close to the actual assumed shortest trajectories computed with a 3D Dubins-like method, which comforts the idea that the pathplanning algorithms developed in this chapter are efficient for computing 3D trajectories compliant with a helicopter flight.


Figure 4.30.3D Trajectory computed with and without pivot

| Type of trajectory | 3D Dubins-like trajectory (m) | Computed trajectory (m) | ratio |
| :---: | :---: | :---: | :---: |
| With a turn | 2375.23 | 2357.85 | 0.9927 |
| Without turn | 3350.33 | 3332.87 | 0.9948 |

Table 4.2. Total curvilinear abscissa of flight trajectories with and without a turn feasible by the aircraft(computed trajectories) and not feasible by the aircraft but corresponding to a shortest 3D Dubins-like trajectory

### 4.5 Conclusion

The trajectory generation functional bloc computes trajectories compliant with the aircraft's dynamic capabilities and taking into account the initial state of the aircraft at a given position. The computed trajectories are part of an envelope covering the space ahead of the current flight position in accordance with the current kinematic constraints. The trajectories form the set of possible trajectory solutions partitioning the immediate environment possibly reachable by the aircraft.

The monitoring of the trajectories envelope collision with the immediate environment illustrates the concept of the short term navigation introduced in chapters 2 and 3. It is developed further in next chapter.

The path-planning algorithms ensure the link between the short term navigation and the long term navigation introduced in chapter 2.

## Chapter 5

## RAMSES : Identifying localized risk of collision in-flight - focus on the Trajectory Evaluation and Risk Assessment Functional Blocs

### 5.1 Introduction

The Risk Assessment and the Trajectory Evaluation functional blocs, focus of this chapter, are parts of the RAMSES functional architecture as shown in Fig. 5.1. Based on the current state of the aircraft and the surrounding environment, the Risk Assessment functional bloc provides a forecast of the current flight situation in the near future by estimating the risk of collision of the aircraft ahead of the current position, with precomputed danger zones (5.2) or directly with the terrain elevation data base (5.3) in-flight. The calculations are based on the drop of remaining safe trajectories and their properties rendered through criteria.

The criteria, characterising the trajectories, necessary to the identification of localised risk of collision in the environment, are derived from observations of simple operational emergency situations (5.4.1), when the helicopter flies close to the ground, at low altitude. They allow to characterise the diagnosis of the current risk of collision in a deterministic way by quantifying the aircraft's approach to the ground in the three-dimensional space frame. However, this information does not constitute the final alarm indicator, relevant for the crew.

These criteria ensure that the sorting of the available trajectory solutions and the choice of the best avoidance trajectory solution, developed further (in chapter 6), are compliant with the operational reality of the flight.

[^13]for the purpose of safety monitoring. The second step is of paramount importance for understanding the concept of short term navigation introduced in chapter 3.

Eventually, the third step of the risk assessment functional bloc addresses possible warning rules, in their first version for this study, as indicators of the 3D danger sight, alternative to those implemented in the existing equipments designed for CFIT (Controlled Flight Into Terrain) accidents prevention. The warning rules suggested in this chapter have been thought with the aim of rendering the threedimensional aircraft approach to the terrain by conveying a perception of the danger more compliant with the pilot's experience 5.6. Once again, the 3D quantification of the aircraft's approach to the ground does not constitute the final alarm indicator for the crew. This has been done in order to provide a quantified situation awareness to the RAMSES avionics function based on safety indicators. Besides, the quantification of the situation awareness, as explained in this chapter, has lead us to compare the safety monitoring approach defended by the RAMSES avionics function concept, to the current equipments in use designed for the avoidance of CFIT accident types.

According to [8] The U.S. Department of Transportation's Federal Aviation Administration (FAA) issued on 20th February 2014 a final rule that requires helicopter operators, including air ambulances, to have stricter flight rules and procedures, improved communications, training, and additional on-board safety equipment. The rule represents the most significant improvements to helicopter safety in decades and responds to government's and industry's concern over continued risk in helicopter operations. In addition, under the new rule, all air ambulance operators are required to:

## - Equip with Helicopter Terrain Awareness and Warning Systems (HTAWS).

- Equip with a flight data monitoring system within four years.
- Establish operations control centers if they are certificate holders with 10 or more helicopter air ambulances.
- Institute pre-flight risk-analysis programs.
- Ensure their pilots in command hold an instrument rating.
- Ensure pilots identify and document the highest obstacle along the planned route before departure.
- Comply with Visual Flight Rules (VFR) weather minimums, Instrument Flight Rules (IFR) operations at airports/heliports without weather reporting, procedures for VFR approaches, and VFR flight planning.
- Conduct the flight using Part 135 weather requirements and fight crew time limitation and rest requirements when medical personnel are on board.
- Conduct safety briefings or training for medical personnel.

The present chapter is fully in line with these FAA rule and recommendation. Airbus Helicopters within its Design Office owns a dedicated department to survey, design, develop and maintain Situational Awareness systems for its Helicopters. With the risk assessment functional bloc that we introduce hereafter, we intend to answer FAA recommendation while going a step further with this new program that can both be used for pre-flight-risk and on line risk analysis.

Airbus Helicopters and LAMIH-UVHC


Figure 5.1. RAMSES functional architecture - focus on the Trajectory Evaluation and Risk Assessment functional blocs

### 5.2 Danger Zones

The risk assessment method described in this chapter estimates the gap between the current flight state and a possible emergency situation in the future, as a forecast of a localized risk of collision in the 3D space frame around the aircraft. The method is self relying in so far as it computes all the data necessary to the process. It doesn't rely on past accident data bases or any accident statistics. Even if the method has been designed on observations and analysis of past accidents, as explained in chapter 3 , the functional architecture of the system provides all the information necessary to the in-flight risk estimation and evaluation of the danger sight.

In addition, the data proper to 3D space discretization are also provided to the RAMSES decision making functional bloc and the classifier functional bloc developed in chapter 6 for a deeper estimation of the flight situation and a choice of the most appropriate avoidance trajectory solution.

The danger zones are part of the collision risk estimation process. We intend by danger zone a surface or envelope above and around the terrain and/or obstacles. It could also be a surface surrounding a forbidden area given as input by the mission data or the crew. The trajectories generated ahead of the current flight position, standing for escape manoeuvres, are rated with respect to possible collisions with danger zones. Indeed, a danger zone could be a forbidden area given as an input by the user or more simply a layer above the ground computed by RAMSES. This last option is going to be developed in this chapter to explain how the risk of collision is locally estimated in-flight.

The danger zones are computed with a method inspired from the distance fields [95] with respect to the terrain elevation data base, given as input to the Trajectory Evaluation functional bloc (Fig. 5.1). This method was chosen because it ensures that the precomputed danger zones are situated at a minimum distance from the ground and because the computations are fast. Besides, the danger zones are compliant with the terrain geometry. An illustration is provided in Fig. 5.2. There are no discontinuities in the precomputed danger zones contrary to methods using quadtrees and/or octrees space partitioning ([91]), which are more fitted for navigation purposes and path planning, on a mission scale. Computing danger zones above the terrain seems more efficient for estimating the localized collision risk around the aircraft for what we call the short term navigation (up to 30 seconds of flight) as specified in chapters 3 and 4 .

Moreover, the purpose of computing danger zones this way is to make sure that the collision threat, at a given flight point, could be evaluated with respect to various danger zones (at the same time or separately) at different altitudes in order to make the approach of the aircraft towards the ground more easily detectable by the system and therefore provide preventive actions to the crew. This way the CFIT accident scenario is more easily detectable and highly depends on the remaining safe avoidance trajectories.

Indeed, in the use cases developed further, different danger zones are computed at the same time above the terrain in order to quantify the collision threat by observing the drop in safe avoidance trajectory solutions when the aircraft approaches the ground or flies at low altitude. The drop in safe avoidance trajectory solutions occurs when the trajectories collide with the danger zones as explained in section 5.3.

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT



Figure 5.2. Danger zone computed 150 meters above the ground (yellow) and terrain elevation data (white)

### 5.3 Trajectory Evaluation

The estimation of the collision risk of each avoidance trajectory solution comes through a careful evaluation of the trajectories horizontal and vertical positions with respect to the danger zones and the terrain elevation. The danger zones can be computed for various altitudes above and around the terrain as shown in Fig. 5.2. The idea is to evaluate the risk of collision by taking the points composing an avoidance trajectory and by estimating their position with respect to the mesh below (danger zone or terrain elevation) as shown in Figs. 5.3, 5.4 and 5.5.

An avoidance trajectory solution is composed of mathematical motion primitives put together as explained in chapter 4. Each motion primitive, composing the trajectory solution, is computed numerically with a given number of points. As a result, according to the precision wanted along the avoidance trajectory solution, the number of successive points composing the trajectory could be more or less important. For that reason, instead of considering all the points of the trajectory for the collision risk estimation; a pre-computation is required to reduce the number of positions to estimate and transform the initial trajectory into a polygonal chain determined by significant points as shown in Fig. 5.6.

It is assumed that the danger zones and the terrain are given in the form of elevation matrices. They are composed of independent cells put together; forming a mesh. Given the precision of the numerical maps and the length of the avoidance trajectory solutions ( 50 meters). It is assumed that the variation in curvature and torsion of the trajectories between two consecutive cells is low. Indeed, in the study, given the set of assumptions (cf. chapter 3) 50 meters represent approximatively 1.39 seconds of flight at 70 knots.

For that reason, the trajectories are transformed into polygonal chains before being used in the risk estimation process. A polygonal chain is composed of the points horizontally and virtually intersecting the danger zone's mesh as shown in Figs. 5.5 and 5.6.

When the risk of collision is estimated, for each section of the polygonal chain, between two

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT



Figure 5.3. Mesh of a the terrain elevation matrix (white) and the three coordinate mapping of the helicopter path (turquoise)


Figure 5.4. Danger zone computed 150 meters above the ground (yellow) and random points along the different possible trajectories situated above the precomputed danger zone-example of a safe flight situation with respect to the Danger Zone, the trajectories are all above the danger zone
successive points, two things are evaluated. Firstly, the method estimates whether the line between two successive points is going above the crossed cell, or below as illustrated in Fig. 5.7. In a second


Figure 5.5. Helicopter path goes below the precomputed Danger zone 150 meters above the ground (yellow) - example of a dangerous flight situation with respect to the Danger Zone


Figure 5.6. Reduction of the number of points of the trajectory in order to estimate the collision risk - Illustration of an avoidance trajectory horizontally intersecting an extract of the the danger zone mesh situated below
step, the method estimates if the points, horizontally positioned on the cell's edges, are above the edge or below.

Finally, the collision method estimates if the trajectory given as input is situated below or above the considered danger zone. By this process, we can have a complete estimation of the collision threat identically in the three-dimensional space frame around the aircraft, locally, for all the computed trajectory solutions composing the reachable flight envelope, at each new flight point during the mission.


Figure 5.7. Focus on a cell of the danger zone mesh; top view (left), possible 3D view (right) with two successive points of a polygonal chain $P_{i}$ and $P_{i+1}$

The next section goes deeper in the trajectory solutions evaluations in order to derive typical behaviours of the complete set of trajectory solutions around the aircraft. Indeed, when the aircraft evolves in a given terrain map, the number of safe trajectory solutions varies and creates typical patterns noticeable when the helicopter goes, as an example, straight to a cliff or when it goes close to an obstacle but moves away etc. These typical behaviours of the flight highlight some direct consequences on the set of remaining trajectory solutions; and these consequences could be quantified for the RAMSES system with criteria, giving an operational meaning to what happens during a collision scenario.

### 5.4 In-flight Diagnosis of the Risk

### 5.4.1 Trajectory Patterns - the disappearance of the reachable helicopter's environment

When a helicopter flies in a hilly terrain, close to the ground, at low altitude, the safe areas are not always reachable in short time periods. Actually, in these situations, the helicopter navigates in a confined space between the hills or the mountains. Therefore, the distribution of available safe avoidance trajectories may change from one flight point to another, with respect to the terrain elevation. If the biggest group of safe avoidance trajectories, extrapolated to 30 seconds of flight, goes in a direction rather than another, this group of trajectories may contain the safest escape trajectory (i.e. the best trajectory solution).

As an example, Figs. 5.8, 5.9 and 5.10 illustrate this phenomenon with a case when the helicopter goes towards a cliff. At the beginning, a lot of safe trajectories (represented in green) are available (Fig. 5.8). As the aircraft approaches the cliff the safe trajectories (green trajectories) disappear because they collide with a danger zone. However, the safe (green) trajectories does not necessary disappear regularly in all the directions.


Figure 5.8. Safe flight situation with many safe (green) trajectory solutions available


Figure 5.9. Less safe flight situation, the safe (green) trajectory solutions start to disappear


Figure 5.10. Not safe flight situation, the safe (green) trajectory solutions are all gone

It is possible to observe trends or patterns in the drop of trajectories composing the global set of trajectory solutions with respect to angle of approach to the terrain or a danger zone. Indeed, if the aircraft flies straight to a danger zone, at some point there will be no more valid trajectories as shown in Fig. 5.11. However, if the aircraft flies close to a danger zone without entering in collision, a significant drop in the trajectory solutions would be observed but the global number of trajectories
won't be zero as shown in Fig. 5.12. Therefore the trends or patterns observed in the global envelope of trajectories during the flight could help to characterize the variations of the cardinal of trajectories at danger sight. Accordingly, that could help to derive criteria to make the approach towards the danger objective; and deduce findings in terms of flight safety.


Figure 5.11. Drop in the total number of safe trajectory solutions when the aircraft flies straight to a danger zone


Figure 5.12. Drop in the total number of safe trajectory solutions when the aircraft flies close to a danger zone and moves away

In order to confirm this hypothesis and compare the results with the existing equipments in use for avoiding CFIT accident causes, three preliminary use cases are studied hereafter:

- A case when the helicopter flies towards a cliff,
- A case when the helicopter goes over a cliff,
- A case when the helicopter goes towards a cliff and moves away.

We assume, for the purpose of this study (given the set of assumptions in chapter 3), that these three cases are representative of the majority of flight situations that could happen in CFIT accident scenarios. Therefore, it seems important to understand how the set of trajectory solutions surrounding the aircraft evolves for these three flight cases in order to forecast the risk of collision in the near future.

For each use case the distribution of the remaining safe avoidance trajectory solutions is analysed with respect to three different danger zones collisions:

- A danger zone computed for 250 meters above the ground,
- A danger zone computed for 150 meters above the ground,
- A danger zone computed for 50 meters above the ground.

The collision of a trajectory is estimated with the method described in section 5.3.

## Preliminary Use Case 1: Helicopter flies towards a cliff

The flight situation described in this preliminary use case attests of a helicopter flying straight towards a steep cliff.

As the helicopter comes close to the cliff, the number of remaining trajectory solutions drops. At the beginning of the simulation, all the trajectory solutions are valid at least 150 meters above the ground. Then we observe a transfer of the cardinal (number of trajectories) of trajectories from those 250 meters above the ground to those 150 meters above the ground.


Figure 5.13. Helicopter flies towards a cliff
At point $\mathbf{1}$ in Fig 5.14, the transfer of the cardinal from trajectories 250 meters above the ground to the trajectories 150 meters above the ground becomes less important than the transfer from the 150 meters above the ground to the trajectories 50 meters above the ground. Potentially, this shows that the first level of security has been overcome.

At point 2 in Fig 5.14, all the trajectory solutions cardinals decrease and transfer to the set of non-solutions (turquoise curve in Fig. 5.14). This is possibly the second level of security to be

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

overcome. All the sets of trajectory solutions decrease and the number of non-valid solutions increases significantly.

At point 2 in Fig 5.14, the number of non-solutions overcomes the number of remaining safe solutions, which shows that the helicopter is moving to the ground imminently.

At point 4, no more safe trajectory solutions are available. All of them intersect the last danger zone before the ground (below 50 meters). The accident is unavoidable if the helicopter continues with the same flight state. By considering the successive disappearance of the safe trajectories in the set of all the trajectory solutions, we identify the localized risk of collision in the surrounding environment of the helicopter, for each flight point. Besides, this permits to identify the flight point from which the accident is very likely to happen given the remaining safe avoidance trajectory solutions.

By analogy to the sequential division of traffic accidents, the point from which the accident is unavoidable is called the accident situation [53].

At point 5 in Fig 5.14, all the trajectory solutions valid 250 meters above the ground disappear. It could be considered that another security level has been overcome; same for the point $\mathbf{6}$, where all the solutions valid 150 meters from the ground are gone.

As a conclusion of this first use case, it could be noticed that there is a relationship between the drop in the cardinal of trajectory solutions and the increase of the risk of collision localized among the trajectories composing the envelope of trajectory solutions.


Figure 5.14. Drop in the number of remaining trajectory solutions when the helicopter flies towards a cliff

The process of transfer of the cardinal between the different sets of trajectory solutions with steps from point $\mathbf{1}$ to point $\mathbf{3}$ (Fig. 5.14) could be illustrated in a diagram as shown in Fig. 5.15. At the beginning of the flight, before point $\mathbf{1}$ (i.e. $<\mathbf{1}$ ), it is possible to notice that trajectories from the set

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

of trajectory solutions safe above 250 meters begin to overflow abundantly into the set of trajectory solutions safe above 150 meters. From an operational point of view, this means that a lot of trajectories safe above 250 meters enter in collision with the danger zone computed 250 meters from the ground but remain valid towards the danger zone computed 150 meters above the ground. Then, between points $\mathbf{1}$ and $\mathbf{2}$, the flow decreases.

In the meantime, between points $\mathbf{1}$ and $\mathbf{2}$ in Fig. 5.14, trajectories from the set of trajectories safe above 150 meters collide with this danger zone and move to the set of trajectories valid above 50 meters and so on.

After point $\mathbf{2}($ i.e. $\geq \mathbf{2}$ ), trajectories contained in the set of trajectories safe above 150 meters above the ground begin to flow abundantly in the set of trajectories valid above 50 meters above the ground an so on until no more valid trajectories (unsafe) are available (point 4 in Fig. 5.14).

Proximity of the ground


Figure 5.15. Transfer of cardinal between the different sets of trajectory solutions with steps $\mathbf{1}$ to 3 from Fig. 5.14

## Preliminary Use Case 2: Helicopter flies over a cliff

The flight situation described here attests of a helicopter flying over a cliff. The simulation starts at a lower altitude, closer to the danger zones than in the previous use case, because the cardinal of avoidance trajectory solutions above 250 meters is much lower: around 2000.


Figure 5.16. Helicopter flies over a cliff

In the simulation, the slope chosen for the experiment is very steep. Given that the transfer of the number of trajectory solutions from a group to another is more important, it confirms that the cliff must be thin and steep.

As the helicopter flies towards the cliff, the number of safe trajectory solutions decreases. The cardinal of all the remaining trajectories drops. However, the flight situations attests that the number of remaining solutions above the critical altitude fixed to 50 meters remains high enough to qualify the situation as a safe one.

As the helicopter approaches the cliff, the number of remaining safe trajectories drops. However, we know that the helicopter can easily fly over the cliff even if the safest trajectories (above 250 meters) are gone.

At point $\mathbf{1}$ in Fig. 5.17, we have lost all the safe avoidance trajectory solutions above 150 meters in favour of those going over 50 meters (closer to the ground). This reflects that the helicopter is getting close to the ground but as a high number of trajectories is still valid, the flight situation cannot be judged threatening in term of collision risk.

At point 2 in Fig. 5.17, the cliff peak has been overcome for the trajectories extrapolated to 30 seconds of flight and the they become safe again, as is shown by the increase of trajectories safe above 150 meters of the ground.

At point $\mathbf{3}$ in Fig. 5.17, the helicopter is close to the vertical of the peak, which means that trajectory solutions, even those with highly soliciting the helicopter, are valid and go above 150 meters of the ground. The flight situation is very safe.


Figure 5.17. Drop in the number of trajectory solutions when the helicopter flies over a cliff

## Preliminary Use Case 3: Helicopter approaches a cliff and moves away

The flight situation described in this preliminary use case attests of a situation where the TAWS equipment would probably generate a false alarm of collision risk. Indeed, from a perception point of view, there is a gap between the danger sensed by the pilot and the estimation computed by an equipment. It is interesting to analyse the flight scenario in order to assess the remaining safe avoidance trajectory solutions, and therefore the safety level, when the helicopter is getting close to the cliff before moving away.

In the flight scenario described in Fig. 5.18 the helicopter follows a trajectory tangential to the side of the cliff. In this case, the speed vector intersects the cliff as the helicopter is moving towards the cliff, which presupposes that an equipment like the TAWS would generate an alarm of collision threat. However, at this moment, when the cardinal of remaining safe trajectories decreases, a sufficient number of emergency avoidance trajectories is available (Fig. 5.19). Therefore, based on these considerations, the collision threat becomes less important.


Figure 5.18. Helicopter flies towards a cliff and moves away
The flight scenario shows objectively that having a high number of safe remaining avoidance trajectory solutions, extrapolated to 30 seconds of flight could decrease the risk of collision in the turn, when the helicopter comes close to a cliff and moves away; without generating alarms, contrary to the TAWS logic.

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

Indeed, the trajectories are computed with the initial conditions of the aircraft at a given flight point, which means that we take into account the global capabilities of motion of the aircraft at the current position, rendering it through the set of trajectory solutions. The TAWS equipment does not take into account the manoeuvrer which is being performed, which is particularly visible on this use case.

Point $\mathbf{1}$ in Fig. 5.19, attests of the moment when the helicopter starts moving away of the cliff, and the trajectories forming the discretized environment around the helicopter become safe again. This explains why the cardinal of trajectory solutions above 250 meters increases again.


Figure 5.19. Drop in the number of trajectory solutions when the helicopter flies towards a cliff and moves away

### 5.5 Multi-dimensional risk of collision assessment - Interpretation of the preliminary use cases

The risk assessment functional bloc ensures short term risk management by reasoning over the amount, the quality and the properties of the remaining alternative trajectories, from the set of trajectories feasible by the aircraft in the near future. The value of risk independently to each trajectory and avoidance manoeuvre depends on the collision with the closest danger zone, and on the number of remaining valid trajectories.

Indeed, the use cases developed previously highlight a direct relationship between the drop in the cardinal of trajectory solutions and the flight close to the ground or to a danger zone. The global set of trajectory solutions computed as an envelope starting at the aircraft's current position to materialize the reachable space in the next 30 seconds of flight disappears with the loss of altitude. Therefore, different patterns could be observed when the set of trajectory solutions enters in collision gradually with all the danger zones. In all the use cases the partitioning of the space with different danger zones at various altitudes renders the progressive approach to the ground, which makes the CFIT accident scenario objective to the RAMSES function. The trajectories are computed in the 3D space frame as explained in chapter 4.

Note :The set of trajectories composing the global envelope, with different manoeuvres and solicitations, are designed to reach the most extended area possible on the sides of the aircraft (around), and ahead of the current position. Popularizing this idea makes us consider that the envelope of trajectories may cover the space "ahead and around the aircraft". Actually that would be true if the trajectories were computed for a longer period of time because they would be able to reach the opposite direction of the flight (literally turn around). In the next sections we will use the phrase "ahead and around the aircraft" to reflect the idea of the 3D envelope evolving in the immediate environment and colliding with the danger zones to convey the localised risk of collision of the aircraft, where the trajectories composing the envelope are not safe anymore.

For all the use cases described above, the progression of the accident scenario could be quantified with performance criteria translating the behaviour of the flight. This way, each trajectory solution composing the global set of trajectory solutions would be rated and would have its own risk value computed with respect to the properties of the trajectory itself; but also with respect to the behaviour of the global set of trajectory solutions approaching the ground.

Given the considerations on safe avoidance trajectories distributions (Section 5.4.1), the performance criteria translating the behaviour of the flight and permitting to formalize the in-flight risk assessment are determined through the following considerations:

- There is a necessity to correlate the number of remaining trajectories to the time to obstacle.
- There is a necessity to identify and formalise the evolution of the density of valid trajectory solutions, in a three-dimensional view around the aircraft because the drop in the solutions is not regular everywhere approaching the ground.
- There is a necessity to characterize the dynamic solicitation of each section of trajectory in order to prepare an appropriate preventive action when needed.


## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

- There is a necessity to choose the right manoeuvre adapted to the preventive action: climb, turn, etc.


### 5.5.1 Set of independent performance criteria

Given the previous considerations, four main independent criteria arise:

- The time to obstacle,
- The density of trajectory solutions,
- The manoeuvrability, representative of each section composing a typical trajectory solution,
- The dynamic solicitation of the trajectory solution.

The time to obstacle translates the remaining time before the collision with a danger zone or the terrain itself (depending on the tested scenario). Each trajectory solution has a time to obstacle, however this criterion is especially conveyed by the extrapolated trajectory of the current state to 30 seconds of flight ahead of the current position. The time to obstacle is analysed with respect to each section $S_{1}, S_{2}, S_{3}, S_{4}$ composing a trajectory as shown in Fig. 5.20.


Figure 5.20. Framework of a trajectory composed of four sections. The time to obstacle is evaluated with respect to the collision of the sections composing the trajectory with the danger zones or the terrain itself

Note: The detection of the convergence or distance to the danger zones could either be conveyed by the extrapolated trajectory of the current state or by the evolution of the density of solutions in a given direction; or by a combination of both criteria. It is of paramount importance for the system to know in what configuration it is: going towards the danger zone or moving away from it. The criteria derived from the simulated approaches have been designed in order to answer this question, however the influence of the speed of convergence towards a danger zone, on the short term safety monitoring, has not been studied in this thesis. It requires further tests and it is left as a perspective.

If a collision is detected in a section, then the time to obstacle is computed with respect to this section and the corresponding cell in the danger zone (or terrain). The time to obstacle $t$ is computed as follows : $t=\frac{d}{v}$, where $d$ stands for the curvilinear abscissa between the beginning of the trajectory

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

and the collision point; and $v$ is the current speed of the aircraft. As concerns the collision point, if the collision occurs between $P_{i}$ and $P_{i+1}$ (Fig. 5.7) then the collision point will be $P_{i}$.

The fourth section $S_{4}$ displayed in Fig. 5.20 is computed exclusively for the trajectories composing the global envelope of trajectories. It stands for the exact continuation of the third section and it is computed in order to have an additional proof of the trajectory's safety.

If many collisions are detected in different sections then the time to obstacle for the trajectory will correspond to the first collision detected along the trajectory.

The criterion distance to obstacle represents the minimum distance to a danger zone along the trajectory. It is not important to target a specific section composing the trajectory, contrary to the criterion time to obstacle.

Each criterion is representative of a behaviour in-flight. They are all independent. In order to complete the time to obstacle. Hence, the density of solutions attests of the collision of the global envelope of trajectories with a danger zone in a given 3D direction ahead of the current position. The manoeuvrability and the solicitation respectively translate the space direction of each section of the trajectory and the performance needed to reach the end of the section.

Each trajectory is then rated and has its own risk value depending on its direction, its proximity to obstacles, its solicitation and the avoidance manoeuvres forming the trajectory. For example, in case of a VIP transport mission, a trajectory with smooth transitions, low solicitation and going far from obstacles is better rated than a trajectory demanding high dynamic constraints with frequent changes in direction. This functional bloc makes RAMSES parametrizable with respect to the mission type.

### 5.5.2 Time to obstacle coupled to the minimum distance along the path

The criterion time to obstacle might be coupled to an additional criterion : the minimum distance to the danger zone. The danger zones are assimilated to obstacles. It is important to consider the minimum distance to the obstacle because if two trajectories have similar values for all the other criteria, the minimum distance to the obstacle could make a difference in the final choice of the best avoidance trajectory.

Besides, the minimum distance to the obstacle translates an operational reality which is the minimum acceptable distance for the mission requirements. For example, in the case of SAR (Search and Rescue) missions, the helicopter might need to get closer to the ground. In this situation the classifier functional bloc should take into account this parameter in the sorting of the trajectory solutions.

### 5.5.3 Time to non solution

The criterion time to non solution was mentioned by one of the experts as a possible perspective of development to better detect the phenomenon of progression to the ground. This criterion means that the extrapolated trajectory of the current state might also be used as a support to finding the best decision point for preventing the accident.

The criterion time to non solution would take the extrapolated trajectory and find along the trajectory the position where the number of remaining trajectories, among the global envelope of trajectory solutions partitioning the space ahead of the current position, is the lowest.

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

The time to non solution could be considered in perspective works as an aggravating factor of the flight, as it permits to compute the validity of the extrapolated trajectory thanks to the evolution of the global envelope of trajectories along it.

In a new future version of the alerting rules, the time to non solution could be integrated in the rules as a criterion.

The risk assessment functional bloc provides a quantification of the current risk in the relation to a given avoidance trajectory solution or in the relation to the evolution of the global set of solutions. The risk is multidimensional and quantified through independent performance criteria computed for each trajectory and for the global set of trajectories. This way the risk assessment functional bloc suggests innovative warning rules for the crew, through alerting indicators provided by rules on combinations of performance criteria as described in the next section.

Hence, the risk assessment functional bloc monitors the current safety of the flight by taking into account the current state of the aircraft and by reasoning over the projection of this current state in the near future. The risk assessment functional bloc contributes to the monitoring of the short term navigation introduced in chapter 3 .

### 5.6 Proposal of new warning rules conveying pilots experience in operational emergency situations that could lead to a crash

In the previous sections, we have explained the concept of in-flight risk diagnosis for safety monitoring. The CFIT accident scenario is very difficult to prevent due to considerations discussed in chapter 3. In this study we defend a hierarchical system composed of different functional blocs including a multicriteria method to feed the decision making layer with indicators (chapter 6), providing a strong analysis tools for discriminating the set of available trajectory solutions. For that purpose, it was necessary to derive the criteria that may characterize a CFIT accident scenario as objectively as possible for setting up a prevention plan in order to avoid the crash.

RAMSES avionics function concept was developed with strong safety concerns to the extent that it was designed in order to compute autonomously, on board, in real-time, an estimate of the current risk of the mission with respect to a possible operational threat leading to a collision, i.e. CFIT type threat. The risk diagnosis is multi-dimensional; it relies on formal criteria, chosen for monitoring the danger proximity. At the same time, the function's operating and alerting rules must not disrupt the pilots from the obligations related to the smooth progress of the mission. RAMSES was designed to act as an unnoticed (not necessary notified to the crew) safety monitor on-board suggesting avoidance manoeuvres in extreme danger scenarios only or autonomously resuming control on a temporarily basis in order to secure the trajectory when the crew didn't notice the risk of collision.

The warning rules must render the reality of the flight criticality without polluting the crew's workload. In this thesis we assume that the warnings stands for internal indicators of danger sight. They are not notified to the crew, they can be accessed by the decision-making functional bloc and serve as means for safety monitoring. By contrast, we assume that an alarm is always reinstituted to the crew. The alarms are given by the decision-making functional bloc (chapter 6).

The TAWS (Terrain Awareness Warning System) is a piloting aid to improve the level of in-flight safety. It aims at preventing Controlled Flight Into Terrain accidents. For that reason, the TAWS
could be used as a good comparison in this study. Despite its availability on board the aircraft, this system is not currently designed to prevent all risks of CFIT accidents, especially in case of its manual deactivation due to an amount of nuisance alerts judged to high by the crew. The TAWS can be composed of several separate functions, it depends on the manufacturer, but the operating principle of the ground proximity warning functionality generally consists of extrapolating the current speed vector and providing an information of collision ahead of the aircraft. In addition, the TAWS often provides a display of the environment around the aircraft with degraded colours according to the collision threats (Fig. 5.21). Usually, the red color on the terrain elevation map specifies that the aircraft won't be able to fly over this zone. The green areas are safe and the orange areas are avoidable considering the current aircraft's dynamic capabilities. The areas are computed by comparison between the aircraft's current elevation and terrain or obstacle elevations provided by data bases.


Figure 5.21. Example of a TAWS function display, dedicated to the Helicopter flight, manufactured by Sandel Avionics - http://www.sandel.com

A system like this one does not take into account the local variations in curvature and torsion for the current state extrapolation (contrary to RAMSES as explained in chapter 4), which leads to many false alarms and thus may decrease the attention given to the prioritized piloting action, which can affect the occupants safety. This is particularly true when the flight is taking place in a hilly environment. Missions covering Search and Rescue (S\&R) operations or Emergency Medical Services (EMS) may require to fly in such areas. Besides, during these mission the flight crew is often composed of one single pilot. False alarms should be avoided in order to maintain a good situation awareness and reduce the crew workload.

Establishing a first version of the RAMSES alerting is part of the study. In order to design the first demonstrator, the warnings related to the RAMSES avionics function concept have been suggested by observing those given by the TAWS for the same flight situation. In order to establish the warning methodology for RAMSES, simple use cases like those described previously been studied and reproduced virtually.

In this section, we suggest a set of new warning rules, alternative to those that could be provided by a TAWS equipment. The rules detailed hereafter constitute a first version for the study, they act as warning indicators accessible by the decision making functional bloc.

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

The rules suggested in this section are used as collision warning indicators conveying the danger perception by the pilots in the 3D space frame around the helicopter; they are based on two main criteria derived from the preliminary use case observations : the time to obstacle and the density of trajectory solutions (cf 5.5.1).


Figure 5.22. Density of trajectories ( $(d s o l 1$ to $d s o l 8$ ) - exploded view in the three-dimensional frame linked to the terrain

The exploded view of the density of solutions in 3D is illustrated in Fig. 5.22. The density of solutions is given in eight directions $d s o l 1, d s o l 2, d s o l 3, d s o l 4, \ldots, d s o l 8$, around the aircraft to be compliant with the generation of trajectory solutions detailed in chapter 4. As illustrated in Fig. 5.22, the density of trajectories is given with respect to the terrain frame, not the helicopter frame. However, the trajectories composing the envelope of trajectory solutions take fully into account the helicopter motion, including variations in torsion, curvature and climb angle.

In this chapter the restitution of the alarms, linked to the density of solutions and the times to obstacle, to the crew will not be mentioned. The research works do not include discussions on the Human Machine Interface as explained in chapter 3. For that reason, this chapter focuses on the quantification of the situation awareness for the RAMSES system. The way the final alarm will be produced is explained in chapter 6.

In order to be compliant with an idea of prevention, the warning rules are based on the availability of low soliciting trajectory solutions. Indeed, we assume that if all the low soliciting trajectories are gone in a direction, then this might be an indicator of danger sight. Fig. 5.23 illustrates the remaining low soliciting valid trajectories and those entering in collision with a danger zone computed above the terrain.

In this use case, when the aircraft goes close to the cliff and moves away, it could be noticed that the time to obstacle of the extrapolated trajectory remains constant (Fig. 5.25) and safe (equal to

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

30 seconds) while the simulated TAWS generates alarms during the approach to the cliff phase at the beginning of the flight (as shown in Fig. 5.26) because it doesn't take into account the initial conditions of the flight, i.e. the initial curvature and torsion.

If we assume that the extrapolated trajectory of the current state as shown in Fig. 5.23 could replace the simulated TAWS evaluation, then we can easily say that all the alarms generated by the simulated TAWS (Fig. 5.26) could be cancelled with this new evaluation of the danger. However, the RAMSES avionics function aims at monitoring the danger sight in 3D thanks to the analysis of collisions of the envelope of trajectory solutions with danger zones. Accordingly, the risk assessment functional bloc is able to provide risk indicators in 3D localised in the flight environment as illustrated with the density of solutions in Fig. 5.22. As a consequence the new set of warning rules suggested in table 5.1, as an alternative to the existing TAWS warning, render the 3D approach to danger zones. This way, we provide a quantified situation awareness to the system, testifying of the flight behaviour, as a potential source of information for the decision-making functional bloc.

The warning rules presented in table 5.1, applied to the case when the aircraft goes towards a cliff and moves away generate alarms during all the flight contrary to the simulated TAWS alarms, which may actually signify that the suggested rules are less efficient than the simulated TAWS ones. However, there is a difference between the two approaches. The rules presented in table 5.1 provide information on localised risk of collision of the envelope of trajectory solutions in 3D. Indeed, it could be noticed in Fig. 5.23 that the flight route (in green) is close to the danger zone on a vertical point of view all along the path. On a horizontal point of view, the flight route is close to the danger zone on a short period of time, so the risk of collision will be localized but it would disappear at some point.

Considering the case when the aircraft flies to the cliff and moves away described by Figs. 5.23, 5.25 and 5.26 , if we apply the alerting rules cited above, warnings would be generated in the direction of the collision threat.

The time to obstacle remains constant on the extrapolated trajectory of the current state all along the flight because the aircraft performs a turn at constant curvature. The criterion time to obstacle is not important for this case.

The first warning level will be generated only for trajectories going downwards (cf Fig. 5.24 dsol1, $d s o l 5, d s o l 6, d s o l 8)$ and in the direction of the cliff. These localized warnings would remain even when the simulated TAWS does not generate an alarm.

The alarms of the simulated TAWS are approximatively localised between iterations 0 and 50 according to Fig. 5.26. For this period, Fig. 5.24 shows that alarms of level 1 appear for dsol1, dsol4, $d s o l 5, d s o l 6, d s o l 8$ and warnings of level 2 appear for $d s o l 1, d s o l 5, d s o l 6, d s o l 8$. However, when the alarms of the simulated TAWS disappears (after iteration 50), the warning of level 2 linked to dsol 1 returns to a warning of level 1. A few time later (around iteration 70), the warnings of level 1 linked to $d s o l 1$ and $d s o l 4$ are cancelled; but the warnings of level 2 linked to $d s o l 5, d s o l 6, d s o l 8$ remain valid.

From a practical point of view, these findings mean that when the aircraft was getting close to the cliff and flying tangentially along the cliff, the distribution of the density of solutions in directions $d s o l 1$ and $d s o l 4$ (cf Fig. 5.22) decreased (especially $d$ sol1) because the envelope of trajectory solutions collided with the danger zone at that moment. Later, when the aircraft moved away from the cliff, $d s o l 1$ and $d s o l 4$ increased again, cancelling the warnings.

In the meantime, the lower part of the envelope of trajectory solutions dsol5, dsol6 and dsol8 collides with the danger zone during all the flight as shown in Fig. 5.23. For that reason, a warning of
level 1 and then of level 2 appears very quickly due to the drop in density solutions and doesn't return to a safe level.

As a conclusion of this case, if we compare the alarms generated by the simulated TAWS and the warnings generated by the rules of table 5.1, we can notice that the TAWS alarms could be compared to those generated by the drop of trajectories in dsol1. However, the alarms of the simulated TAWS does not render the vertical approach to the danger zone. Indeed, during all the flight the rules of table 5.1 convey a more complete evaluation of the envelope of trajectories localised collision risk. Hence, the new warnings rules suggested in this section provide a more realistic approach to the danger. Moreover, even if the rules generate risk indicators in a given space direction, this doesn't mean that the crew would be immediately notified. We generate collision risk indicators for the decisionmaking functional bloc, which is going to adapt to the current situation to warn the crew in the most appropriate way (chapters 3 and 6) in order to avoid false alarms. The warnings rules presented in table 5.1 are more efficient than the alarms of the simulated TAWS to notify a localised collision risk because they take into account the degradation of the global envelope of trajectories. The envelope partitions the space ahead of the current position with all the trajectories feasible by the aircraft in 3D and it collides with danger zones as the aircraft flies towards the terrain. In CFIT accident scenarios, it is of paramount importance to make the approach to the ground progressive and comprehensible by the system with objective rules testifying of the loss of altitude or of the approach to the ground.

Based on these considerations, it is possible to render the danger approach in the immediate environment around the aircraft. However, as a perspective for alarm restitution to the crew, it could be imagined that, additionally to the warning rules mentioned in table 5.1, the direction of the extrapolated trajectory of the current state could be taken into account for the restitution of the final alarm through a Human Machine Interface or directly as an avoidance manoeuvre managed by the Autopilot (Automatic Flight Control System). This direction of the extrapolated trajectory of the current state could be physically materialised by the closest density of solutions, i.e. the closest bunch of trajectories corresponding to a direction.

In the case when the aircraft flies close to the cliff and moves away, it could be noticed that the extrapolated trajectory (Fig. 5.23) appears to be very close to the bunch of trajectories from dsol2. Accordingly, the final alarm should probably take it into account. That would mean that the level of safety, for the crew, in this particular case, could be considered as acceptable.

The warnings suggested for the system must always go from the lower level (1) to the higher level (2). There cannot be a switch to the second warning without notification of the first warning level to the crew. The two levels of warning are the following:

| Warning level 1 | Warning level 2 |
| :--- | :--- |
| Time to obstacle $<20$ seconds AND $d$ sol $_{i}<32$ | Time to obstacle $<10$ seconds AND $d s o l_{i}<32$ |
| OR Time to obstacle $<15$ seconds | OR $d s o l_{i}<10$ |
| OR $d s o l_{i}<20$ |  |

Table 5.1. Warning rules as risk indicators for the system, rendering possible threats in 3D related to the evolution of the envelope of trajectory solutions during the flight


Figure 5.23. Case where the aircraft goes close to the cliff and moves away - display of all the low soliciting trajectory solutions at a given flight point (turquoise) and the extrapolated trajectory of the current state (magenta) coinciding partly with the flight trajectory (green)


Figure 5.24. Case where the aircraft goes close to the cliff and moves away - display of all the low soliciting density of solutions in the three-dimensional space frame


Figure 5.25. Case where the aircraft goes close to the cliff and moves away - display of the time to obstacle of the extrapolated trajectory of the current state


Figure 5.26. Case where the aircraft goes close to the cliff and moves away - display of the alarms generated by a simulated TAWS. When the data is higher than zero, the simulated HTAWS generates an alarm of collision.

## CHAPTER 5. RAMSES : IDENTIFYING LOCALIZED RISK OF COLLISION IN-FLIGHT

### 5.7 Conclusion

As a conclusion, the Risk Assessment functional bloc provides a forecast of the flight situation in term of 3D collision with the danger zones in a near future (next 30 seconds of flight). More precisely, based on the Trajectory Evaluation functional bloc results, it provides the system with a vision of the aircraft's approach towards the ground by quantifying the situation awareness on the drop in the remaining safe avoidance trajectory solutions and hence by revealing nearby dangerous areas. In other words, it monitors the danger sight by reporting the collision of the global envelope of trajectories with danger zones computed at different altitudes.

More generally speaking, the collision of the envelope of trajectories with danger zones varies with the angle of approach to the terrain. The collisions may be more or less localised in a direction rather than in another. As an example, if the aircraft flies at low altitude, the trajectories composing the envelope and going downwards would probably collide with the danger zones. This has lead us to study various flight approaches to the terrain, possibly dangerous. As a conclusion four independent objective criteria have been derived empirically to characterise the flight by observing the aircraft's behaviour in various situations.

Besides, the results of the warning rules have been compared to the alarms produced by a simulated version of the TAWS, which has lead us to quantify a significant number of alarms that could be avoided because they are not adapted to all operational flight conditions (operational reality) and to the perception of the danger corresponding to the pilot's experience. Reciprocally, the analysis have permitted to highlight situations where the set of warning rules suggest a possible danger while the simulated TAWS does not produce any alarm. Consequently, the set of warning rules provide a good vision of the aircraft's situation awareness, through safety indicators in flight situations of approach to the ground. However, the study does absolutely not consider these indicators as the final alarm that should be reported to the crew. For that reason, the Risk Assessment functional bloc also computes additional values more specifically associated to each trajectory solution.

Indeed, the criteria mentioned before are also computed independently for each trajectory of the Central Data Structure (Fig. 5.1), composing the global envelope of trajectories. Hence, each trajectory has information related to its time to obstacle, its dynamic solicitation, its manoeuvrability and its density of solution (the dsoli it is belonging to as shown in Fig. 5.22).

Accordingly, this information is computed for the Classifier functional bloc and the Decision Making functional bloc (detailed in chapter 6) in order to provide the crew with a reliable avoidance trajectory among all the computed trajectories.

As stated before, the Risk Assessment functional bloc computes data to characterise the current flight situation and provide a good vision on what could happen in the short term navigation framework, i.e. how the global safety might evolve in the next 30 seconds of flight. However, it doesn't give the final alarm towards the danger nor a possible avoidance trajectory before the crash would occur. In 5.6, the discussion over new warning rules rendering the approach to the terrain has lead us to highlight the need for a unit of comparison of trajectory solutions between themselves and to the extrapolated trajectory of the current state in order to "orientate" the final decision for an alarm and the final escape manoeuvre if necessary.

The next chapter treats of these issues and will explain the stakes and perspectives of the Classifier and the Decision Making functional blocs based on the considerations and the data computed by the previous blocs composing the RAMSES functional architecture.

## Chapter 6

## RAMSES : Decision Making

### 6.1 Introduction

The Decision-Making functional bloc is part of the RAMSES functional architecture (Fig. 6.1). It stands for the final step of the system's chain. The Decision-Making functional bloc ensures the reporting of alarms to the crew and the restitution of all the information related to safety monitoring.

This chapter is going to address the parametrisation of PROMETHEE II (Classifier functional bloc) through an experimental positioning and interpretation of interviews conducted at Airbus Helicopters with flight test pilots and experts of the design office and the fleet safety department. The discussions with the pilots and the experts have been conducted in order to provide a parametrisation of the Classifier functional bloc for trajectories ranking and the choice of the best avoidance trajectory solution adapted to the flight situation.

In order to pave the way for future improvements of the RAMSES avionics function concept, this chapter will suggest several possibilities for parametrising the Classifier functional bloc based on discussions concerning the criteria definitions. Indeed, the valuation and the influence of the criteria could be adapted to the operational situation of the flight.


Figure 6.1. RAMSES functional architecture - focus on the Classifier and the Decision Making functional blocs

### 6.2 Trajectories sorting and ranking

PROMETHEE II (Preference Ranking Organization METHod for Enrichment Evaluations) is a multicriteria method, it provides a complete ranking based on pairwise comparisons of solutions. This method is used to compare and rank solutions according to selected criteria. This outranking method was chosen due to its efficiency and to the fact that it is easy to understand and to tune by decision-makers. For more details about PROMETHEE II, see [82, 36, 33]. As mentioned in [20], PROMETHEE has already been used in many R. \& D. projects all over the world, including several of our projects as stated in section 3.6.4.

One aim of this research is to combine efficiently several components, including a specific version of PROMETHEE II, in one real-time decision aid-making tool to be embedded in aircraft.

In PROMETHEE, the objective associated with each criterion is either to minimize or to maximize the value of this criterion among the solutions. In the following paragraphs, $A_{1}, A_{2}, \ldots, A_{i}, \ldots, A_{n}$ denote $n$ potential alternatives i.e. actions or solutions, and $C_{1}, C_{2}, \ldots, C_{j}, \ldots, C_{m}$ are $m$ criteria. In the implemented version of PROMETHEE II, several simplifications imply that each evaluation $C_{j}\left(A_{i}\right)$ must be a real number. PROMETHEE II builds an outranking relation using a preference function, which represents the decision makers' preference $P_{j}\left(A_{i}, A_{k}\right)$ for a solution $A_{i}$ with regard to a solution $A_{k}$ on the $j^{\text {th }}$ criterion.

In this simplified version of PROMETHEE II, the preference function is fixed for all criteria. Based on an linear shape, defined by $g_{j}(x)$ (a symmetrized representation of the linear shape is given in Fig. 6.2), it translates the difference between the evaluations obtained by the two alternatives $A_{i}$ and $A_{k}$ in terms of the particular criterion $C_{j}$ into a preference degree ranging from 0 to 1:

$$
P_{j}\left(A_{i}, A_{k}\right)=g_{j}\left(d_{j}\left(A_{i}, A_{k}\right)\right)
$$

where

$$
d_{j}\left(A_{i}, A_{k}\right)= \begin{cases}C_{j}\left(A_{k}\right)-C_{j}\left(A_{i}\right) & \text { if } C_{j} \text { is maximized } \\ C_{j}\left(A_{i}\right)-C_{j}\left(A_{k}\right) & \text { if } C_{j} \text { is minimized }\end{cases}
$$



Figure 6.2. Preference function: linear shape
For each criterion $C_{j}$, the decision makers have to give the weight $\omega_{j}$ (positive or zero) and the "uncertainty" concerning the values of the criterion via indifference $\left(q_{j}\right)$ and preference $\left(p_{j}\right)$ thresholds. The next step of PROMETHEE II consists in computing the outranking index, which represents the strength of the decision makers' preference for solution $A_{i}$ over solution $A_{k}$. It is computed for each pair of solutions $A_{i}$ and $A_{k}$ as the weighted average of preferences computed for each criterion:

$$
\pi\left(A_{i}, A_{k}\right)=\frac{\sum_{j=1}^{m} \omega_{j} \cdot P_{j}\left(A_{i}, A_{k}\right)}{\sum_{j=1}^{m} \omega_{j}}
$$

This index measures the preference for $A_{i}$ on $A_{k}$ over all the criteria. On the basis of these indexes, PROMETHEE II computes positive and negative preference flows for each solution. Based on the difference between these flows, the net flow $\phi$ is obtained and used to rank the solutions:

$$
\left.\begin{array}{l}
\phi^{+}\left(A_{i}\right)=\frac{1}{n-1} \sum_{k=1}^{n} \pi\left(A_{i}, A_{k}\right) \\
\phi^{-}\left(A_{i}\right)=\frac{1}{n-1} \sum_{k=1}^{n} \pi\left(A_{k}, A_{i}\right)
\end{array}\right\} \phi\left(A_{i}\right)=\phi^{+}\left(A_{i}\right)-\phi^{-}\left(A_{i}\right) .
$$

The positive preference flow expresses how much a solution is dominating the other solutions, and the negative preference flow how much it is dominated by the other solutions. Based on the net outranking flows, PROMETHEE II provides a total order of the solutions [36]. Therefore, the solution $A_{i}$ outranks the solution $A_{k}$ if, and only if, $\phi\left(A_{i}\right)>\phi\left(A_{k}\right)$, and solutions $A_{i}$ and $A_{k}$ are indifferent solutions if, and only if, $\phi\left(A_{i}\right)=\phi\left(A_{k}\right)$.

Thanks to PROMETHEE II, the resulting tool is able to incorporate gradation, tinge and fuzziness in the judgment of decision makers while comparing several solutions. PROMETHEE II allows the discounting of one criterion while improving another criterion. This perfectly matches a situation where a decision maker accepts a solution which is worse than another on one criterion if this solution leads to significant improvements on some (or all) of the other criteria. Moreover a sensitivity analysis shows that, in most cases, these results are robust with respect to the weights [68].

This means that the resulting ranking given by PROMETHEE II is not modified as long as each weight remains in a particular interval, so called interval of stability.

The ranking of the solutions might benefit from our CPU/FPGA architecture [91, 92, 13, 15].

### 6.3 Interview with flight test pilots and experts, Questionnaires and Experimental Initiatives

The content of this section has a restricted access.

### 6.3.1 Weighting of criteria

The content of this section has a restricted access.

### 6.4 Interpretation of Airbus Helicopters flight test pilots and experts interviews

The content of this section has a restricted access.

### 6.5 Criteria chosen for parametrizing PROMETHEE II

Four criteria have been presented to the Airbus Helicopters experts in order to collect their advice for the system's parametrisation. The criteria have been derived from observation of simulated approaches that could potentially lead to an accident of CFIT (Controlled Flight Into Terrain) type, explained in chapter 5.

The four criteria are:

- The time to obstacle (given in seconds),
- The manoeuvrability,
- The solicitation,
- the density of solutions.

However, during the interviews the experts have given advice, which resulted in the definition of a new criterion. The additional criterion serves to discriminate the type of the trajectory in terms of its directions and the number of actions required to perform it. Indeed, in emergency situations, the pilot should receive information that would cause the minimum of disruption. The preferred avoidance trajectories are climb and lateral ones (Fig. 4.2) because they necessitate only one action at a time, be it an increase or decrease in the roll angle or in the vertical speed. Oblique trajectories necessitate to perform two actions at a time. For that reason, it could be difficult for the pilot to perform them in emergency situations. In addition, for the CFIT case presented to the experts and detailed in section 7.2, the avoidance trajectories going upwards are not recommended. The four criteria presented to the pilots do not render this preference.

This criterion is different from the manoeuvrability criterion in the sense that it focuses on the direction and the number of actions necessary to perform one section of the trajectory, while the manoeuvrability criterion only focuses on the number of different sections composing a single trajectory.

We define the fifth criterion as follows:
The criterion called Type exists in two different configurations:

- Normal configuration: the trajectories containing oblique sections are discriminated in the choice of the final trajectory solution, i.e. the best avoidance trajectory solution seen by the Classifier. This is done in order to ensure that the final trajectory solution, potentially suggested to the crew, is as simple as possible.
- Lateral: 1
- Descent: 1
- Climb: 1
- Oblique-climb: 2
- Oblique-descent: 2
- Special configuration: the trajectories containing oblique sections and going upwards are discriminated in the choice of the final trajectory solution, i.e. the best avoidance trajectory solution seen by the Classifier. The special configuration is meant to be adapted to the case treated in section 7.2, and corresponds to all the additional preferences given by Airbus Helicopters experts for this case.
- Lateral: 1
- Descent: 1
- Climb: 3
- Oblique-climb: 4
- Oblique-descent: 2

The configuration is meant to be selected before the mission starts, in the preparation phase of the mission, by the crew. Hence the Classifier functional bloc has different configurations in memory and it is able to switch according to the requests of the Decision-Making functional bloc, which collects the needs of the crew via the HMI (Human Machine Interface) as shown in Fig. 6.1. the configuration is not supposed to change during the mission except if the mission conditions change.

We have tested different configurations in this study, however we are going to present only one, corresponding to the use case treated in section 7.2. It is a first result of parametrisation of PROMETHEE II, obtained through dialogue with the experts. We assume that other simulations on pilot cases and feedbacks with the experts would be necessary to establish the final parametrisation of PROMETHEE II.

### 6.6 Criteria valuation and influence

The criteria identified in the study to parametrise the Classifier functional bloc are :

- timeObst: the time to obstacle
- dsol: density of trajectory solutions in a space direction
- manoeuvr: the manoeuvrability criterion
- sollicit: the solicitation criterion
- type: the type criterion with two possible configurations

The detailed description of the criteria is given in table 6.1.
Each criterion is either MAXimised or MINimised as specified in table 6.1; and we have :

- $\min _{j}$ and $\max _{j}$ respectively standing for the minimum and the maximum values a criterion could take.
- $\delta_{j}$ is the minimum variation that could be observed between two consecutive values of the criterion. For an integer, $\delta_{j}=1$, for a percentage $\delta_{j}=0.01$ and so on.
- $q_{0 j}$ is the relative threshold below which two trajectory solutions do not show a discernible effect.
- $p_{0 j}=\left|\max _{j}-\min _{j}\right|$ is the relative threshold above which two trajectory solutions are strictly ranked.

The parameters described above are given to the Classifier functional bloc of the RAMSES avionics function concept (Fig. 6.1 and section 3.6.4), equally to both instantiations of PROMETHEE II. As a perspective, it could be imagined that the two instantiations of PROMETHEE II could have different parametrisations and even more different criteria to consider.

However, in this thesis, we aim to provide a first version of the RAMSES avionics function concept and test the results on separate possible operational collision threats (treated in section 6.7) and on a reconstituted accident scenario of the Airbus helicopters fleet in section 7.2.

As a first parametrization of PROMETHEE II, it is possible to consider $q_{j}=q_{0 j}$ and $p_{j}=p_{0 j}$. The final parametrization depends on the considered mission and on feedbacks given by Airbus Helicopters experts.

The parameters listed in table 6.1 are given as input to PROMETHEE II for ranking the trajectory solutions computed by the Trajectory Generation functional bloc (Fig. 6.1, chapter 4).

| Name | Obj | $\min _{j}$ | $\max _{j}$ | $\delta_{j}$ | $q_{0 j}$ | $p_{0 j}$ | Description |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :--- |
| timeObst | MAX | 0 |  |  |  |  |  |


|  |  |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |

Table 6.1: Criteria description and influence

### 6.7 Results on preliminary use cases

Two preliminary use cases have been tested with the criteria and the parametrisation described in table 6.1:

- Case 1: The case when the helicopter goes close to the terrain and moves away (Fig. 6.3),
- Case 2: The case when the helicopter goes straight towards the terrain (Figs. 6.4 and 6.5).

As concerns the Type criterion, in the following discussions only the Type special CFIT configuration will be analysed as it corresponds to the case commented by Airbus Helicopters experts. The trajectories will be evaluated with respect to a danger zone computed above the terrain elevation data with the method described in chapter 5.

The preliminary use cases have served to parametrise PROMETHEE II and test the RAMSES avionics function concept on simple operational situations that could present a collision threat. Accordingly, the parametrisation of the Classifier functional bloc, in its first version has been established by considering the simulated approaches to the terrain presented in Figs. 6.3, 6.4 and 6.5, and by analysing the Airbus Helicopters experts interviews.

In Figs. 6.3, 6.4 and 6.5, the display shows the flown trajectory in green, the extrapolated trajectory of the current flight situation in magenta, and the five best trajectories computed, by the Classifier functional bloc (Fig. 6.1, and section 3.6.4) for different iterations successively in cyan and yellow in order to provide a better transparency between the computed trajectories.

Eventually, the red trajectory is the best avoidance trajectory solution, ranked first by PROMETHEE II, of the last iteration of the flown path (green).

The two cases treated in this section are computed with respect to a danger zone situated at an altitude of 250 meters above the terrain.

Case 1 The preliminary case 1 covers the situation where the helicopter flies towards the terrain and moves away. In Fig. 6.3, this case is reproduced with a circular trajectory (green), with constant curvature and altitude. The positions composing the trajectory stand for the successive positions taken by the helicopter during the flight.

It could be noticed that when the helicopter is far from the terrain, especially from the little hill in the middle of the map, the trajectories ranked as best ones (displayed successively in cyan and yellow) are fully compliant with the experts interviews and preferences:

- They are contained in the horizontal plane and composed of one action at each section of 10 seconds of flight (compliance with criterion type in special configuration,
- They are composed of one or two manoeuvres (compliance with criterion manoeuvr),
- They have gradual solicitation (compliance with criterion sollicit),
- The time to obstacle of the best ranked trajectories is 40 seconds (they are clear from obstacles, compliance with the criterion timeObst),
- They are contained in the direction where the density of solutions is the most important (compliance with the criterion $d s o l$ ).

However, when the helicopter gets very close to the hill, the best ranked trajectory solution given by PROMETHEE II are directed upwards which is not recommended by the experts in a special CFIT configuration. The best ranked trajectory solutions are still compliant in terms of manoeuvrability, solicitation, time to obstacle and density of solution, however the type criterion requirements are not fully respected because the first section of the avoidance trajectories is going upwards, while the next two sections remain in the horizontal plane.

Actually, when we look closer to the ranking of the trajectory solutions in the case when the aircraft gets close to the danger zone, it is possible to notice that the density of solutions of trajectories going upwards in the first section is a little higher than those who remain in the horizontal plane from the beginning.

According to the experts feedbacks, the criteria time to obstacle timeObst and density of solution $d s o l$ are considered to be the most important criteria in the final choice of the preferred trajectory solutions for a given flight point.

As a consequence, the trajectories going upwards are preferred in the ranking, in the situation when the aircraft gets very close to the danger zone. This phenomenon could be tuned later through simulation and discussions with the experts on more cases and it is not disturbing here because the trajectories provided by PROMETHEE II are still safe; they permit to fully avoid the danger zone and they remain fully compliant with all the other criteria taken into consideration in the final ranking.

Note: These observations could even make the discussion go further by evaluating the influence of the danger zones proximity to the ranking of the trajectory solutions. It could be envisaged in the future works to add another criterion which conveys the minimum acceptable distance to a danger zone. This distance could be different from a mission to another, and it makes the system adaptable to the crew preferences. As an example, for a Search and Rescue ( $S \& R$ ) mission the crew may require to fly at low altitudes, close to the terrain and obstacles. For such missions, the minimum acceptable distance from the obstacles will certainly be different from a regular flight mission transporting passengers from a point A to a point B.

The flight situation represented in Fig. 6.3 could be decomposed in three phases.

- Phase 1: The helicopter flies towards the terrain, it is still far from the hill but it is getting closer, the preferred trajectory solutions are contained in the horizontal plane and they are composed of one or two manoeuvres and they are of type 3 (compliant with criterion type),
- Phase 2: The helicopter is flying close to the hill tangentially, which implies that the trajectory solutions on the left side of the aircraft are not valid. The global number of available trajectory solutions has decreased. The system provides escape trajectory solutions going up, and composed of one or two manoeuvres and they are of type 3,
- Phase 3: The helicopter moves away from the hill, the global number of trajectory solutions increases again and the trajectory solutions provided by the system are similar to those in Phase 1.

As a conclusion of Case 1, as long as the aircraft is far enough from the terrain, the best ranked trajectory solutions are fully compliant with the experts feedbacks.

When the aircraft gets close to the terrain and the number of trajectories decreases, the preferred avoidance trajectories are partly compliant with the experts feedbacks as concerns the criterion type. Despite this, they remain fully compliant with all the other criteria and still permit to avoid the danger zone safely.

Besides, as the time to obstacle of the extrapolated trajectory of the current state is constant and judged safe (see discussion in chapter 5), and the system takes into account that the aircraft is going towards the danger zone tangentially with the aim to avoid it, there are no needs to notify the crew of a collision threat.

The system provides the best ranked trajectory solutions for all the three phases illustrated in Fig. 6.3. In all cases they allow to avoid the danger zone safely. It could be noticed that the proximity of a danger zone may influence the ranking of trajectory solutions because some criteria should have higher influence than others according to the experts. This phenomenon can be tuned in simulation though discussions with experts, and the weighting could be adapted to satisfy the requirements imposed by a specific mission or a difficult terrain, if necessary.

In the future developments of the RAMSES avionics function concept, it could easily be imagined that the criteria weighting and parametrisation evolve in the next versions of the Decision-Making functional bloc, as a perspective work, through more detailed discussions, concerning the decisionmaking functional bloc, with Airbus Helicopters experts and with the University of Valenciennes. It could also be imagined to study the influence of a danger zone's proximity to the current flight position in order to add another criterion reflecting this idea if necessary.


Figure 6.3. Preliminary use case where the helicopter goes towards the terrain and moves away

Case 2 The preliminary case 2 covers the situation where the aircraft flies towards the hill and the system tries to avoid it. Figs. 6.4 and 6.5 display the results.

It could be be noticed that all along the flight the set of best trajectory solutions ranked by PROMETHEE II is compliant with the experts feedbacks.

On the same scheme that Case 1, and for the same reasons, when the aircraft gets too close to the hill (approaching 10 seconds time to obstacle of the extrapolated trajectory of the current state, or below), trajectories containing climb sections appear among the best ranked avoidance trajectory solutions. However, the best ranked trajectory that would be suggested to the crew in a special configuration of criterion type, if an avoidance becomes necessary, is fully compliant with the experts feedbacks and it is always ranked first if available.

In Figs. 6.4 and 6.5, we have pushed the tests as far as possible to see what kind of trajectories the system would suggest when it gets very close to the danger zone, which means that the time to obstacle of the extrapolated trajectory of the current state is nearly equal to zero (the collision is imminent if no avoidance action is provided). In this case the aircraft faces the danger zone ahead of its current position, contrary to the previous case 6.3 where the aircraft could be close to the danger zone ahead of its current position or on the sides.

For the last iteration illustrated in Figs. 6.4 and 6.5 all the trajectory solutions contained in the horizontal plane are unsafe and the Classifier functional bloc suggested the red trajectory which is safe and permits to avoid the danger zone perfectly well.

As a conclusion of this use case, the trajectory solutions ranked by PROMETHEE II fully satisfy the experts feedbacks. Moreover, according to the experts interviews the system should provide the last acceptable alarm for avoidance when the time to obstacle of the extrapolated trajectory of the current state decreases to 10 seconds before the impact. As noticed in Fig. 6.5, around 10 seconds before the impact, trajectories going upwards appear in the best ranked trajectory solutions which confirms that the aircraft gets close to the danger zone. However, the best ranked trajectory solution remains in the horizontal plane and always satisfies the recommendations given by the experts for a special CFIT type configuration treated here.


Figure 6.4. Preliminary use case where the helicopter goes straight towards the terrain


Figure 6.5. Preliminary use case where the helicopter goes straight towards the terrain with preferred trajectories (in black) indicating the best avoidance trajectory solution 10, 20 and 30 seconds before the impact

### 6.8 Conclusion

This chapter covers discussions on the design, implementation and validation of the DecisionMaking functional bloc and the Classifier functional bloc.

These two parts of the RAMSES avionics function concept strongly rely on feedbacks given by Airbus Helicopters experts, interviewed on the case of a reconstituted CFIT (Controlled Flight Into Terrain) accident occurred in degraded meteorological conditions.

In an attempt of trying to parametrise the PROMETHEE II tool, implemented in the Classifier functional bloc, two preliminary possible CFIT accident scenarios have been tested in an environment different from the reconstituted accident scene presented to the experts. This way we tried to have a generic configuration that could be valid for the reconstituted accident later on.

The parametrisation suggested in this chapter shows a certain flexibility because two different configurations are envisaged:

- Type normal CFIT configuration: the avoidance trajectories could be directed upwards,
- Type special CFIT configuration: the trajectories going upwards are not recommended because the cloud ceiling is supposed low. This case is covered by the experts interviews.

In the two cases presented in this chapter only the Type special CFIT configuration is presented because it is covered by the experts interviews and used to test the RAMSES avionics function for the reconstituted accident in section 7.2.

As a conclusion we can say that the PROMETHEE II parametrisation reflects the experts feedbacks on the use cases treated in this chapter. The results are compliant with the expectations deduced from the interviews. The best ranked trajectories given by the Classifier functional bloc permit to avoid the danger safely all the time with a minimum of constraints as recommended by the Airbus Helicopters experts feedbacks.

## Chapter 7

## Practical application of the RAMSES avionics function concept

### 7.1 Introduction

In order to test and validate the RAMSES avionics function concept, two CFIT accident scenarios of the Airbus Helicopter's fleet have been considered. For legal reasons and consideration for the families of the victims, the types of the aircraft and the accidents details permitting to identify the cases will not be revealed in this document. However, for the purpose of the study, in order to test and validate or adjust the RAMSES avionics function concept, the investigator in charge of the cases has provided a description of the flight conditions and the available flight data, including the 3D coordinates of the aircraft before the impact.

For each case (7.2, 7.3), the operational context of the accident will be discussed, along with the available flight data for studying the accident scenario. Additional information computed or recovered from the flight data will be commented for a better understanding of the cases.

### 7.2 First use case: RAMSES avionics function test along a helicopter path leading to a crash

### 7.2.1 Accident Context and positioning of the problem

The 3D flight coordinates of the last minutes before the impact have been recovered and reconstituted in a simulated three-dimensional environment of the crash site in order to assess whether the RAMSES avionics function concept can highlight proper safety barriers (operational or analytical ${ }^{1}$ ) before the collision would occur. The preliminary use cases developed in chapter 5 have highlighted some specific flight patterns when the helicopter evolves at low altitude. In chapter 6 the criteria derived from the patterns of chapter 5 have been completed with rules extracted from the Airbus Helicopters flight test pilots interviews.

The three-dimensional environment of the crash site has been reproduced with and elevation matrix of the area as shown in Fig. 7.2. The visual rendering has been done using the OpenGL API

[^14]
## CHAPTER 7. PRACTICAL APPLICATION OF THE RAMSES AVIONICS FUNCTION

(Application Programming Interface) ${ }^{23}$. For the purpose of this study, the flight data positions of the helicopter have been smoothed using the Bezier curves in order to derive the discrete distributions of the curvature and the torsion along the path (Fig. 7.1). This way the initial conditions in torsion and curvature are taken into account at each flight position along the path by the trajectory generation functional bloc of RAMSES, which sustains continuity at third order of the immediate environment reachable by the helicopter.

The initial conditions in the helicopter state at each flight point are computed over the last 100 positions (as explained in subsection 4.3.4) in order to take into account the local variations in torsion, curvature and direction. This way the discontinuities in the flight data would be less apparent from one flight point to another. Indeed, the original flight data is very discontinuous as shown in Fig. 7.1, and might produce significant differences between two consecutive 3D positions especially in torsion and direction. For that reason, it is preferable to have averaged results in torsion, curvature and direction values in the helicopter initial state in order to take into account local variations in the flight data.

Helicopter path smoothed using Bezier curves


Figure 7.1. Helicopter path smoothed using the Bezier curves - 3D view

The accident reconstitution has been achieved from the flight positions of the aircraft provided by the Flight Safety Department of Airbus Helicopters. The accident area has been simulated in 3D numerically, as shown in fig. 7.2, from an experimental terrain elevation data base exported from Google Earth ${ }^{4}$ in .asc format.

### 7.2.2 Assessing the current flight situation

For each flight point (represented in black in Fig. 7.2), the set of avoidance trajectory solutions is computed and evaluated according to the best avoidance trajectory solution considered to be the extension of the current flight state. If the extrapolation of the current flight sate happens to be risky

[^15]

Figure 7.2. The three-dimensional test environment rendered with the OpenGL API with the 3D flight position coordinates (in black) of the last minutes before the impact (in the back of the scene)
according to the evaluation method described in chapter 6, then the best avoidance trajectory solution is selected from the set of all the trajectory solutions, and it is eventually suggested to the crew as an escape manoeuvre valid for 30 seconds of flight. An example of the set of trajectory solutions is illustrated in Fig. 7.3 along with the best avoidance trajectory (in red). It could be noted that some trajectory solutions go below the 3D danger zone. These are not considered safe and won't be taken into account for the final ranking at the current flight point.

The best escape trajectory solution is computed at each flight point even if it is not suggested to the crew. A top view of the best ranked avoidance trajectory solutions chosen from the set of all the trajectory solutions is displayed in Fig. 7.4 in the test environment. The crash area is situated on the right side of the graph. At some point, on the graph, no more avoidance trajectory solutions appear clearly. This is due to the fact that they disappear below the danger zone used for the trajectory evaluation. Hence, the RAMSES avionics function concept keeps suggesting emergency manoeuvres but they are not considered $100 \%$ safe with respect to the danger zone.

It could be noticed from the plot in Fig. 7.4 that the best avoidance trajectory solutions tend to go far from the terrain and reminds of the patterns identified in chapter 5.


Figure 7.3. The three-dimensional danger zone 150 meters above the ground rendered with Matlab with 3D flight coordinates (in green); the set of avoidance trajectory solutions (turquoise) and the the best avoidance trajectory solutions computed in real-time (in red) and chosen among the set of valid trajectory solutions

### 7.2.3 The CFIT (Controlled Flight Into Terrain) accident scenario

Several danger zones have been computed in order to test the collision of the envelope of trajectory solutions for this accident scenario. The aim was to understand the logic of approach towards the ground and the evolution of the envelope of trajectory solutions computed for each flight point presented in black in Fig. 7.2; along with the best ranked trajectory solutions given by PROMETHEE II for the type special CFIT configuration.

Fig. 7.4 presents an example of the best trajectory solution computed for each 3D flight position along the path. Figs. 7.5, 7.6, 7.7 present results of collision analysis for a danger zone computed 200 meters above the ground. It is possible to notice the sharp slope around iteration 40 in fig. 7.6 in the density of solution distributions when the aircraft enters in collision with the danger zone. Moreover, the thresholds notifying the danger sight, given by the experts in chapter 5 are quickly overcome.

As the aircraft flies at low altitude in this case, we will discuss the results hereafter with a danger zone computed 50 meters above the ground. Fig. 7.8 presents the variation of the density of solutions for the 3D space frame presented in Fig. 5.22. It could be noticed that the distributions of $d s o l_{i}$ $i=1,2, \ldots, 8$ are high and that the danger of collision is essentially situated in the directions going downwards like $d s o l_{5}, d s o l_{6}, d s o l_{8}$ and close to the end of the flight.

Fig. 7.9 shows the extrapolated trajectory for successively 10,20 and 30 seconds of time to obstacle. The extrapolated trajectory is computed for every flight position and it constitutes the comparison reference for all the other trajectories composing the envelope of trajectory solutions. According to


Figure 7.4. Example of the best avoidance trajectory solution ranked by PROMETHEE II for successive 3D positions
the experts interviews, 10 seconds is last acceptable time frame for an emergency avoidance trajectory. However, the notification for the avoidance should be given earlier in this case, starting at 30/35 seconds of time to obstacle.


Figure 7.5. Time to obstacle given for the extrapolated trajectory of the current flight state, given with respect to a danger zone computed 200 meters above the terrain elevation


Figure 7.6. Distribution of the density of solutions in the 3D frame for directions described in Fig. 5.22 , for the danger zone computed 200 meters above the ground


Figure 7.7. Results of alarms given by the simulated TAWS during the flight, by analysis of collision with a danger zone computed 200 meters above the ground


Figure 7.8. Distribution of the density of solutions in the 3D frame for directions described in Fig. 5.22 , for the danger zone computed 50 meters above the ground

Figure 7.9. Time to obstacle given by the extrapolated trajectory 10,20 and 30 seconds before the impact with the danger zone

## CHAPTER 7. PRACTICAL APPLICATION OF THE RAMSES AVIONICS FUNCTION

Figs. 7.10 and 7.11 display respectively the trends of the best avoidance trajectory solutions along the path and the distributions of avoidance trajectory solutions for 30 and 20 seconds of time to obstacle.

It could be noticed in Fig. 7.10 that the best ranked trajectory solutions are compliant with the experts feedbacks, i.e. it is recommended to avoid the danger zone by a lateral avoidance or vertically by a descent and then a turn to go back, out of the valley. The trajectories become partly compliant for criterion type, for a time to obstacle of the extrapolated trajectory close to 30 seconds. The best ranked trajectories are then directed upwards which is not recommended in this case. However they are safe and allow to avoid the danger zone. This happens because the situation is becoming more dangerous, the aircraft looses altitude and gets closer to the danger zone on the sides, which results in the loss of available trajectory solutions.

As a result, Fig. 7.11 displays the best ranked trajectory solutions 30 and 20 seconds of time to obstacle. The are not fully compliant with the type criterion. However they are safe and suggested because the avoidance trajectories on the side are either not available or not safe enough. In this case it is highly possible that trajectories on the sides are still valid but as discussed in chapter 6, not suggested because of criteria timeObst and dsol, which are "dominating" the final ranking. According to the experts, these two criteria are the most important ones, timeObst comes before $d s o l$.

In this thesis we assume that a trajectory is safe regarding the criterion timeObst if it has a time to obstacle bigger or equal to 30 seconds. In order to have a better evaluation, we have ensured that the time to obstacle with a danger zone could be evaluated up to 40 seconds. Now if a trajectory going upwards has a bigger time to obstacle than a trajectory providing lateral avoidance then it will be preferred.

The same discussion applies for the density of solution criterion dsol, discussed more in details in chapter 6.

It is interesting to notice that the bests ranked trajectory solutions given by PROMETHEE II are directed towards the alternative flight plan illustrated in Fig. B.1.

Figure 7.10. Display of the top 5 trajectory solutions ranked by PROMETHEE II for successive positions along the path in the Type special CFIT configuration

Figure 7.11. Focus on top 5 trajectory solutions ranked by PROMETHEE II for 30 (cyan) and 20 (yellow) seconds time to obstacle of the extrapolated trajectory (magenta). The danger zone is computed 50 meters above the terrain elevation data.

## CHAPTER 7. PRACTICAL APPLICATION OF THE RAMSES AVIONICS FUNCTION

### 7.2.4 Conclusions on this accident scenario

In this accident scenario we have shown that the parametrisation of PROMETHEE II detailed in the previous chapter satisfies the constraints of the reconstituted accident presented in this section. Indeed, the best ranked trajectories are compliant with the experts feedbacks and always provide a safe avoidance trajectory solution.

The choice of the best ranked trajectory solutions may be influenced by the proximity of the danger zone because it is linked to the evolution of the envelope of all the trajectory solutions. When the time to obstacle reaches the neighbourhood 30 seconds of flight, the situation becomes dangerous because the aircraft starts loosing altitude and gets closer to the danger zones vertically and on the sides.

These results give important clues for the generation of the alarms aiming to prevent the crash in the future works.

The case treated in this section may not fully reflect the usefulness of the RAMSES avionics function concept at first sight because the accident scenario takes place in a very difficult area and in a difficult operational situation. The case has been selected because it is representative of a typical CFIT accident. Moreover it fits the hypothesis of this study (detailed in section 3.3). However, according to the experts the parametrisation of PROMETHEE II cannot be done directly on a case like this one because it is too complex.

For that reason, the parametrisation of PROMETHEE II has been done has been done on separated use cases developed in the previous chapter.

In the future works, if other operational situations are to be covered by the RAMSES avionics function, the experts recommend that the multicriteria method should be parametrised on "simple" cases characteristic of the very operational situation to be covered. In this thesis, chapters 5 and 6 cover the analysis of the preliminary use cases that served to parametrise PROMETHEE II for this accident scenario.

## CHAPTER 7. PRACTICAL APPLICATION OF THE RAMSES AVIONICS FUNCTION

### 7.3 Path-planning - reconstruction of the last two minutes of an accident of the Airbus Helicopter fleet with 3D Trajectory Generation algorithms

### 7.3.1 Accident context and positioning of the problem

The accident scenario studied in this section has occurred due to a loss of visibility, in a hilly area. The flight data available for the study won't be presented entirely because reconstituting the whole flight is not possible with the hypothesis taken in chapter 3. The data collected after the crash is not as complete as for the previous accident case. There is one minute of time between two consecutive flight points. The other positions are unknown. For that reason, in this case we have demonstrated the interest of the path-planning algorithms detailed in chapter 4 for computing the trajectory of the last two minutes before the crash. The last three consecutive positions have been recorded with the same speed.

The original aircraft implied in the crash won't be revealed. Accordingly, the parameters used to compute a possible trajectory are those derived from the basic flight loop.

For each flight point used to reconstitute the accident, the following information is available:

- The time ( $\mathrm{UTC}^{5}$ ),
- The latitude and the longitude,
- The position,
- The altitude,
- The track,
- The speed.

As displayed in Fig. 7.12 two different connection paths are needed between points A, B and C, each time with a turn. Fig. 7.12 presents a diagram of the positions and orientations of the last three points.


Figure 7.12. Diagram of the positions with directions before the crash (occurred at point C )

[^16]
### 7.3.2 Reconstitution of an estimated path between the three last known waypoints before the crash

Using the path planning algorithms detailed in chapter 4 the path from $A$ to $C$ is presented in fig. 7.13. The trajectory presented in Fig. 7.13 is one possible reconstitution. Given the flight data collected after the crash we have no information on what happened between the positions $\mathrm{A}, \mathrm{B}$ or C .

It is assumed, for the two sections composing the reconstituted trajectory that the constraints on the transitions have been saturated with the curvature on the entire trajectory. The torsion has been adapted with respect to the vertical distance between two consecutive positions. The continuity in torsion and curvature along the path is ensured with three-dimensional spiral transitions making the link between different motion primitives.

Reconstituted trajectory of the last two minutes of flight


Figure 7.13. One possible trajectory connecting the three last positions known of the aircraft before the crash

### 7.3.3 Conclusion on this accident scenario

The path-planning algorithms described in the study ensure the link between the short term navigation concept for safety monitoring and the long term navigation at the mission scale. The study was conducted in a frame of a complete system for the avoidance of CFIT accident types ensuring the interface with the research works conducted previously on path planning [91]. For that reason, the path-planning algorithms presented in chapter 4 present many advantages.

Whether it is for deviating the flight of the current route or connecting the current 3D position and state to an alternative flight plan, the path-planning algorithms computing trajectories with and

## CHAPTER 7. PRACTICAL APPLICATION OF THE RAMSES AVIONICS FUNCTION

without a turn are very useful. In the same context, this accident scenario demonstrates another useful application of these algorithms in the reconstitution of accidents for investigation purposes.

The trajectory represented in Fig. 7.13 constitute one possible reconstitution of the flight two minutes before the crash. In the future works, it is possible to compute an envelope of trajectories on the same principle by varying the following parameters:

- The length of the three-dimensional spiral transitions: by doing so, the constraints on the torsion and curvature and their derivatives may be altered in order to provide a smoother transition between the different 3D positions;
- The speed: it is possible to include variations on the trajectories between two consecutive positions;
- The influence of the wind (not treated in this study but envisaged in a future version of the RAMSES avionics function).

The method for computing the envelope of the possible trajectories for the last two minutes of the flight treated in this section may serve to extend the reconstitution to the whole flight. This way the reconstituted possible trajectories of this flight could be tested with the RAMSES avionics function concept in a simulated environment, as seen in the previous section, to determine the flight point where the in-flight safety started to decrease and where the CFIT accident loop began. Each CFIT accident may be considered as unique because the flight situation, the state of mind of the crew make this situation singular. However, common trends could be derived form the study of these accidents. Besides, replaying the accident scenario in simulation with pilots may bring new answers, new opinions and new advice for completing the current equipments and technologies in use. For that reason, it is of paramount importance to provide the investigators and engineers with all the means for understanding each accident in details. The accurate reconstitution of the trajectories is one of them.

## Chapter 8

## Conclusion and Perspectives

This study was conducted in collaboration between the Innovation department of Airbus Helicopters in Marignane and the LAMIH (Laboratory of Industrial and Human Automation control, Mechanical engineering and Computer Science) of the University of Valenciennes and Hainaut-Cambresis. The study has been carried out within the framework of warning equipments and systems dedicated to collision avoidance with the terrain and surrounding obstacles. More specifically, the research targets the reduction of operational accident causes (with a focus on Controlled Flight Into Terrain - CFIT - accidents) with a new avionics function concept tested in simulated environments on reconstituted accident scenarios.

The current equipments dedicated to the avoidance of CFIT accidents (like the Terrain Awareness and Warning System - TAWS) do not perform a thorough analysis of possible avoidance manoeuvres in the three-dimensional space frame taking into account the full point of an in-flight danger situation along with the dynamic capabilities of the aircraft. For that reason, the study provides a detailed discussion on a new functional architecture thought and designed for the detection of threatening operational situations according to the mission type, the aircraft involved in the mission and the pilot's needs and preferences in terms of mission progress.

Accordingly, the research involves advanced discussions and analysis of Airbus Helicopters flight test pilots and experts interviews, put in emergency flight situations on basic collision threats and especially on a reconstituted CFIT accident of the Airbus Helicopters fleet. The collected answers have been thoroughly examined in order to derive new warning rules rendering the danger perception as sensed by a human operator and providing a basis for the establishment of new alarms. As a result, the design of the new avionics function concept provides enhanced situation awareness and decision-making functionalities based on a better knowledge of the surrounding environment and on the flexibility of manoeuvres of the aircraft in hazardous flight situations.

### 8.1 Outline of the study objectives

The industrial context of the research addresses issues related to complex autonomous systems and delegation of tasks between several decision-making bodies with a strong concern of securing the aircraft in degraded flight conditions, with the aim to reduce the operational accident rate. In order to make the system compliant with the mission requirements and to provide a reliable solution fulfilling the safety concerns, a survey on operational accidents of the Airbus Helicopters fleet has been conducted and studied to understand the accident loop.

## CHAPTER 8. CONCLUSION AND PERSPECTIVES

From a technical perspective, the studies on accidents of the fleet have permitted to derive a functional architecture with main features covering a possible avionics function concept solution for avoiding CFIT accident scenarios to take place.

The scientific approach intended to confront the flexibility of evolution of an aircraft in its immediate surrounding area with a possibly constraining physical environment. The idea lies in making the notion of danger objective by confronting these two concepts :

- Immediate environment,
- and the evolution of the aircraft in this immediate environment.

Therefore, the biggest challenge of the study was to measure the danger sight dynamically for each flight position. As a consequence, the study introduced the notions of short term navigation and long term navigation; where the short term navigation is used to focus on the immediate environment around the aircraft (approximatively 30 seconds of flight ahead of the current position). The notion of long term navigation is employed to ensure a complete logic of collision avoidance through path-planning in the event of diversion during the flight by linking this study to the research works developed in [91].

The concept of short term navigation have ensured capabilities to explore the space ahead and around of the current flight position with trajectory generation and evaluation units. The envelope of trajectories standing for the immediate reachable environment was generated with gradual dynamic solicitation, and various manoeuvres to cover the biggest area from the current flight position. This was possible in the study due to a preliminary focus of the research works on the design and the validation of a reliable kinematics model derived from a helicopter flight loop in Airbus Helicopters simulation tools.

Accordingly, the collision of this envelope of trajectories with the immediate environment and the analysis of the safe remaining trajectories and manoeuvres translates the flexibility of evolution of the aircraft in the vicinity of its current flight position.

### 8.2 Review of the contributions and findings

The study has addressed dynamic autonomy and decision-making issues through a discussion and positioning over safety and risk-management in-flight. More specifically, the findings describe a system given as a possible solution to the reduction of operational accident types like the CFIT (Controlled Flight Into Terrain).

The first contribution addresses the functional architecture initiative of the avionics function concept which has been thought in a framework for the design and evaluation of autonomous systems. The study of accidents of the Airbus Helicopters fleet has permitted to set up a layered approach to system design by insisting on specific functionalities capable of understanding and making objective the CFIT accident loop. In a concern of answering all the operational accidents the global architecture of the system is generic enough to report various operational in-flight emergencies.

## CHAPTER 8. CONCLUSION AND PERSPECTIVES

The second contribution addresses the partitioning of the immediate space around the aircraft with trajectories demonstrating the flexibility of the aircraft, with gradual dynamic solicitation. The constitution of the envelope of feasible trajectories has been performed with a kinematics model extracted from a simulated flight loop. The second contribution has permitted to identify mathematical motion primitives self reliant to characterise accurately the helicopter flight. The method used to construct the model is independent from the helicopter type.

The third contribution has permitted to make objective the aircraft's approach to the terrain with criteria derived from observations of simulated flight scenarios, potentially threatening in terms of collision. This has permitted to derive warning rules as safety indicators, confirmed by the Airbus Helicopters experts.

The fourth contribution addresses the decision-making functionality and more precisely the selection of the best avoidance trajectory solution based on parameters given by Airbus Helicopters experts. Their answers have permitted to parametrise a multicriteria method implemented in the RAMSES avionics function concept architecture: PROMETHEE II which reflects the preferences of the crew in given flight situations; and testifies of a possible autonomous reaction of the system facing a collision threat.

### 8.3 Perspectives and future works for in-flight and ground applications

The research works have been completed in a highly demanding and competitive industrial context. Several practical applications have been envisaged for promoting the results within Airbus Helicopters. For that purpose, some assumptions taken to validate the concepts developed in this work must be reconsidered and improved.

Indeed, one of the main improvements that could be done in this work is to introduce the variations of speed, weight, altitude and complete the aircraft's set of possible manoeuvres in the 3D space frame by introducing motion primitives related to the wind influence. In hilly environments as the case described in the accident analysis 7.2 , the function must be able to take into account variations related to the wind, even if additional safety thresholds must be taken to complete the dynamic risk diagnosis of the flight situation. As an example, in such situations, the RAMSES avionics function concept could compute a degraded version of the manoeuvres under wind constraints as an additional guarantee for safety monitoring. Hence the global envelope of trajectories would contain less performing trajectory solutions from a kinematic perspective, but they would reflect more accurately the operational reality of the flight situation in terms of possible avoidance manoeuvres and danger sight. However, despite the precautions taken to report the wind influence on the aircraft's immediate safety in constrained environments, some flight situations would always require the pilot's experience for the choice of the final escape manoeuvre.

In chapter 6, two different configurations of the criterion type have been presented: the special CFIT configuration (treated in section 7.2, for which the experts have given their feedback) and the normal CFIT configuration.

This illustrates the possibilities of different parametrizations of the Classifier functional bloc composing the RAMSES functional architecture (cf Fig. 3.3). On the same scheme, if necessary, it could be imagined as a perspective that the crew may enter a certain number of preferences via the HMI

Airbus Helicopters and LAMIH-UVHC

## CHAPTER 8. CONCLUSION AND PERSPECTIVES

(Human Machine Interface) (cf Fig. 3.3), to adapt the parametrization of the function to the current operational scenario and by extension to the current mission. In chapter 6, an additional criterion is mentioned, conveying the influence of the danger zones proximity to the ranking of the trajectory solutions. This idea seems worth exploring in the future works.

Moreover, as a perspective, it could be imagined that the second instantiation of PROMETHEE II would take into account these additional preferences, and eventually provide alternative parametrizations to the first instantiation for the choice of the best trajectory solution.

As a short term perspective, it could be considered that the RAMSES avionics function concept could be tested on Airbus Helicopters simulation tools for a chosen helicopter of the fleet, on reconstituted accident scenarios as those explained in 7.2 and 7.3. Thus, the warning rules and the alerting principles recommended by Airbus Helicopters flight test pilots and experts could be reviewed in terms of alarm restitution and potentially extended for completing the decision-making functional bloc. The simulation process is of paramount importance in this study as it ensures a good comprehension of the concepts and innovative ideas studied and experimented in the frame of intelligent systems and embedded architectures.

Eventually, there is a discussion to have around the certification issues of a function like RAMSES in the sense that it could address various levels of in-flight safety; on the one hand there is situation awareness, on the other hand the function presents decision-support capabilities with new alerting principles and a close interface with the crew and the AFCS (Automatic Flight Control System).

The studies conducted for the design of the RAMSES avionics function concept could be an entry point for advanced modes of the AFCS, which is a differentiating key factor in line with the Airbus Helicopters business.

The ground applications for such systems could be very useful within Airbus Helicopters in terms of mission preparation. Some landing areas could present difficult approaches and may require a tool to test all the feasible approaches in order to select the best one, corresponding to the environmental constraints and to the mission type.

The perspective works could also cover issues related to the anti-collision functionalities based on increased situation awareness and in-flight safety monitoring, with the development of autonomous functionalities for the insertion of the aircraft in civil air traffic in order to satisfy the problematic of sense and avoid systems.

## Bibliography

[1] https://www.airbushelicopters.com/website/docs_wsw/pdf/ IN2255-I-00-REV1-FR.pdf. Accessed: 2015-12-2.
[2] http://www.ihst.org/portals/54/2009_SMS_Toolkit_ed2_Final.pdf. Accessed: 2015-12-21.
[3] https://www.informs.org/About-INFORMS/What-is-Operations-Research. Accessed: 2015-12-14.
[4] http://www.roadef.org/content/roadef/pdf/LivreBlancRO.pdf. Accessed: 2015-12-14.
[5] http://rgl.faa.gov/Regulatory_and_Guidance_Library/ rgAdvisorycircular.nsf/0/7ca84861d31651a5862569b2006dbcfe/ \$FILE/ATTOVW46/AC23-18.pdf. Accessed: 2015-12-14.
[6] http://www.promethee-gaia.net/assets/bibliopromethee.pdf. DOI : 10.13140/RG.2.1.1704.392; Accessed: 2015-12-14.
[7] http://wiki.flightgear.org/Flight_Dynamics_Model. Accessed: 2016-0124.
[8] http://www.faa.gov/news/press_releases/news_story.cfm?newsId= 15795. Accessed: 2015-12-18.
[9] https://www.ntsb.gov/investigations/reports_aviation.html. Accessed: 2014-04-17.
[10] http://www.nasa.gov/sites/default/files/files/DRC-012-033_ LicensingWebinar_SlidesHandout.pdf. Accessed: 2015-12-16.
[11] Airbus helicopters presentation, 2014.
[12] D. Aboutajdine, A. Skalli, B. Benchekroun, and A. Artiba, editors. Proceedings of the International Conference on Industrial Engineering and Systems Management (IEEE-IESM'2013), Rabat, Morocco, October 28-30 2013. École Mohammadia d’Ingénieurs de Rabat (EMI), International Institute for Innovation, Industrial Engineering and Entrepreneurship ( $I^{4} \mathrm{e}^{2}$ ). ISBN 9782960053241.
[13] G. Afonso, Z. Baklouti, D. Duvivier, R. Ben Atitallah, and E. Billauer. Heterogeneous cpu/fpga reconfigurable computing system for avionic test application. In Proceedings of the Reconfigurable Architectures Workshop (RAW'13), Boston, USA, May 2013.
[14] A. Artiba, V. Dhaevers, D. Duvivier, and S. Elmaghraby. A Multi-Model Approach for Production Planning and Scheduling in an Industrial Environment, volume 152 of International Series in Operations Research and Management Science, chapter 19, pages 489-530. Kluwer Academic Publishers, 2011.
[15] Z. Baklouti, D. Duvivier, R. Ben-Atitallah, A. Artiba, and N. Belanger. Real-Time Simulator supporting Heterogeneous CPU/FPGA Architecture. In Proceedings of the International Conference on Industrial Engineering and Systems Management (IEEE-IESM'2013) [12], pages 743-750, Rabat, Morocco, October 28-30 2013. École Mohammadia d’Ingénieurs de Rabat (EMI), International Institute for Innovation, Industrial Engineering and Entrepreneurship ( $\mathrm{I}^{4} \mathrm{e}^{2}$ ). ISBN 9782960053241.
[16] M. G. Balchanos. A probabilistic technique for the assessment of complex dynamic system resilience. PhD thesis, 2012. http://hdl.handle. net/1853/43730.
[17] T. F. Banchoff and S. T. Lovett. Differential geometry of curves and surfaces. CRC Press, 2010. ISBN 9781568814568.
[18] P. Banerjee and R. Nevatia. Dynamics based trajectory segmentation for uav videos. In $A d-$ vanced Video and Signal Based Surveillance (AVSS), 2010 Seventh IEEE International Conference on, pages 345-352. IEEE, 2010.
[19] J. Barreiro, M. Do, and D. E. Smith. Guidance \& control, intelligent uas sense-and-avoid utilizing global constraints. Feb 12013 to Feb 28 2014. http: //nari.arc.nasa.gov/ sites/default/files/Smith_iSAA_0.pdf.Accessed2016-01-31.
[20] M. Behzadian, R. Kazemzadeh, A. Albadvi, and M. Aghdasi. Promethee: A comprehensive literature review on methodologies and applications. European Journal of Operational Research, 200(1):198-215, 2010. ISSN 0377-2217, DOI 10.1016/j.ejor.2009.01.021.
[21] C. M. Belcastro. Validation and verification of future integrated safety-critical systems operating under off-nominal conditions. In AIAA Guidance, Navigation, and Control Conference, pages 1-28, 2010.
[22] C. M. Belcastro. Aircraft loss of control: Analysis and requirements for future safety-critical systems and their validation. In Control Conference (ASCC), 2011 8th Asian, pages 399-406. IEEE, 2011.
[23] C. M. Belcastro and J. V. Foster. Aircraft loss-of-control accident analysis. In AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2010.
[24] C. M. Belcastro and S. R. Jacobson. Future integrated systems concept for preventing aircraft loss-of-control accidents. In AIAA Guidance, Navigation, and Control Conference, pages 2-5, 2010.

Airbus Helicopters and LAMIH-UVHC
[25] R. Ben Atitallah, G. Afonso, N. Belanger, M. Rubio, and N. Damiani. Hybrid and multicore optimized architectures for test and simulation systems. In Proceedings of the Sixth International Conference on Simulation Tools and Techniques (ICST-SIMUTOOLS'13). ACM, July 2013. DOI 10.4108/icst.simutools.2013.251759.
[26] Y. Bestaoui. General representation of 3d curves for an unmanned aerial vehicle using the frenet-serret frame. AIAA, 2007.
[27] Y. Bestaoui and E. Kahale. Generation of time optimal trajectories of an autonomous airship. In Robot Motion and Control 2011, pages 319-329. Springer, 2012.
[28] P. Bezier. Essais de definition numeriques des courbes et surfaces non mathematiques. Systeme Unisurf, Automatisme, 13, 1968.
[29] J.-D. Boissonnat, A. Cérézo, and J. Leblond. Shortest paths of bounded curvature in the plane. Springer, 1993. ISBN 978-3-540-57132-2; pages 3-18.
[30] C. L. Bottasso, D. Leonello, and B. Savini. Path planning for autonomous vehicles by trajectory smoothing using motion primitives. Control Systems Technology, IEEE Transactions on, 16(6):1152-1168, 2008.
[31] D. Boukraa, Y. Bestaoul, and N. Azouz. Transition trajectories characterization of an uninhabited aerial vehicle. In Digital Avionics Systems Conference, 2005. DASC 2005. The 24th, volume 2, page 8. IEEE, 2005.
[32] J. Brans. L'ingénierie de la décision : élaboration d'instruments d'aide à la décision. La méthode PROMETHEE. Presses de l'Université Laval, 1982.
[33] J. Brans and B. Mareschal. PROMCALC \& GAIA: A new decision support system for multicriteria decision aid. Decision Support Systems (DSS), 12:297-310, 1994.
[34] J. Brans and B. Mareschal. PROMETHEE-GAIA. Une Méthodologie d'Aide à la Décision en Présence de Critères Multiples. Ellipses, Paris, France, 2002. ISBN 2729812539.
[35] J. Brans and P. Vincke. A preference ranking organisation method: The promethee method for mcdm. Management Science, 1985.
[36] J. Brans, P. Vincke, and B. Mareschal. How to select and how to rank projects: The promethee method. European journal of Operational Research, 24:228-238, 1986.
[37] C. G. Cassandras and S. Lafortune. Introduction to Discrete Event Systems. Springer, New York, 2. edition, 2008. ISBN 9780387333328, DOI 10.1007/978-0-387-68612-7.
[38] C. M. Chamberlin, J. Edwards, A. Schulte, R. Taylor, and M. Waters. Chapter 5 - artificial cognition and co-operative automation chapter lead: A. schulte, July 2007.
[39] H. Chitsaz and S. M. LaValle. Time-optimal paths for a dubins airplane. In Decision and Control, 2007 46th IEEE Conference on, pages 2379-2384. IEEE, 2007.
[40] B. T. Clough. Metrics, schmetrics! how the heck do you determine a uav's autonomy anyway. Technical report, DTIC Document, 2002.
[41] Y. Collette and P. Siarry. Optimisation multiobjectif. Algorithmes: Eyrolles. Eyrolles, 2002. ISBN 9782212111682.
[42] D. Dey, C. Geyer, S. Singh, and M. Digioia. Passive, long-range detection of aircraft: Towards a field deployable sense and avoid system. In Field and Service Robotics, pages 113-123. Springer, 2010.
[43] S. Dicheva and Y. Bestaoui. 3d waypoint generation in a dynamic environment for an airborne launch mission. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2011.
[44] X. Ding and C. Fang. A novel method of motion planning for an anthropomorphic arm based on movement primitives. Mechatronics, IEEE/ASME Transactions on, 18(2):624-636, 2013.
[45] J. S. Dittrich, F.-M. Adolf, and S. Schopferer. Impact of obstacle sensor choice on preliminary umanned helicopter design and mission performance in obstacle fields. 2015.
[46] L. E. Dubins. On curves of minimal length with a constraint on average curvature, and with prescribed initial and terminal positions and tangents. American Journal of mathematics, pages 497-516, 1957.
[47] C. DUHAMEL, E. CHATELET, A. C. SANTOS, and B. BIRREGAH. An optimization model for the post-disaster response in terms of system resilience. 2013. Workshop Interdisciplinaire sur la Securite Globale.
[48] D. Duvivier. Contributions au couplage de l'optimisation et de la simulation. Thèse d'habilitation à diriger des recherches, Université de Valenciennes et du Hainaut-Cambrésis, LAMIH UMR CNRS 8201, Valenciennes, France, Sept. 2015.
[49] D. Duvivier, N. Meskens, and M. Ahues. A fast multicriteria decision-making tool for industrial scheduling problems. International Journal of Production Economics (IJPE), 145(2):753760, 2013. ISSN 0925-5273, DOI 10.1016/j.ijpe.2013.05.028.
[50] D. Duvivier, O. Roux, V. Dhaevers, N. Meskens, and A. Artiba. Multicriteria optimisation and simulation: an industrial application. Annals of Operations Research (AOR), 156(1):45-60, 2007. DOI 10.1007/s10479-007-0228-7.
[51] EHEST. Ehest analysis of $2000-2005$ europeean helicopter accidents. Technical report, EHEST, 2010. ISBN 92-9210-095-7.
[52] M. R. Endsley. Toward a theory of situation awareness in dynamic systems. Human Factors: The Journal of the Human Factors and Ergonomics Society, 37(1):32-64, 1995.
[53] F. Ferrandez and T. Brenac. L'étude détaille d'accidents orientée vers la sécurité primaire: méthodologie de recueil et de pré-analyse. Presses de l'Ecole Nationale des Ponts et Chaussées, 1995.
[54] S. GERIN. Une démarche évaluative des Plans de Prévention des Risques dans le contexte de l'assurance des catastrophes naturelles. PhD thesis, Paris, Univ. Paris VII.,modifiée, 2011.
[55] S. HIMA and Y. BESTAOUI. Nonholonomic motion generation on trim aerostatics trajectories for an autonomous underactuated airship. 4th International Airship Convention and Exibition, 2002.
[56] S. Hota and D. Ghose. Optimal path planning for an aerial vehicle in 3d space. In Decision and Control (CDC), 2010 49th IEEE Conference on, pages 4902-4907. IEEE, 2010.
[57] S. Hota and D. Ghose. Optimal trajectory planning for unmanned aerial vehicles in threedimensional space. Journal of Aircraft, 51(2):681-688, 2014.
[58] M. Hwangbo, J. Kuffner, and T. Kanade. Efficient two-phase 3d motion planning for small fixed-wing uavs. In Robotics and Automation, 2007 IEEE International Conference on, pages 1035-1041. IEEE, 2007.
[59] Z. Jiang and R. Ordónez. Trajectory generation on approach and landing for rlvs using motion primitives and neighboring optimal control. In American Control Conference, 2007. ACC'07, pages 1091-1096. IEEE, 2007.
[60] E. B. K. Kajantie and E. Byckling. Particle kinematics. Three Particle Final State, JohnWiley \& Son Ltd, 1973.
[61] V. P. Kostov, E. V. Degtiariova-Kostova, et al. The planar motion with bounded derivative of the curvature and its suboptimal paths. Acta Math. Univ. Comenianae, 64(2):185-226, 1995.
[62] P. Ky and B. Miaillier. Sesar: towards the new generation of air traffic management systems in europe. Journal of Air Traffic Control, 48(1), 2006.
[63] A. Lampe and R. Chatila. Performance measure for the evaluation of mobile robot autonomy. In Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on, pages 4057-4062. IEEE, 2006.
[64] T. Langer, A. Belyaev, and H.-P. Seidel. Analysis and design of discrete normals and curvatures. 2005.
[65] J.-P. Lebailly and N. Belanger. About the influence of virtualization and open source technologies on v\&v lifecycle. International Journal on Advances in Systems and Measurements, 4(3-4):147-156, 2011. http://www.iariajournals.org/systems_and_measurements/.
[66] J. Litt, Y. Liu, T. S. Sowers, A. K. Owen, and T.-H. Guo. Piloted Simulation Evaluation of a Model-Predictive Automatic Recovery System to Prevent Vehicle Loss of Control on Approach. 2014.
[67] B. MacAllister, J. Butzke, A. Kushleyev, H. Pandey, and M. Likhachev. Path planning for non-circular micro aerial vehicles in constrained environments. In Robotics and Automation (ICRA), 2013 IEEE International Conference on, pages 3933-3940. IEEE, 2013.
[68] B. Mareschal. Weight stability intervals in multicriteria decision aid. European Journal of Operational Research, 33:54-64, 1988.
[69] B. Mareschal and J. Brans. Geometrical representations for mcda. the gaia module. European Journal of Operational Research, 34:69-77, 1988.
[70] Murphy, Robin, and J. Shields. Dod defense science board task force report: The role of autonomy in dod systems. Technical report, DoD, 2012.
[71] R. Nadeau and M. Landry. L'Aide à la décision: nature, instruments et perspectives d'avenir. Sciences de l'administration. Presses de l'Université Laval, 1986. ISBN 9782763770840.
[72] K. Nikolajevic, N. Belanger, D. Duvivier, R. Ben Atitallah, and A. Artiba. A method to compute efficient 3d helicopters flight trajectories based on a motion polymorph-primitives algorithm. In Proceedings of the International Conference on Control and Automation Systems (ICCAS 2015), Amsterdam, The Netherlands, Aug. 2015.
[73] R. Onken. Cognitive cooperation for the sake of the human-machine team effectiveness. Technical report, DTIC Document, 2003.
[74] K. A. Ouedraogo, S. Enjalbert, and F. Vanderhaegen. How to learn from the resilience of human-machine systems? In Analysis, Design, and Evaluation of Human-Machine Systems, volume 11, pages 374-379, 2010.
[75] N. Ozalp and O. K. Sahingoz. Optimal uav path planning in a 3d threat environment by using parallel evolutionary algorithms. In Unmanned Aircraft Systems (ICUAS), 2013 International Conference on, pages 308-317. IEEE, 2013.
[76] M. J. Pariès, E. Hollnagel, M. J. Wreathall, and D. D. Woods. Resilience engineering in practice: A guidebook. Ashgate Publishing, Ltd., 2012.
[77] C. Patchett and D. Ansell. The development of an advanced autonomous integrated mission system for uninhabited air systems to meet uk airspace requirements. In Intelligent Systems, Modelling and Simulation (ISMS), 2010 International Conference on, pages 60-64. IEEE, 2010.
[78] P. Pharpatara, B. Hérissé, and Y. Bestaoui. 3d-shortest paths for a hypersonic glider in a heterogeneous environment. In Workshop on Advanced Control and Navigation for Autonomous Aeroespace Vehicles-ACNAAV 2015, 2015.
[79] P. Pharpatara, B. Hérissé, R. Pepy, and Y. Bestaoui. Sampling-based path planning: a new tool for missile guidance. In 19th IFAC Symposium on Automatic Control in Aerospace, volume 19, pages 131-136, 2013.
[80] M. Pivtoraiko, D. Mellinger, and V. Kumar. Incremental micro-uav motion replanning for exploring unknown environments. In Robotics and Automation (ICRA), 2013 IEEE International Conference on, pages 2452-2458. IEEE, 2013.
[81] J.-C. Pomerol. Decision-Making and Action. ISTE. Wiley, Aug. 2012. ISBN 9781848214101.
[82] J.-C. Pomerol and S. Barba-Romero. Multicriterion decision making in management: Principles and practice. Kluwer, New York, 2000.
[83] J. Reason. Human error: models and management. Bmj (British Medical Journal), 320(7237):768-770, 2000.
[84] J. Reeds and L. Shepp. Optimal paths for a car that goes both forwards and backwards. Pacific journal of mathematics, 145(2):367-393, 1990.
[85] O. Roux, D. Duvivier, V. Dhaevers, N. Meskens, and A. Artiba. A multicriteria approach to rank scheduling strategies. International Journal of Production Economics (IJPE), 112(1):192-201, 2008. DOI10.1016/j.ijpe.2006.08.020.
[86] R. G. Sanfelice and E. Frazzoli. On the optimality of dubins paths across heterogeneous terrain. In Hybrid Systems: Computation and Control, pages 457-470. Springer, 2008.
[87] A. A. Shabana. Dynamics of multibody systems. Cambridge university press, 2013.
[88] M. Shah and N. Aouf. 3d cooperative pythagorean hodograph path planning and obstacle avoidance for multiple uavs. In Cybernetic Intelligent Systems (CIS), 2010 IEEE 9th International Conference on, pages 1-6. IEEE, 2010.
[89] M. Shanmugavel, A. Tsourdos, R. Zbikowski, B. A. White, C. Rabbath, and N. Lechevin. A solution to simultaneous arrival of multiple uavs using pythagorean hodograph curves. In American Control Conference, 2006, page 6. IEEE, 2006.
[90] S. Simonovic. Understanding risk management. In Proceedings of the 30th Annual conference of CSCE, Montreal, Quebec, Paper GE108, page 12, 2002.
[91] O. Souissi. Path planning on a high performance Heterogeneous CPU/FPGA Architecture. PhD thesis, Université de Valenciennes et du Hainaut-Cambrésis, Valenciennes, France, Dec. 2015. Soutenue le 12 Janvier 2015.
[92] O. Souissi, R. Ben Atitallah, D. Duvivier, and A. Artiba. Optimization of matching and scheduling on heterogeneous cpu/fpga architectures. In Proceedings of the 7th IFAC Conference on Manufacturing Modelling, Management, and Control (MIM'13), Saint Petersburg, Russia, June 2013.
[93] O. Souissi, R. Ben-Atitallah, D. Duvivier, A. Artiba, N. Belanger, and P. Feyzeau. Path Planning: A 2013 Survey. In Proceedings of the International Conference on Industrial Engineering and Systems Management (IEEE-IESM'2013) [12], pages 849-856, Rabat, Morocco, October 28-30 2013. École Mohammadia d'Ingénieurs de Rabat (EMI), International Institute for Innovation, Industrial Engineering and Entrepreneurship ( $\mathrm{I}^{4} \mathrm{e}^{2}$ ). ISBN 9782960053241.
[94] H. J. Sussmann. Shortest 3-dimensional paths with a prescribed curvature bound. In Decision and Control, 1995., Proceedings of the 34th IEEE Conference on, volume 4, pages 3306-3312. IEEE, 1995.
[95] D. E. Swihart, A. F. Barfield, E. M. Griffin, R. C. Lehmann, S. C. Whitcomb, B. Flynn, M. Skoog, K. E. Processor, et al. Automatic ground collision avoidance system design, integration, \& flight test. Aerospace and Electronic Systems Magazine, IEEE, 26(5):4-11, 2011.
[96] U. J. H. S. A. Team. The compendium report: The u.s. jhsat baseline of helicopter accident analysis. Technical report, IHST, 2011.
[97] A. Travers. Reactive planning and mps: Two pieces to the autonomous puzzle. In AI, Simulation and Planning in High Autonomy Systems, 1992. Integrating Perception, Planning and Action., Proceedings of the Third Annual Conference of, pages 194-200. IEEE, 1992.
[98] B. Vanek, T. Péni, P. Bauer, and J. Bokor. Vision only sense and avoid: A probabilistic approach. In American Control Conference (ACC), 2014, pages 1204-1209. IEEE, 2014.
[99] T. R. Wan, W. Tang, and H. Chen. A real-time 3d motion planning and simulation scheme for nonholonomic systems. Simulation Modelling Practice and Theory, 19(1):423-439, 2011.
[100] J. Yang, Y. Li, and K. Wang. Invariant trajectory indexing for real time 3d motion recognition. In Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on, pages 3440-3445. IEEE, 2011.
[101] J. Yang, J. Yuan, and Y. Li. Flexible trajectory indexing for 3d motion recognition. In Applications of Computer Vision (WACV), 2015 IEEE Winter Conference on, pages 326-332. IEEE, 2015.
[102] K. Yang, S. K. Gan, and S. Sukkarieh. An efficient path planning and control algorithm for ruavís in unknown and cluttered environments. Journal of Intelligent and Robotic Systems, 57(1-4):101-122, 2010.
[103] S. H. Young, T. A. Mazzuchi, and S. Sarkani. A model-based framework for predicting performance in self-adaptive systems. Procedia Computer Science, 28:513-521, 2014.
[104] B. Zeigler. Guide to Modeling and Simulation of Systems of Systems - User's Reference. SpringerBriefs in Computer Science. Springer, London, 2013. ISBN 9781447145691 , DOI 10.1007/978-1-4471-4570-7.
[105] B. Zeigler, T. G. Kim, and H. Praehofer. Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems. Academic Press, New York, 2000. 2nd Edition, ISBN 9780127784557.
[106] B. Zeigler and H. S. Sarjoughian. Guide to Modeling and Simulation of Systems of Systems. Simulation Foundations, Methods and Applications. Springer, London, 2012. ISBN 9780857298645, DOI 10.1007/978-0-85729-865-2.
[107] B. P. Zeigler. Theory of Modeling and Simulation. Wiley Interscience, New York, 1976. 1st Edition, ISBN 0127784551.
[108] B. P. Zeigler. Multifacetted Modeling and Discrete Event Simulation. Academic Press, London, Orlando, 1984. ISBN 9780127784502.

Airbus Helicopters and LAMIH-UVHC
[109] B. P. Zeigler. Theory of Modeling and Simulation. Krieger Publishing Compagny, 1984. 2nd Edition, ISBN 978-0898748086.
[110] T. I. Ören, B. P. Zeigler, and M. S. Elzas, editors. Simulation and Model-Based Methodologies: An Integrative View, volume 10 of NATO ASI Series. Springer-Verlag, Berlin, 1984. ISBN 9783642821462, DOI 10.1007/978-3-642-82144-8.

## Appendix A

## Approaching the curvature and the torsion by discrete computation methods

The RAMSES Trajectory Generation functional bloc is one of the contributions of this thesis. It is developed in chapter 4. This functionality relies on accurate computations of emergency trajectories feasible by a helicopter from the study of the flight loop data. The research method adopted in the thesis consists of smoothing the data with Bezier curves before extracting the intrinsic properties of each characteristic movement of the aircraft, translated by the curvature, the torsion and their derivatives.

In order to justify this choice we have tested two alternative methods to approach the curvature and the torsion, on row flight data without smoothing the recordings, with discrete computation methods:

- From the Frenet-Serret formulas, where the curvature is computed in the $(\mathbf{X}, \mathbf{Y})$ plane with two points, and the torsion is computed in 3D by considering variations on three different points,
- Using the approach formulated in [64]. by Langer et al., Max Planck Institute für Informatik ${ }^{1}$, by computing the curvature on three points and the torsion on five points.

Using the Frenet-Serret formulas:

$$
\left\{\begin{array}{l}
\frac{d \mathbf{T}}{d s}=\kappa \mathbf{N}  \tag{A.1}\\
\frac{d \mathbf{N}}{d s}=-\kappa \mathbf{T}+\tau \mathbf{B} \\
\frac{d \mathbf{B}}{d s}=-\tau \mathbf{N}
\end{array}\right.
$$

where the two scalars $\kappa$ and $\tau$ are respectively the curvature and the torsion and $\mathbf{T}, \mathbf{B}$ and $\mathbf{N}$ are respectively the tangent, binormal and normal vectors constituting the Frenet-Serret frame (Fig. 4.4).

Discrete expressions of the curvature and the torsion can be derived from the Frenet-Serret formulas in Cartesian coordinates as:

[^17]\[

\left\{$$
\begin{array}{l}
\kappa=\frac{x^{\prime \prime} y^{\prime}-y^{\prime \prime} x^{\prime}}{\left(x^{\prime 2}+y^{\prime 2}\right)^{3 / 2}}  \tag{A.2}\\
\tau=\frac{x^{\prime \prime \prime}\left(y^{\prime} z^{\prime \prime}-z^{\prime} y^{\prime \prime}\right)+y^{\prime \prime \prime}\left(x^{\prime \prime} z^{\prime}-x^{\prime} z^{\prime \prime}\right)+z^{\prime \prime \prime}\left(x^{\prime} y^{\prime \prime}-x^{\prime \prime} y^{\prime}\right)}{\left(y^{\prime} z^{\prime \prime}-y^{\prime \prime} z^{\prime}\right)^{2}+\left(x^{\prime \prime} z^{\prime}-x^{\prime} z^{\prime \prime}\right)^{2}+\left(x^{\prime} y^{\prime \prime}-x^{\prime \prime} y^{\prime}\right)^{2}}
\end{array}
$$\right.
\]

The approach covered by Langer et al in [64] also provide a discrete method for computing the curvature and the torsion. However the method uses five points in order to obtain a better accuracy in the results contrary to the expressions of curvature and torsion in equations A. 2 where the curvature and the torsion are computed with only three points. Moreover, the curvature expression given by the Frenet-Serret formulas does not take into account the vertical component of the positions. It is a plane calculation.

The results of the two methods are displayed in Figs. A. 1 to A. 5 on different flight data. Figs. A.1, A. 2 and A. 3 display the results of discrete curvature and torsion of the two methods cited previously on mathematically computed space curves with variations in torsion and curvature. The space curves calculations have been detailed in chapter 4; this is the 3D spiral transition, which can take three different shapes (cf Fig. 4.20).

The 3D spiral transition is $\mathcal{C}^{3}$ (see chapter 4). Thus, it is possible to compute the torsion and the curvature with equations A.1.

It may be observed on Figs. A.1, A. 2 and A. 3 that both methods for computing the torsion are very close; taken together the results show very little difference and point in the same direction towards the final torsion value given analytically by $\tau=\kappa_{\max } \tan \left(\theta_{\max }\right)$, where $\kappa_{\max }$ is the maximum curvature and $\theta_{\max }$ the final angle of climb reached at the end of the space curve. The curvature is supposed to vary linearly in all cases for this space curve (see chapter 4), however it can be noticed that when the torsion varies strongly the discrete curvature computation given by the Frenet-Serret formulas is not compliant with the curve behaviour anymore, while the method suggested in [64] gives a satisfying approach of the curvature. This phenomenon can be explained by the fact that when the torsion becomes important, the difference between two consecutive osculating planes (Fig. 4.4) becomes important too. The curvature, derived from the Frenet-Serret formulas, does not take into this difference because it is computed in the $(\mathbf{X}, \mathbf{Y})$ plane. For that reason Fig. A. 3 shows the limits of this method. The more the torsion increases the more the curvature computed with Frenet-Serret formulas is diverging.

Figs. A. 4 and A. 5 display the results on computations of discrete curvature and torsion on flight data, respectively the path-planning data produced in simulation and the flight data provided by the Airbus Helicopters Flight Safety Department in relation with the accident study covered in chapter 7. It is clearly noticeable that the discrete values of the curvature and the torsion on the flight data results, do not allow the identification of representative motion behaviours. Actually, these curves do not represent a smooth path, even those recorded during a real flight because the helicopter flight is not smooth at all. In reality, a helicopter flight goes through up and down phases generated by the turbulences of the atmosphere. For that reason, the curves displayed in Figs. A. 4 and A. 5 are not continuous, and require an appropriate smoothing before computing the curvature and torsion distributions, because these computations require the curve to be $\mathcal{C}^{3}$.

## APPENDIX A. APPROACHING THE CURVATURE AND THE TORSION

In order to identify clear variations in curvature and torsion along the recorded flight paths generated in simulation and taken from real flight missions, in this study, the flight data has been smoothed with the Bezier curves [28], before extracting the curvature and the torsion characteristic values. Given that Bezier curves are polynomials, they are $\mathcal{C}^{\infty}$ and therefore $\mathcal{C}^{3}$.

The results presented in this section testify that the curvature and torsion of the flight data cannot be approximated otherwise, by discrete methods for example, because the row flight data is discontinuous.






Figure A.2. Three-dimensional Euler spiral, with linear curvature and torsion.
$3 D$ representation of the space curve





Figure A.3. Space curve computed with increasing torsion.
$3 D$ representation of the space curve





Figure A.4. Analysis of path-planning recordings for the Dubins Gliding Symmetry curve fitting, with opposite curvature at it ends. The results have been produced with the simulated Airbus Helicopters Basic Flight Loop.


Figure A.5. Analysis of the helicopter path of the use case developed in Chapter 7. Curvature and Torsion values computed with two

## Appendix B

## TAWS Bench

The TAWS is not adapted in a context of warning in areas with high density of obstacles, because of the many false alarms due to the extrapolation of the speed vector, which does not reflect the operational reality of the flight.

A part of the study is dedicated to the establishment of new warning rules based on a threat perception derived from interviews with Airbus Helicopters flight test pilots.

For that reason, complete initial conditions of the helicopter are used, i.e., the speed vector, the acceleration vector and their variations.

The discretization of the surrounding environment of the helicopter is done for $30-40$ seconds of flight with feasible trajectories computed in the 3D space frame in all directions around the helicopter, without overcoming the flight envelope .

These trajectories are evaluated with respect to the collision risk of the extrapolated trajectory to 30 seconds of flight, characteristic of the current flight situation, in order to establish a collision risk distribution around the helicopter.

The best avoidance trajectory solution is computed in real-time and available in emergency case, as a suggestion to the crew; the best avoidance trajectory solution is not necessary displayed to the pilot.

The best avoidance trajectory solution is chosen by the Decision Making functional bloc of the RAMSES avionics function concept. The Decision Making functional bloc relies on rules derived from the Airbus Helicopters flight test pilots expertise, put in a situation of in-flight emergency, in the case of a specific accident scenario.

In Fig. B. 1 and B.2, an alternative flight route is computed with the path-planning tool detailed in [91], in the case a dynamic mission replanning is needed.

Figure B.1. Case when the simulated TAWS detects a danger while the extrapolated trajectory of the current state does not encounter a collision threat

Figure B.2. Case when the simulated TAWS does not detect a danger threat while the extrapolated trajectory of the current state
enters in collision with a danger zone


[^0]:    ${ }^{1}$ Air Traffic Controller

[^1]:    ${ }^{2}$ In this manuscript, real-time refers to what is more commonly called soft real-time in the research literature in this field.
    ${ }^{3}$ http://www.ihst.org
    ${ }^{4}$ http://easa.europa.eu/essi/ehest/
    ${ }^{5}$ Visual Meteorological Conditions

[^2]:    ${ }^{6}$ Controlled Flight Into Terrain

[^3]:    ${ }^{7}$ Instrumental Meteorological Conditions
    Airbus Helicopters and LAMIH-UVHC

[^4]:    ${ }^{1}$ http://astraea.aero
    ${ }^{2}$ http://www.midcas.org

[^5]:    ${ }^{3}$ The acronym GN \& C in Fig. 2.1 refers to Guidance Navigation and Control functions.

[^6]:    ${ }^{4}$ https://en.wikipedia.org/wiki/Terrain-awareness-and-warning-system
    ${ }^{5}$ https://en.wikipedia.org/wiki/Traffic-collision-avoidance-system

[^7]:    ${ }^{6}$ Terrain Avoidance Warning System
    ${ }^{7}$ Helicopter Terrain Avoidance Warning System

[^8]:    ${ }^{8}$ http://www.promethee-gaia.net

[^9]:    ${ }^{1}$ The aircraft accident investigation boards (per country) are listed at http://aviation-safety.net/investigation/aaibs.php

[^10]:    ${ }^{1}$ This method has been developed with Airbus Helicopters simulation tools in order to test and validate the RAMSES avionics function concept. It has to be compliant with the use of any other Airbus Helicopters simulated flight loop.

[^11]:    ${ }^{2}$ taken from https://en.wikipedia.org/wiki/Frenet-Serret-formulas
    ${ }^{3}$ The heading, in navigation, is the direction the aircraft's nose is pointing while the orientation of the aircraft may also include a vertical component.

[^12]:    ${ }^{4}$ The period between two flight points highly depends on the flight recordings provided by the Airbus Helicopters Flight Safety department for testing the RAMSES avionics function concept. Thereafter, several practical use cases will be developed either for validating the algorithms partially or for testing the global system.

[^13]:    In this chapter, the Risk Assessment of the current flight situation is approached in three steps. The first step describes the collision estimation method for a given trajectory among the global envelope of trajectories computed by the Trajectory Generation functional bloc, with respect to a danger zone or directly to the terrain elevation data base. The second step explains how the criteria necessary to the risk characterisation of each trajectory solution and of the current flight situation, are derived from the observations of typical possible collision scenarios, and what operational reality they are conveying

[^14]:    ${ }^{1}$ Operational barriers refer to actions (avoidance manoeuvres) that could be performed by the crew of the automatic pilot in case of emergency. Analytical barriers refer to the analysis of the flight patterns studied in chapter 5 and the evolution of the set of avoidance trajectory solutions with respect to the danger zones precomputed above the terrain elevation data base used for the tests.

[^15]:    ${ }^{2}$ Open Graphics Library, OpenGL.org
    ${ }^{3}$ It is possible that the rendering of the environment and the 3D coordinates is not $100 \%$ accurate regarding to elevation precisions given by the GPS. Besides, the scene rendering in the simulation might appear visually more compacted, this is due to the scene stretching.
    ${ }^{4}$ Google Earth, https://www.google.com/earth/

[^16]:    ${ }^{5}$ Coordinated Universal Time

[^17]:    ${ }^{1} / /$ www.mpi-inf.mpg.de/home/

